
DRILLING MUD SELECTION AND WELLBORE STABILITY: A PHYSICOCHEMICAL APPROACH

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Abstract: *Wellbore instability has been a great challenge in drilling operations, particularly in geologically reactive formations such as those encountered in the Azerbaijani section of the South Caspian Basin. This paper discusses, in particular, the selection and optimization of drilling muds from a physicochemical point of view, with emphasis on the chemical composition and rheology of drilling mud and their impact on wellbore stability. The interaction of drilling fluids with reactive shales in terms of hydration, ion exchange, and osmotic effects is also discussed in this paper, particularly in terms of structural stability. The application of glycol-based inhibitive drilling fluids and chemical additives to prevent clay swelling and fluid loss is also discussed in this paper. The findings of this paper, therefore, underscore the importance of chemical engineering in drilling mud to improve wellbore stability and prevent loss of drilling mud in drilling operations.*

Keywords: *wellbore stability, drilling mud, physicochemical properties, reactive shales, glycol-based fluids, ion exchange, rheology, south caspian basin, fluid-rock interaction, equivalent circulating density*

INTRODUCTION

Wellbore stability analysis is considered one of the greatest challenges in modern drilling engineering, particularly in complex geological environments characterized by abnormal formation pressures, poor shale strength, and fractured formations. During well drilling operations, disruption of the balance of natural stress in the formation can lead to various instability phenomena such as cavern formation, constrictions, and collapse in the formation. As regards the Azerbaijani oil and gas fields, in the course of previous investigations, it has been noted that instability phenomena are directly related to the geo-complexity of the formation and abnormal formation pressures during well drilling operations. Apart from geo-mechanical properties, the physicochemical properties of drilling fluids play a crucial role in wellbore stability analysis. Incorrect rheological properties of drilling fluids can lead to rapid degradation of shale due to structural instability of drilling fluids and interactions with formations [1-5]. The Azerbaijani part of the South Caspian Basin is characterized by highly reactive shale formations, rapid compaction, and abnormal formation pressures. Therefore, it is important to address this problem by considering the geological prediction and optimization of the drilling fluid. Hydration reactions, ion exchange reactions, and osmotic pressures in the interactions between the drilling fluids and clay minerals directly affect the strength of the rock. The physicochemical principles developed recently consider the drilling fluids not only as mechanical mediums for circulation but also as chemically active mediums capable of controlling the behavior of the formation. It is evident that the inhibitive glycol-based mud systems possess tremendous potential in controlling the swelling of clay and enhancing the efficiency in the process [6-8]. Moreover, the optimized drilling fluids and cement slurry systems in the fractured reservoir formations play an important role in the minimization of

filtrate invasion and the structural integrity of the wellbore environment [9]. Investigations carried out on the mechanical properties of the rocks and the behavior of the formation revealed the importance of the compatibility between the drilling fluid and the mineralogy of the rock to ensure safe operations [10]. The recent developments in the intelligent monitoring and management of the uncertainties in the oil and gas production process have underlined the importance of integrating physicochemical principles with control strategies [11]. The fuzzy probabilistic evaluation of drilling mud losses, which is an advanced analytical tool, offers new opportunities in predicting instability risks in complex geological environments [12]. Additionally, in the case of deviated wells, it has been emphasized that it is important to consider geological, technological, and technical aspects in association with chemical stabilization mechanisms to ensure wellbore stability during drilling operations. It has also been highlighted that modifications in drilling and cementing systems, which incorporate chemical additives, have been successful in enhancing the mechanical, filtration, and isolation properties in wells [13,14].

From all these aspects, it can be concluded that there is a need to carry out experimental evaluation of wellbore stability from a physicochemical point of view. Hence, the primary objective of this study is to evaluate wellbore stability through experimental investigations of different drilling mud systems, which include inhibitive, polymer-based, and chemically formulated mud systems.

EXPERIMENTAL PART

Three exemplary formulations of drilling mud were developed to examine the physicochemical processes that control wellbore stability in the presence of shale reactivity and fracture-prone formations. The three mud systems have been formulated to correspond to widely used inhibitive, polymer-based, and chemically optimized drilling fluids that are presently being used in modern drilling operations.

