Nano-Film-Forming Plugging Drilling Fluid and Bridging Cross-Linking Plugging Agent Are Used to Strengthen Wellbores in Complex Formations

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ABSTRACT: Lost circulation is one of the great challenges during the drilling process as it can not only increase the risk of drilling operations but also cause an increase in drilling costs, thus greatly affecting the drilling efficiency. Wellbore strengthening has been widely used to prevent lost circulation, which ultimately expands the mud density window by increasing the formation fracture pressure. This paper proposes a combination of "preventive" wellbore strengthening and "remedial" wellbore strengthening to prevent leakage and plug and stabilize wellbores by means of summarizing the characteristics of lost circulation and wellbore instability in the Hasan area. The formula of the bridging cross-linking plugging agent is determined by experiments as well slurry + 8−10% granular material + 3−5% fiber material + 2−4% elastic material + 0.5−1% cementing material. The formula of the nano-film-forming plugging drilling fluid is determined to be 3% bentonite + 0.2NaOH + 0.2% KPAM + 3% SMP + 1% PB-1 + 2% SMNA-1 + 2% lubricant SMLUB-1 + 1% modified nano-SiO2 particles. Then, the performance evaluation of the composite system is carried out by the high-temperature and high-pressure plugging simulation evaluation device. The results show that the bridging and cross-linking plugging agent can effectively block the 1−3 mm crack, the pressure-bearing capacity is greater than 10 MPa, and the anti-liquid return capacity is greater than 4 MPa. The nano-film-forming plugging drilling fluid has lower fluid loss and better rheological properties.

1. INTRODUCTION

Lost circulation is an engineering and technical problem in drilling operations in the oil and gas industry as it can easily lead to drilling accidents such as wellbore instability and collapse, blowout, sticking, and formation damage, which seriously affect the drilling efficiency. In order to prevent this problem, it is necessary to strengthen the wellbore. Wellbore strengthening is a technique implemented to keep formation integrity and control losses when drilling challenging formations, which can increase the maximum sustainable pressure for a wellbore through fracture sealing or fracture plugging and bridging. In recent years, wellbore strengthening has been highly emphasized, and a large number of studies have been conducted by both domestic and international researchers. Pu et al. conducted experiments based on the principle of shielding bridge blocking and selected suitable filler particles as the bridge blocking system. The combination of experiments proved that the system can quickly establish a shielding layer. Whitfill and Kumar studied many advantages of the elastic graphite material in drilling fluid plugging through experiments: it can be applied to various leakage layers and has high timeliness. Yuan et al. studied the effect of nano-silica on the filtration loss of the drilling fluid at different temperatures and found that nano-silica can effectively reduce the water loss of the drilling fluid base slurry. Contreras and Nwaoji invented a method for an oil-based drilling fluid to strengthen wellbores, respectively adding nano-calcium carbonate and nano-iron powder materials to the oil-based drilling fluid. The addition of these nanomaterials makes the drilling fluid system very efficient to protect and strengthen the wellbore and improve the pressure-bearing capacity of the formation.

In this paper, the lost circulation and wellbore instability data of six wells in the Hasan area are counted, as shown in Tables 1 and 2. Two of the wells had lost circulation, and three wells had borehole instability. The average single-well borehole complex aging is as long as 579.8 h. The strata where leakage and borehole instability occurred in the Hasan area are the...
Table 1. Statistical Table of Lost Circulation in the Hasan Area

| well number | well depth where lost circulation occurred, m | layers where lost circulation occurs | leakage velocity, m³/h | leakage amount, m³ |
|-------------|---------------------------------------------|-------------------------------------|------------------------|------------------|
| Hasan 2     | 671.27                                      | Carboniferous system                | 26                     | 158.3            |
|             | 1227.71                                     |                                     | 26                     | 27.7             |
|             | 2434.66                                     |                                     | 6                      | 27.7             |
| Hasan 201   | 3322.64                                     | Carboniferous system andesite       | 6                      | 173.1            |

Table 2. Statistics of Shaft Wall Instability in the Hasan Area

| well number | well depth, m | causes of well wall instability | time-consuming to deal with wellbore instability |
|-------------|---------------|---------------------------------|--------------------------------------------------|
| Hasan 2     | 2037          | drop block stuck drill          | 1287 h                                           |
|             | 5173.5        | drop block stuck drill          | 48 h                                             |
|             | 5238.26       | drop block stuck drill          | 195.5 h                                          |
| Hasan 3     | 3828.12       | drop block stuck drill          | 137 h                                            |
| Hasan slant 1 | 2215         | drop block                      | 3 d                                               |

Carboniferous and Permian strata. The Carboniferous strata develop basalt, volcanic breccia, andesite, tuff, and so on. The Permian stratum develops mudstone intercalated with tuffaceous sandstone, dolomitic mudstone, volcanic breccia, dark-gray tuffite, andesite, and so forth. Because the formation is broken and the fractures are connected, the drilling fluid is easy to enter the deep formation along the fracture and cause leakage. After the filtrate or drilling fluid enters the fracture, it will change the stress state around the well, and it is easy to produce blocks and cause the instability of the well wall.

