Numerical Simulation and Analysis of Leakage Resistance of Plugging Materials

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Abstract: Addressing the well leakage issues encountered during drilling in volcanic clastic rock formations, this paper thoroughly analyzes the causes of well wall instability and frequent loss, and explores the possibility of improving plugging efficiency and well wall stability through scientifically formulated plugging materials (lost circulation materials, LCMs). Focusing on the common problems of plugging materials in such complex formations—such as poor adaptability to the leakage layer, inadequate temperature resistance, and insufficient pressure-bearing capacity, the paper introduces a new scientific plugging strategy aimed at increasing the success rate of plugging and improving the replicability of plugging methods. The study employs experimental and numerical simulation methods to optimize and evaluate different formulas of plugging materials for their leakage resistance and borehole wall stabilization in the drilling fluid system. The research results show that a carefully designed combination of rigid and flexible materials can achieve better plugging results in performance tests for fractures of various widths, with formulas one and four performing particularly well. Therefore, choosing the appropriate plugging material formulation plays a significant role in enhancing the success rate of a single plugging attempt and well wall stability, which is crucial for ensuring drilling safety and progress.

Keywords: Plugging Material; Leakage Resistance; Borehole Wall Stabilization; Numerical Simulation

1. Introduction

The East Third section of block 2-27 in the Nanbao No. 2 structure develops multiple sets of igneous rocks, with fractures and pores, low pressure-bearing capacity, mainly consisting of gray and dark gray mudstone with thin layers of siltstone and thick layers of volcanic rocks, topped by tuffaceous sandstone [1]. The same well section of dark gray mudstone is prone to collapse, and the volcanic rock fractures are prone to leakage, especially in high-inclination wells where collapse and leakage issues are particularly prominent, easily triggering multiple complex accidents [2,3]. Lyu Jinshuai and others [4,5] analyzed the causes of well leakage, proposed corresponding preventive measures, and studied the application of well leakage technology in the drilling process in-depth. Wang Jian and others [6-9] analyzed the physicochemical properties of mid-deep mud shale and explored the collapse mechanism of mud shale, proposing that the selection of strong plugging and inhibitory drilling fluid is the fundamental measure to effectively prevent the peeling and falling of mid-deep mud shale.

Research on leakage and plugging mechanisms encountered in drilling engineering began earlier abroad. China started researching plugging materials in the 1960s, during which the understanding of the nature of the leaking layers was not comprehensive and the types of plugging materials were limited. In the 1980s, the variety of plugging materials gradually enriched [10]. Thereafter, drilling fluid plugging materials evolved from single plugging to composite plugging. The development of drilling plugging materials can be divided into three stages: plugging upon detection, developing new plugging materials, and composite plugging materials. For well leakage problems, plugging materials are an indispensable part of the drilling process and are the foundation and key to successful sealing [11]. This paper targets the fracture and leakage characteristics of the volcanic clastic rock strata in the No. 2 structure. By conducting comprehensive evaluation of the drilling fluid system's mechanical characteristics, including tests for leakage resistance and borehole wall stabilization, both before and after the introduction of various plugging materials, and by carrying out numerical simulations and analyses of leakage resistance of the plugging materials, the study identifies optimal plugging materials suitable for the volcanic clastic rock formations in the NanBao No. 2 structure.

2. Reservoir Study and Borehole Wall Instability Analysis

2.1 Analysis of Reservoir Mineral Composition

The mudstone clay mineral content in the reservoir is 15%-51.9%, mainly consisting of illite/smectite mixed layers and illite, which are prone to hydration reactions that reduce rock strength; diabase clay mineral content is 3.6%-29.4%, mainly consisting of montmorillonite and illite; sandstone and tuffaceous sandstone clay mineral content is 7.5%-21.1%, mainly consisting of kaolinite and illite/smectite mixed layers.