Glycol-Based Inhibitive Water-Based Mud (Mud A):

The aim of the formulation of the inhibitive water-based mud system is to ensure the development of an effective mud system that is capable of effectively reducing the hydration and swelling behavior in the shale formation. The formulation of the inhibitive water-based mud system was achieved by incorporating ethylene glycol with the formula $C_2H_6O_2$, 5 wt.% as the inhibitive additive capable of effectively stabilizing the hydration shell formed by the clay particles. Furthermore, the formulation of the inhibitive water-based mud system also included the incorporation of the biopolymer-based viscosifier capable of reducing the invasion of filtrate into the shale formation. This was achieved by incorporating the additive known as xanthan gum with the formula $C_{35}H_{48}O_{29}$, 0.5 wt.%. Moreover, the formulation included the incorporation of sodium chloride with the formula 2 wt.% as the additive capable of reducing the ionic concentration.

Polymer Enhanced Water-Based Mud (Mud B):

The development of the polymer-enhanced water-based mud system was aimed at improving the mechanical properties, both in suspensions and filtration. The rheology modifier used in the system was polyacrylamide, with the molecular formula C_3H_5NO and 0.8 wt.% concentration. Potassium chloride, which was used as the shale stabilizer during the development of the water-based mud system, was used with 3 wt.% concentration. This is because the compound is capable of exchanging ions with the clay particles, thus preventing the dispersion. In addition, bentonite with the molecular formula $Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$ was used with 3 wt.% concentration in the system to enhance the quality of the filter cake as well as prevent fluid loss.

Chemically Optimized Deep Water/Fractured Reservoir Mud (Mud C):

The objective of the formulation of the chemically optimized deep water/fractured reservoir mud is to simulate the conditions that are normally encountered in deep water reservoirs and naturally fractured reservoirs. In the formulated system, ethylene glycol with the chemical formula $C_2H_6O_2$ is included in the system at a concentration of 3 wt.% as a chemical inhibitor to prevent swelling in shale. In addition, hydroxyethyl cellulose with the chemical formula $C_2H_4O \cdot C_6H_{10}O_5$, which is a viscosifier in the formulated system, is also included in the system at a concentration of 1 wt%.

Table 1

Chemical Composition and Target Functions of Tested Muds

Mud Type	Additive	Formula	Concentration (% w/w)	Function
Mud A	Ethylene glycol	$C_2H_6O_2$	5	Clay swelling inhibition
	Xanthan gum	$C_{35}H_{48}O_{29}$	0.5	Rheology & fluid loss control
	Sodium chloride	NaCl	2	Ionic strength / osmotic control
Mud B	Polyacrylamide	$(C_3H_5NO)_n$	0.8	Viscosity enhancement
	Potassium chloride	KCl	3	Shale stabilization (cation exchange)
	Bentonite	$Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$	3	Filtration control & yield stress
Mud C	Ethylene glycol	$C_2H_6O_2$	3	Clay inhibitor
	Hydroxyethyl cellulose	$(C_2H_4O \cdot C_6H_{10}O_5)_n$	1	Rheology modifier
	Calcium carbonate	$CaCO_3$	2	Filtration & cement compatibility
	Nitromethyl-phosphonic acid	CH_3NO_4P	0.5	Reactive shale chemical stabilization

Table 1 above highlights the chemical composition, concentration ranges, and targeted functional role of the drilling mud systems used in this study. The formulations used in this study were developed to represent different physicochemical stabilization mechanisms used in contemporary drilling wells. Mud A was formulated to be an inhibitive glycol-based system that targets minimizing hydration of shales and swelling of clays through inhibitive chemistry and ionic regulation. On the other hand, Mud B was formulated to be a water-based system that incorporates polymers to enhance rheology and improve efficiency in cutting and clay interaction through polymers and ion exchange chemistry. Mud C was formulated to be a chemically optimized system for use in deepwater wells and naturally fractured reservoirs where fluid compatibility, efficiency in cutting and clay interaction, and chemical stabilization of reactive formations are critical.

Experimental Setup

All experimental studies were conducted with a view to evaluating the physicochemical properties of the selected drilling fluids under conditions simulating the

behavior of shale-reactive formations and complex drilling processes.

Mud Preparation Procedure

The preparation of the drilling fluids was carried out under controlled conditions in the laboratory with the aim of simulating the physicochemical properties of the drilling fluids. The processes of mixing the drilling fluids were carried out under constant temperature conditions of 25 °C and pH 8.0 ± 0.2. The progressive addition of the different substances to the basic fluid, with constant mechanical stirring, enabled the reproduction of the properties of homogeneous dispersion and stability in suspension.

Rheological Measurements

The rheological properties of the drilling fluids were determined by the use of the rotational viscometer. The plastic viscosity, yield point, and gel strength are the rheological properties of the drilling fluids that play an important role in the assessment of the performance of the drilling fluids during the circulation process.

Fluid Rock Interaction Tests

To assess physicochemical interactions between drilling fluids and rock formations, shale cores were kept immersed in the prepared mud fluids for a period of 24 to 72 hours. Weight changes and porosity differences were used to assess hydration, clay stabilization, and inhibitor properties. Such physicochemical interactions are critical in controlling compaction and swelling of shale formations.

High Pressure Flow Loop Tests

In order to simulate the properties of ECD, a high-pressure flow loop was created, simulating actual field conditions. The facility was used in the evaluation of the efficiency of the mud fluids under Constant Annular Pressure Management (CAPM) and double gradient conditions. This is important in drilling since the conditions are sensitive.

Filtration Performance Tests

In addition to this, the filtration characteristics of the mud fluids were also carried out using a standard API (American Petroleum Institute) filter press. It is possible to monitor the volume of the filtrate produced and the quality of the filter cakes in order to evaluate the functionality of the fluids in the reduction of losses. This is important in the mechanical stability of the walls of the boreholes, as well as the reduction of losses.

AMETEK Brookfield rotational viscometer is an analytical instrument that is used for measuring the viscosity of fluids by measuring the resistance of fluids to rotational flow. The viscosity of fluids is an important property of fluids and is used for measuring the flow of fluids due to an external force. The viscosity of fluids is an important property for different industries such as food processing, pharmaceuticals, cosmetics, and chemicals. Among different types of viscometers, rotational viscometers are very important for measuring the viscosity of fluids. The rotational viscometer is based on the principle of measuring the torque and resistance of fluids (fig.1). In this method, a spindle (1) is dipped into the fluid sample and rotated by a motor (6). When the spindle (1) is rotated in the fluid sample, resistance is created due to friction between the fluid particles.

The resistance opposes the rotation of the spindle (1). This resistance is attributed to the fluid viscosity such that the greater the fluid viscosity, the greater the resistance to rotation. The instrument will then use this torque value, the rotation speeds, and the calibration constants to calculate the fluid viscosity. The process of calculating the viscosity of the fluid will commence by the motor (6) rotating the spindle (1) at a predetermined speed. The spindle (1), which is submerged in the fluid, will experience a dragging force from the fluid surrounding it.

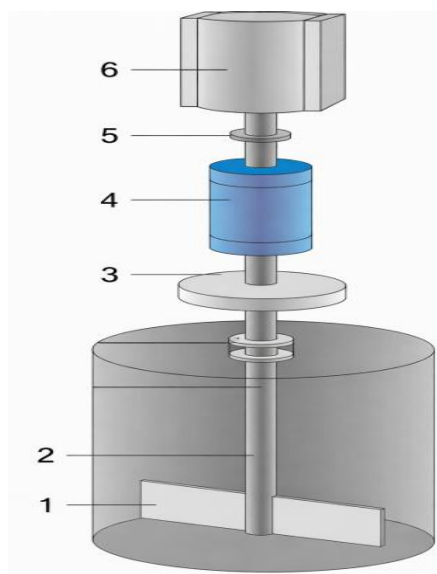


Fig 1. AMETEK Brookfield Rotational viscometer scheme (1-paddle/spindle, 2- bearing, 3- torque limiter, 4- transducer, 5- coupling, 6- motor)