2.2 Macroscopic Fracture Development Characteristics

(1) Diabase: Development of open fractures, with apertures reaching several millimeters under surface conditions;
(2) Mudstone: Exhibits certain bedding structure characteristics; some rock samples show fractures parallel to the bedding with small apertures;
(3) (Tuffaceous) Sandstone: Pure sandstone samples are generally intact, while tuffaceous sandstone shows obvious fractures.

2.3 Borehole Wall Instability Mechanism

(1) The east third mudstone and thick volcanic rock with bedding and fractures may lead to formation fragmentation and induce borehole wall instability if drilling fluid plugging performance is poor; under the action of drilling pressure differential, capillary forces, and chemical potential, the liquid phase will invade the formation along fractures causing hydraulic fracturing effects.
(2) The strength at structural surfaces is weak; under the influence of stress release and drilling tool mechanical disturbance, it is easy to cleave or slip along the structural surfaces, providing pathways for drilling fluid invasion. The action of drilling fluids further reduces the rock strength of mudstones, inducing and exacerbating borehole wall instability [12].

3. Anti-leakage Performance Testing of Plugging Materials under the Effect of Sealing Materials

Based on the principles of rigid bridging and deformative sealing [13], different particle sizes of rigid plugging materials as well as flexible sealing materials were optimally selected, as shown in Table 1 and Table 2.

Table 1. Optimally Selected Domestic Materials

Category	Mesh	Category
XNZD-1	2500	Rigid
XNZD-2	1250	Rigid
Graphene EP-3		Flexible

Table 2. Commonly Used Materials on Site

Category	Mesh	Category
Ultrafine Calcium	2200	Rigid
Ultrafine Calcium	1000	Rigid
Asphalt		Flexible

3.1 Preparation of Plugging Agents

3.1.1 Formulation of plugging agents

Base slurry formula: 4% bentonite slurry (hydrated for 24h) + 0.5% polymer + 1% loss circulation material + 2% lubricant + 3% potassium salt (aged at 120°C for 16h before use)
Formula 1: Base formula + 1.5% XNZD-1 + 1.5% XNZD-2 + 3% EP-3
Formula 2: Base formula + 1.5% ultrafine calcium 1000 mesh (13μm) + 1.5% ultrafine calcium 2200 mesh (6μm) + 3% sulfonated asphalt SAS
Formula 3: Base formula + 1.5% XNZD-1 + 1.5% XNZD-2 + 3% sulfonated asphalt SAS
Formula 4: Base formula + 1.5% ultrafine calcium 1000 mesh (13μm) + 1.5% ultrafine calcium 2200 mesh (6μm) + 3% EP-3
Formula 5: Base formula + 1.5% XNZD-1 + 1.5% XNZD-2
Formula 6: Base formula + 3% EP-3

Formula 7: Base formula + 1.5% ultrafine calcium 1000 mesh (13μm) + 1.5% ultrafine calcium 2200 mesh (6μm)

Formula 8: Base formula + 3% sulfonated asphalt SAS

3.1.2 Viscosity measurement

Using a high-speed mixer to stir uniformly, and setting the viscometer speed to 300 r/min, 600 r/min to measure the viscosity of each plugging agent formula. The measured viscosity of each prepared plugging agent formula is as shown in Table 3:

Table 3. Viscosity Table for Each Plugging Agent Formula

Formula	300 r/min	600 r/min	Plastic Viscosity (Pa·s)
Control Group (Base Formula)	15	45	30
Formula 1	85	160	75
Formula 2	80	130	50
Formula 3	235	300	65
Formula 4	230	300	70
Formula 5	50	100	50
Formula 6	85	140	55
Formula 7	45	105	60
Formula 8	15	60	45

3.2 Testing the Plugging Effect

3.2.1 Testing the plugging effect of different formulas on fractures with widths of 40μm, 60μm, 80μm, and 100μm.

The cores with fracture widths of 40μm, 60μm, 80μm and 100μm are placed in a core holder, as shown in Figure 1., and confining pressure is applied using a hand pump; then placed in a constant temperature box at the temperature required by the simulated stratum, with the inlet end of the holder connected to a middle container filled with water, and the outlet end leading to a graduated cylinder, ensuring the entire device is free of liquid leakage; under confining pressures of 20MPa, 30MPa, and 40MPa, water is injected into the core at a rate of 0.01ml/min using an injection pump, observing the pressure difference until water comes out of the outlet end; injecting different plugging agents into cores with fracture widths of 40μm, 60μm, 80μm, and 100μm, allowing it to settle and solidify before repeating the above steps, comparing the results to select the best formula.