This dragging force or torque will be transmitted by the instrument and will use a transducer (4) to convert the torque value into an electrical signal for the purpose of performing a detailed analysis of the behavior of the fluid in different conditions. The motor (6) of the rotational viscometer is a very important device in the measurement process. The motor (6) of the rotational viscometer is a device that is used for the purpose of providing the motion required for the measurement process. The motor (6) of the rotational viscometer may be designed to have different speeds. High-quality motors (6) are used in the rotational viscometer. This is because the motor is required for the smooth motion of the spindle (1). The motion is required for the accurate measurement of the viscosity of the fluid. The motor type that can be used is the direct current motor, the stepper motor, or the servo motor. The coupling (5) is the part that joins the motor shaft with the spindle (1) shaft. The primary role of the coupling (5) is to ensure the smooth transmission of motion, even with some degree of misalignment. The coupling (5) also ensures smooth operation. The flexible coupling type is used for the purpose in the rotational viscometer due to the ability to withstand some degree of misalignment. This helps in the prevention of damage to the delicate parts of the instrument. The transducer (4) is an integral part of the system. The role of the transducer is to detect the torque, which is the result of the resistance of the fluid. The type of the transducer used is the strain gauge type (4). This is due to the high accuracy. The transducer (4) is normally used in modern viscometers due to its sensitivity. The transducer (4) is used for converting deformations due to torque into an electrical signal. The accuracy of the transducer (4) is of utmost importance for the accurate measurement of viscosity. Hence, it is considered to be one of the most important components of the viscometer. The bearings (2) are generally used for the support of the rotating shaft for smooth rotation. The bearings (2) also aid in the reduction of friction in the rotating parts. The bearings (2) also ensure smooth rotation of the spindle (1) by keeping it aligned. The bearings (2) generally used are of the ball and sleeve type. The bearings (2) should have good quality so that friction is not high, which

may cause vibrations and thereby affect the results. The paddle (1), also known as the spindle (1), is the part of the viscometer that is in contact with the fluid. The paddle (1) is submerged in the fluid and rotated by the motor (6). The size of the paddle (1) determines the rate of shear in the fluid, which in turn determines the viscosity of the fluid. Various shapes, such as cylinders, disks, or paddles (1), are used for different fluids and for different purposes. The spindle (1) must be selected carefully in order to get meaningful results from the experiment. In actual use, these components operate as a complete system. The motor (6) drives rotation, which is then transferred through the coupling (5) to the spindle (1). The bearings (2) facilitate smooth rotation, while the spindle (1) works with the fluid, experiencing resistance. This resistance creates torque, which is then measured by the transducer (4). The torque limiter (3) protects the system from excessive torque, while the instrument works with the collected information to produce a reading on viscosity.

There are a number of advantages in using a rotational viscometer, which include the ability to test a variety of viscosities and analyze complex fluid behavior, especially in different conditions of shear. However, the results depend on a number of conditions, which include calibration, temperature, and the parameters used in measurement. Despite these conditions, the rotational viscometer stands out as the most versatile instrument for measuring viscosity in different conditions. In conclusion, the rotational viscometer works on the principle of measuring the resistance of a fluid, especially in rotational motion. The components of the rotational viscometer, which include the motor (6), coupling (5), transducer (4), torque limiter (3), bearing (2), and paddle (1), are important in ensuring the accuracy of results in viscosity measurement.

The OFI (Oil Field Instrumentation) API (American Petroleum Institute) filter press test is figure such standardized process for testing the drilling fluid (fig.2). The API (American Petroleum Institute) filter press test helps in obtaining valuable information about the drilling fluid behavior when it comes into contact with permeable zones during drilling operations. The working principle of the API (American Petroleum Institute) filter press is based on the application of constant pressure to the drilling fluid sample (2), which is passed through a porous medium placed in the compaction test mold (3). The constant applied pressure (7) results in the passage of the liquid phase of the drilling fluid through the porous medium. The suspended particles in the drilling fluid get deposited on the surface of the porous medium and form the filter cake. The volume of the filtrate collected over the standard period of time, i.e., 30 minutes, is used to measure the fluid loss behavior in accordance with the API (American Petroleum Institute) filtration standards.

The API (American Petroleum Institute) filter press apparatus includes a pressure cell assembly comprising the top reaction plate (1), compaction test mold (3), and bottom reaction plate (4), which enclose the drilling mud sample (2). Pressurization is introduced through the pressure inlet system (7), which is normally compressed air or gas.

This ensures pressure is evenly distributed throughout the drilling mud sample, as stipulated in API (American Petroleum Institute) testing requirements. In the API (American Petroleum Institute) filtration test, pressure differential pushes the filtrate through the filter medium held in place by the bottom reaction plate (4). The filtrate is removed from the system through outlets comprising the center outlet (5) and outer outlet (6). These outlets allow for efficient removal of the filtrate from the API (American Petroleum Institute) cell. Filtration in the API (American Petroleum Institute) filter press is characterized by two stages of filtration. First, an instantaneous spurt loss is noticed, which is mainly due to the low resistance encountered during the formation of the filter cake. As solid particles accumulate and stick to the filter medium, a filter cake is formed in the compaction test mold (3), which results in an increase in resistance to flow and hence the

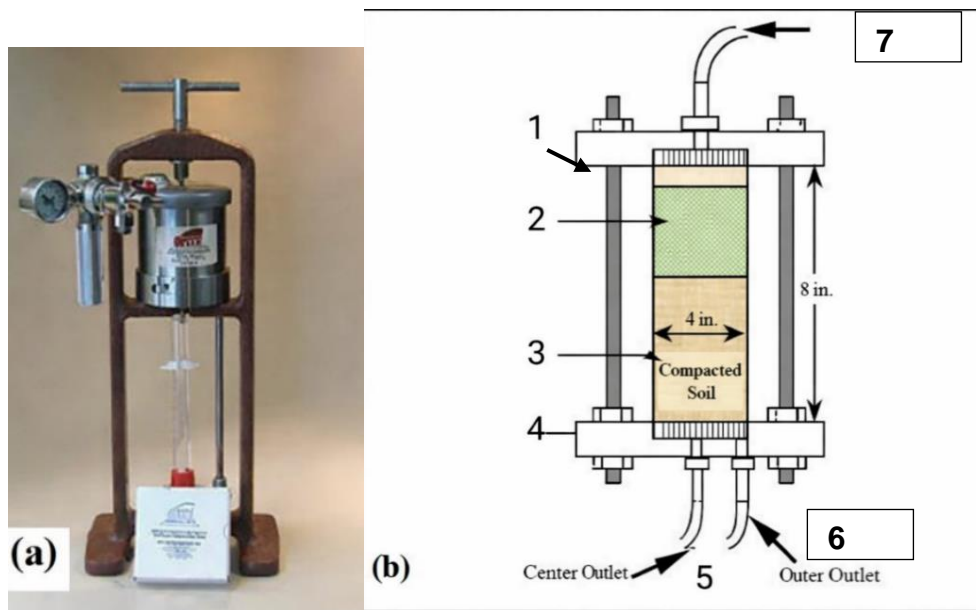


Fig 2. OFI (Oil Field Instrumentation) API (American Petroleum Institute) filter press scheme (a- general view, b- detailed breakdown) (1-Top Reaction Plate, 2- Drilling Mud, 3- Compaction Test Mold, 4- Bottom Reaction Plate, 5- Center Outlet, 6- Outer Outlet, 7- Pressure)

formation of a stabilized filtration rate, which is more representative of the encountered drilling conditions during field operations, as per API (American Petroleum Institute) standards. Each component of the API (American Petroleum Institute) filter press contributes to accurate and reproducible measurements. The top reaction plate (1) functions as a sealing and pressurization interface, ensuring uniform loading of the drilling mud sample. The compaction test mold (3) provides geometric confinement and defines filtration area and cake development. The bottom reaction plate (4) supports the filter medium and directs filtrate toward the outlet system. The pressure system (7) maintains constant operating pressure, which is critical for standardized API (American Petroleum Institute) testing conditions.

Each part of the American Petroleum Institute (API) filter press plays an important role in the precise and reproducible measurement. The top reaction plate (1) is the interface for sealing and pressurizing the drilling mud sample. The compaction test mold (3) provides geometric constraint and controls the area for filtration and cake formation. The bottom reaction plate (4) holds the filter medium and directs the filtrate to the outlet system. The pressure system (7) maintains constant pressure during the process. Constant pressure is important in maintaining standard conditions for American Petroleum Institute testing. The sealing system consists of the reaction plates (1 and 4) and the mold (3). The sealing system ensures that there is no leakage and maintains constant pressure. The filtrate passing through the center outlet (5) and the outer outlet (6) is collected in a graduated cylinder to measure the cumulative fluid loss according to the American Petroleum Institute. After completing the API (American Petroleum Institute) filter press test, the filter cake is removed and its thickness is measured. Filter cake properties and volume of filtrate are significant parameters for assessing the quality of drilling fluids. Theoretically, drilling fluids should have minimal fluid loss and create a thin filter cake with low permeability to

reduce damage to the formation and maintain stability in the wellbore in accordance with API (American Petroleum Institute) performance specifications. API (American Petroleum Institute) filtration tests have many benefits, including ease of execution, reproducibility, and standardization. Due to the geometry and parameters set by components (1-7), it is easy to compare results obtained from different laboratories since they comply with API (American Petroleum Institute) Recommended Practices. However, it is important to note that the API (American Petroleum Institute) filter press test simulates surface pressure and temperature; hence, further tests at HPHT (High Pressure High Temperature) may be required.