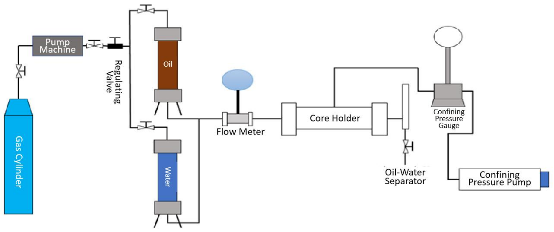

Figure 1. Schematic Diagram of the Experimental Process

From the leakage plugging experiment, it was found that all eight formulas had good plugging effects under 40um core fractures, indicating that rigid materials (XNZD-1 and XNZD-2, ultrafine calcium 1000 mesh and ultrafine calcium 2200 mesh) and flexible materials (EP-3, sulfonated asphalt SAS) could function independently under 40um fractures; under 60um core fractures, formulas one, three, four, and seven could effectively plug the fractures, indicating that rigid materials XNZD-1, XNZD-2, ultrafine calcium 1000 mesh and 2200 mesh, and flexible materials graphene EP-3 and sulfonated asphalt could form a good plugging effect to achieve rigid bridging and deformable plugging. As ultrafine calcium has a larger particle size compared to XNZD, it can effectively plug 60um fractures even without the action of flexible materials. For 80um to 100um core fractures, only formulas one and four exhibited good plugging performance, indicating that the rigid materials XNZD-1 and XNZD-2 with graphene EP-3 system and rigid materials ultrafine calcium 1000 mesh and 2200 mesh with sulfonated asphalt system had good plugging effects under 40um core fractures. A comprehensive evaluation concluded that formulas one and four were the best options.

3.2.2 Pressure resistance curves for different fracture width cores

The pressure resistance curves, as shown in Figure 2-5., show that as the fracture width increases, the magnitude of the pressure resistance curve decreases, and the time for the rise inflection point to appear is significantly shortened. This is because in the plugging experiment, the larger the fracture width, the shorter the time for the injection pressure to push the injected fluid into the core. The moment the injection pressure contacts the core, the pressure difference continues to increase under the action of the plugging agent, resulting in a rising inflection point. The greater the pressure difference indicates the stronger the core pressure resistance effect, the better the plugging effect of the plugging agent [14]. Formula one produced the largest rise magnitude and the highest pressure difference, hence the best leakage plugging effect.