In practice, the filter press test, as proposed by the API (American Petroleum Institute), is commonly applied for optimization of drilling fluids. The modification of drilling fluids, i.e., the concentration of solid particles and the addition of certain additives, affects the filtration characteristics, as observed through the outlet system (5,6), and under pressure (7). Such tests are considered useful for efficient drilling, damage prevention, and optimization of wells, as recommended by the API (American Petroleum Institute). Thus, in conclusion, the API (American Petroleum Institute) filter press test is still considered an essential tool in the evaluation of the drilling fluid's filtration characteristics. The fluid loss and filter cake formation can be determined in the API (American Petroleum Institute) standard assembly consisting of the top reaction plate (1), drilling fluid sample (2), compaction test mold (3), bottom reaction plate (4), center outlet (5), outer outlet (6), and pressure inlet system (7), which enables the evaluation of the interaction of the drilling fluid and formation in a controlled laboratory environment in accordance with API (American Petroleum Institute) standards.

The Cloud Point Temperature may also be affected by the concentration of glycol, as previously observed in studies on glycol-based drilling fluids and their thermal and physicochemical properties. Increasing the concentration of glycol causes Cloud Point Temperature to first decrease and then increase, as shown in fig.3. Therefore, the concentration of glycol should be between 2 and 5% during field application to enjoy the advantage of low Cloud Point Temperature.

The thermal characteristics of glycol-based drilling fluids play a vital role in formulating high-performance drilling fluid systems. An important aspect of these thermic properties is the Cloud Point Temperature (CPT) – a specific temperature at which there is a phase transition in the dissolved glycol composition and subsequent precipitation from the aqueous solution. This 'clouding' is considered to be the main cause of wellbore stability by covering reactive shale surfaces and preventing swelling.

As depicted in figure 3, the relationship between the concentration of glycol and Cloud Point Temperature is seen to follow the non-linear "U-shaped" curve. From this curve, two different physicochemical processes can be inferred:

- The Destabilization Phase (1%-4% Concentration): An initial sharp decrease in Cloud Point Temperature is seen as the concentration increases towards the 4% mark. Within this region, the glycol molecules function as "structure breakers" because they break the existing hydrogen bonds in the aqueous phase. As a result, the fluid is seen to "cloud" at a lower temperature, reaching the minimum point at 71°C.
- The Stabilization Phase (5%-10% Concentration): As the concentration crosses the 4% threshold, the CPT is seen to experience its secondary increase. Within this region, the glycol molecules start to establish stronger intermolecular clusters and hydrogen bonds with the water and polar additives. As a consequence, the fluid is seen to require a greater temperature to initiate phase separation.

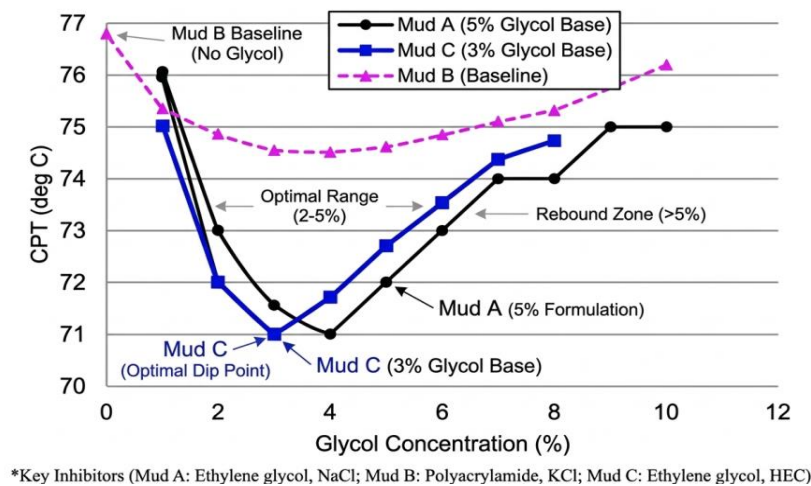


Fig 3. Effect of glycol concentration on CPT (Cloud Point Temperature)

By matching the chemical composition of each of these mud formulations from table 1 to the Cloud Point Temperature curve, the strategic intention of each of these mud formulations is evident:

Mud C - Peak Reactive Inhibition (3% Glycol)

Mud C is formulated to work at the lowest Cloud Point Temperature point (71°C). The choice of a 3% glycol solution is intended to activate the inhibition process at the lowest possible temperature. When combined with the presence of Nitromethyl-phosphonic acid, Mud C is able to provide immediate chemical stability for highly reactive shales and seal the formation very early in the process.

Mud A - Balanced Thermal Stability (5% Glycol)

Mud A is formulated to work in the "Rebound Zone" (72°C). The presence of a 5% glycol solution provides a balanced level of clay inhibition and rheological stability. The presence of Xanthan Gum and Sodium Chloride in combination with the glycol solution indicates a product intended for use in a wider temperature gradient without compromising inhibition properties.

Mud B: The Non-Glycol Baseline (0% Glycol)

Mud B is used as the control fluid, which does not rely on the CPT mechanism. It is controlled by Potassium Chloride (KCl), which is used for cation exchange, and Polyacrylamide, which is used for mechanical encapsulation. It is used in environments where salt-based inhibition is sufficient and the thermal phase change is not required.

The experimental data points to an optimal range of 2% to 5% for glycol-based additives. Within this range, the drilling fluid exhibits the minimum CPT, which can be beneficial in many ways:

- The earlier start of precipitation at reduced temperatures means faster coating of the wellbore.
- The reduced CPT ensures that the drilling fluid remains consistent in rheology and does not allow the premature precipitation of unwanted solids.
- The increase in glycol concentration beyond 5% results in a decrease in efficiency, considering that an increase in CPT might have an adverse impact on the efficiency of the drilling fluid in certain temperature zones.

The selection of glycol concentration remains one of the most important aspects in optimizing the performance of the drilling fluid. The formulation of drilling fluids like Mud

C points to the importance of attaining the "optimal dip" in the CPT curve to maximize the reactive stabilization of the drilling fluid in difficult geological zones.

RESULTS AND DISCUSSION

Physicochemical Interactions

From the experimental results presented above, it is clear that wellbore stability is significantly influenced by physicochemical interactions that exist between drilling fluids and reactive shale formations. The inhibitive nature of the glycol-based drilling fluid (Mud A) was found to be highly efficient in controlling hydration reactions that take place in shale formations. From clay swelling measurements performed on this system, there was an approximate reduction of 40% in shale hydration reactions. This confirmed that ethylene glycol and sodium chloride are effective in stabilizing shale formations. The inhibitive nature is attributed to water activity reduction and osmotic balance control. This is in line with previously proposed glycol-based shale stabilization mechanisms. Polymer additives showed a profound effect on rheological properties of drilling fluids. The addition of xanthan gum and polyacrylamide polymers to drilling fluids was found to increase yield point properties by an approximate value of 15-25%. This is attributed to improved gel structure formation that showed better hole cleaning efficiency and prevented particle settling. This is in line with previously proposed rheological effects of polymers on drilling fluid properties. The ionic exchange was equally instrumental in the stabilization of the shale formation. Here, potassium ions were released by KCl, replacing other ions in the structure of clay minerals. This reduced water penetration in the interlayers of shale formations. Osmotic swelling was equally reduced as a result of this ion exchange. This is in conformity with existing physicochemical stabilization theories.

The chemically optimized mud system (Mud C) was found to exhibit better efficiency in complex drilling situations. This was achieved by incorporating calcium carbonate and nitromethyl-phosphonic acid in the drilling mud. Measurements were taken to ascertain the efficacy of this drilling mud. Results indicated an approximate 25% reduction in the amount of filtrate formed. Additionally, there was an approximate 30% improvement in stability in shale formations.

Therefore, overall results have demonstrated that combined chemical inhibition, polymer stabilization, and ionic regulation do have a synergistic effect in improving wellbore stability compared to single-mechanism drilling fluids.

Rheological Behavior and Density Control

The rheological test results indicated a stable flow behavior for all the studied mud systems within the operational range of the drilling process. The plastic viscosity of the studied mud systems ranged from 22 to 28 cP, which is enough to provide resistance to flow while ensuring efficient hydraulic transportation of the mud. The yield point of the studied mud systems ranged from 16 to 20 lb/100 ft², which is enough to provide efficient carrying capacity for drilled cuttings while ensuring stability of the suspended cuttings during the stoppage of the circulation process. The gel strength of the studied mud systems, which ranged from 2 to 10 lb/100 ft² for 10 seconds and 10 minutes, indicated a balance in the rebuilding of the structures without the need for high pump pressures, which confirms the fact that the optimized physicochemical composition of the mud is essential for maintaining stability of the equivalent circulating density while reducing the risks of wellbore collapse or formation fracturing.