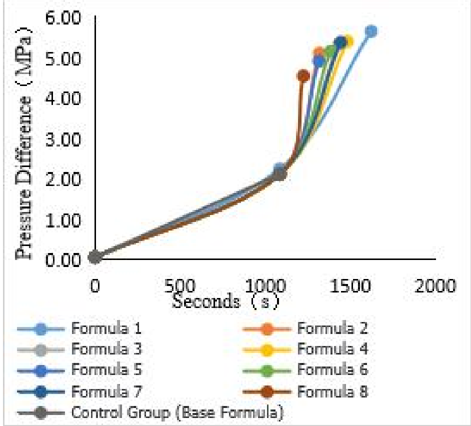

Figure 2. Comparison of Pressure Differences for Different Formulas at 40um

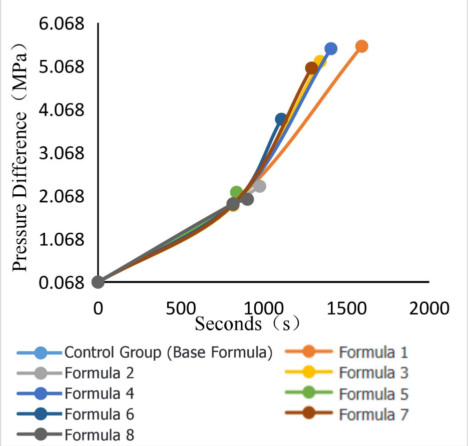

Figure 3. Comparison of Pressure Differences for Different Formulas at 60um

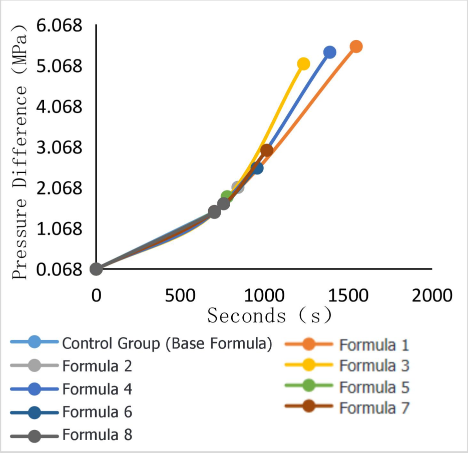

Figure 4. Comparison of Pressure Differences for Different Formulas at 80um

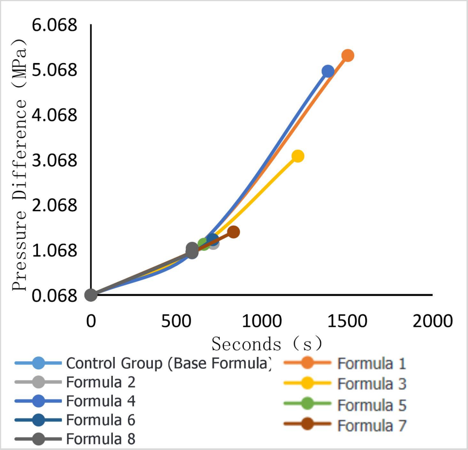

Figure 5. Comparison of Pressure Differences for Different Formulas at 100um

3.2.3 Numerical simulation study of plugging agent in microfractures.

From the numerical simulation results, the plugging effect of the base slurry formula itself is poor, and the particle size cannot play an effective role. However, Formulas One and Four use different particle sizes of rigid materials to form plugging and then use flexible sealing materials of deformable particles, which can bridge, wedge, and fill in the simulated fluid, and they have better plugging effects during the same time period, as shown in Table 4.

Table 4. Plugging Rate of Different Formulas

Formula	Plugging Rate%
Formula 1	99.8%
Formula 2	80.7%
Formula 3	90.6%
Formula 4	98.7%
Formula 5	57.3%
Formula 6	88.5%
Formula 7	90.1%
Formula 8	69.7%

3.2.4 Changes in elastic modulus and compressive strength before and after plugging

The plugging materials of Formula One were specifically used for testing the mechanical properties of rock before and after plugging for three sample sizes: 40-60μm, 60-80μm, and 80-100μm. Comparing the experimental results of the rock's elastic modulus and compressive strength before and after plugging, as shown in Figure 6 and Figure 7. , it is shown that for the microfractures of 40-60μm, the elastic modulus increased from 14.15 MPa to 19.19 MPa, a 1.36-fold increase. The compressive strength of the rock increased from 83.71 MPa to 144.02 MPa, a 1.72-fold increase; for the microfractures of 60-80μm, the elastic modulus increased from 13.15 MPa to 19.17 MPa, a 1.46-fold increase. The compressive strength increased from 56.80 MPa to 136.59 MPa, a 2.40-fold increase; for the microfractures of 80-100μm, the elastic modulus increased from 6.60 MPa to 17.97 MPa, a 2.72-fold increase. The compressive strength increased from 5.014 MPa to 116.79 MPa, a 23.29-fold increase. It is evident that after plugging, the mechanical properties of the rock increased, enhancing the stability of the wellbore. Further research found that the larger the width of the microfractures, the greater the increase in mechanical properties after plugging, and the better the plugging effect.