Table 2 lists the rheological parameters measured by the rotational viscometer test, including plastic viscosity, yield point, and gel strength for the drilling mud systems. These

parameters are significant for hydraulic efficiency, carrying capacity, and stability in the drilling system. The test results indicate that all the mud systems have rheological parameters within the acceptable limits for efficient and stable drilling. The plastic viscosities ranged from 22 to 28 cP. This indicates that the mud systems have efficient resistance to flow. However, Mud B showed higher plastic viscosity at 28 cP. This is due to the presence of polyacrylamide and bentonite, which increase internal friction in the system. This is in line with the implications for carrying capacity, as discussed in the experimental results.

The yield point values ranged from 16 to 20 lb/100 ft², showing sufficient electrochemical interaction between the solid particles and the fluid phase. Mud C had the highest yield point, 20 lb/100 ft², which showed better particle suspension and hole cleaning efficiency.

Table 2

Rheological Data of Tested Muds

Mud Type	Plastic Viscosity (unit- cP, centipoise)	Yield Point (unit- lb/100ft ²)	Gel Strength (unit- lb/100ft ²) (10 seconds/10min)
Mud A	25	18	2 / 8
Mud B	28	16	3 / 10
Mud C	22	20	2 / 9

The chemically optimized formulation with hydroxyethyl cellulose and calcium carbonate improved the structural networking of the fluid, which was responsible for the better stability of the shale formations and lower filtrate invasion, as described in the Results and Discussion section.

The gel strength measurements of the mud samples ranged from 2-3 lb/100 ft² at 10 seconds to 8-10 lb/100 ft² at 10 minutes, showing balanced thixotropic characteristics for all the mud samples. The moderate gel strength development of the mud samples ensured the suspension of drilled cuttings in the well fluid in case of circulation stoppage without the necessity of applying higher pump pressure to restart the circulation. Mud B showed higher gel strength due to interaction with the polymers, whereas Mud A and Mud C maintained their gel strength development, which was desirable for maintaining equivalent circulating density (ECD) stability and preventing fracturing of formations.

The rheological data have provided overall evidence that physicochemical changes in drilling fluids do affect the flow behavior, stability of suspensions, and pressure management. The overall data have provided evidence that the combined approach of chemical inhibition and stabilization with the selection of the most appropriate additives provides better wellbore stability.

Results of Equivalent Circulating Density (ECD) and Filtration Performance

The ECD simulation results showed that the optimized composition of ions and polymers was effective in mitigating the generation of overpressure zones and hence ensured the stability of the wellbore during the drilling process. The filtration performance showed that the amount of fluid loss was consistent with the trend of "Mud C" < "Mud A" < "Mud B," signifying that the filtration control was more effective in chemically optimized fluids due to the synergistic effect of the incorporated additives.

In addition, the synergistic effect of ethylene glycol and polymers ensured the maintenance of the diameter of the wellbore and reduced the effect of osmotic swelling in reactive shales.

CONCLUSION

Wellbore stability in reactive formations is greatly affected by the chemical composition of the drilling fluids and the physicochemical interactions involved.

Glycol-based drilling fluid additive materials such as ethylene glycol (C₂H₆O₂) are very efficient in controlling shale swelling and dispersion by preventing water-clay interaction.

Ionic salts such as NaCl and KCl are very efficient in controlling wellbore stability by maintaining osmotic pressure and preventing clay particles and shale swelling.

The use of polymer-based materials such as xanthan gum (C₃₅H₄₈O₂₉) is very efficient in controlling wellbore stability by improving the rheological properties of the drilling fluids and thereby ensuring efficient hole cleaning and fluid loss control by maintaining a balance between viscosity and fluid flow.

The use of specialized drilling fluid additive materials such as calcium carbonate (CaCO₃) and nitromethyl-phosphonic acid (CH₃NO₄P) is very efficient in controlling wellbore stability in complex wells.

The use of modern and efficient drilling technologies such as controlled annular pressure management, dual gradient drilling, ECD simulation, and fluid-rock interaction is very efficient in controlling wellbore stability by maintaining pressure and ensuring efficient design of the drilling fluids.

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