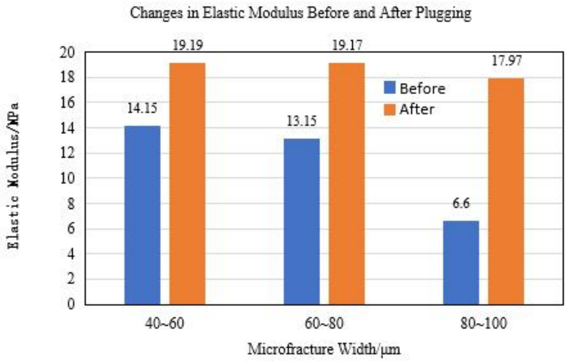

Figure 6. Changes in Elastic Modulus before and after Fracture Plugging

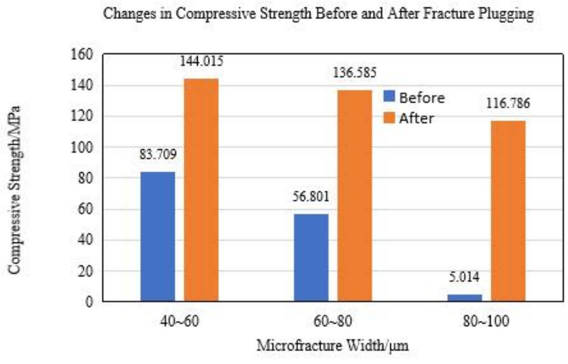

Figure 7. Changes in Compressive Strength before and after Fracture Plugging

4. Conclusions

Through systematic analysis and rigorous experimental design of volcanic clastic rock formations, this research meticulously examines the disparities in borehole wall stabilization and leakage resistance across different plugging material formulations. It has been discovered that specific formulations can significantly enhance the plugging effect and compressive strength. Employing a combination of numerical simulations and experiments, this study not only optimizes the formulation of plugging materials but also provides effective solutions for plugging under complex downhole conditions.

From the plugging experiments, it was found that all eight formulas had good plugging effects under 40um core fractures, indicating that rigid materials (XNZD-1 and XNZD-2, ultrafine calcium 1000 mesh and 2200 mesh) and flexible materials (EP-3, sulfonated asphalt SAS) can act independently on 40um fractures. Under 60um core fractures, Formulas One, Three, Four, and Seven were able to plug effectively, indicating that rigid materials XNZD-1, XNZD-2, ultrafine calcium 1000 mesh and 2200 mesh, and flexible materials graphene EP-3 and sulfonated asphalt can form good plugging effects, achieving rigid bridging and deformative plugging. Due to the larger particle size of ultrafine calcium compared to XNZD, it can effectively plug 60um fractures even without the action of flexible materials. For 80um-100um core fractures, only Formulas One and Four had good plugging performance, indicating that the systems of rigid materials XNZD-1 and XNZD-2 with graphene EP-3, as well as ultrafine calcium 1000 mesh and 2200 mesh with sulfonated asphalt, had good plugging effects under 40um fractures.

As shown by the confining pressure curves, as the fracture width increases, the rise in the confining curve decreases, and the time for the turning point of the increase shortens significantly. A larger pressure differential indicates stronger pressure-bearing effects of the core and better plugging effects by the sealing agent, with Formula One showing the best plugging results.

The numerical simulation results showed that the base slurry formula without rigid and flexible materials did not have ideal plugging effects due to particle sizes that could not effectively function. However, other formulas, due to the use of different particle sizes of rigid materials to form a bridge plug followed by deformable particles of flexible sealing materials, allowed them to bridge, wedge, and fill within the simulated fluid, achieving better plugging effects within the same timeframe, with Formulas One and Four showing more pronounced effects.

Looking at the changes in elastic modulus and compressive strength before and after plugging, the mechanical properties of the rock increased after plugging, enhancing the stability of the wellbore. Further research found that the larger the width of the microfractures, the greater the increase in mechanical properties after plugging, and the better the plugging effect.

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