Two different wellbore strengthening methods are widely used, that is, “preventive” wellbore strengthening and “remedial” wellbore strengthening. While previous studies have focused on one of these two methods, this paper combines both methods. After analyzing the data in the Hasan area, the countermeasures for preventing leakage and plugging and stabilizing the wellbore are put forward by summarizing the characteristics of lost circulation and wellbore instability. In addition, the formulations of bridging glue-connected lost circulation plugging agents and nano-film-forming plugging drilling fluid formulations are evaluated by a high-temperature and high-pressure plugging simulation evaluation device.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1. Experiment Material. Bentonite, NaOH, Na₂CO₃, polyacrylamide potassium salt (KPAM), sulfomethylated phenolic resin (SMP), polymer-modified asphalt waterproof coating (PB-1), inlaid film-forming anti-slump agent (SMNA-1), asphalt anti-slump agent (NRK-2), aluminum-based anti-slump agent (J-1), silicone anti-slump agent (EQS-2), modified nano-SiO₂ particles, lubricant (SMLUB-1), KCl, and superfine calcium carbonate were provided by Beijing Hanqian Technology Co., Ltd.

2.2. Experiment Methods. 2.2.1. Optimization of Nano-Anti-Slump Agents for the Film-forming Plugging Drilling Fluid. For fractured formations, the plugging performance of the film-forming plugging drilling fluid can be used to prevent the drilling fluid or filtrate from entering the interior of the formation along the fracture and causing rock stress changes, thus achieving the effect of stabilizing the well wall and preventing falling blocks.

Base slurry preparation: 4% bentonite + 0.15% Na₂CO₃ was stirred and aged for 24 h at room temperature. Four kinds of anti-slump agents with different mass fractions are selected (inlaid film-forming anti-slump agent SMNA-1, asphalt anti-slump agent NRK-2, aluminum-based anti-slump agent J-1, and silicone anti-slump agent EQS-2). They are added to the base slurry, and the change of the fluid loss is measured using an SD-type multi-pressure fluid loss meter.

2.2.2. Pressure-Transfer Experiment. Due to the low permeability of the mud shale, the pressure-transfer experiment is conducted. The principle of the pressure-transfer experiment is shown in Figure 1. The basic method of the pressure-transfer experiment is shown as follows: first, an initial pressure difference (\(p = p_{\text{up}} - p_{\text{down}}\)) is established between the upstream and downstream of the rock sample. Then, under the conditions of keeping \(p_{\text{up}}\) unchanged, the pressure dynamic change law of the downstream closed end of the rock sample is detected in real time by the pressure sensor and the differential pressure sensor.

Simulation experiment parameters are shown as follows: the confining pressure is 5 MPa, the axial pressure is 5 MPa, and the temperature is 65 °C. During the forward pressure-transfer experiment, the \(p_{\text{up}}\) is 3.5 MPa, and the \(p_{\text{down}}\) is 0.5 MPa; during the reverse pressure-transfer experiment, the \(p_{\text{up}}\) is 0.5 MPa, and the \(p_{\text{down}}\) is 3.5 MPa. The shale permeability is calculated by the following formula:

\[
K = \frac{\mu \beta V L}{A (t_2 - t_1)} \ln\left(\frac{p_{\text{up}} - p_{\text{down}}}{p_{\text{up}} - p(L, t_2)}\right) - \ln\left(\frac{p_{\text{up}} - p_{\text{down}}}{p_{\text{up}} - p(L, t_1)}\right)
\]

In the formula, \(K\) is the permeability; \(\mu\) is the drilling fluid filtrate viscosity, mPa·s; \(\beta\) is fluid static compressibility, 4.5 × 10⁻⁴ MPa⁻¹; \(V\) is the downstream closed volume (about 12.57 cm³); \(A\) is the cross-sectional area of the rock sample, cm²; \(L\) is the length of the rock sample, cm; \(p_{\text{up}}\) and \(p_{\text{down}}\) are the fluid pressure and pore pressure, respectively, where \(p_{\text{in}} = p_{\text{up}}\) and \(p_{\text{in}} = p_{\text{down}}\).
$p_{down}$ and $p(L,t)$ is the time $t$ at the lower end of the rock sample pressure.

2.2.3. Determination of the Formula of the Bridging Cross-Linking Plugging Agent. In terms of the particle size, density, strength, and so forth, relevant materials such as granular materials, fibrous materials, elastic materials, and cementing materials are selected through laboratory experiments to ensure that the formed plugging layer is dense and has good cementation with the formation, preventing falling blocks and causing breakage ground leaks. On the basis of bridging and plugging, different shapes and sizes of bridging and plugging materials are used to bridge, accumulate, and fill the fractures to form a fracture plugging layer that blocks the transmission of fluid pressure and the passage of fluid media. At the same time, the sealing layer is required to have the characteristics of a dense structure and high bearing capacity. The introduction of an elastic material is conducive to the formation of an elastic blocking layer and the expansion of the blocking range. When the cementing material is introduced, the polymer and the cross-linking agent undergo cross-linking reaction in the mixed and flowing states and stay in the leakage layer to form a viscoelastic body with a three-dimensional network structure to achieve leakage plugging.

2.2.4. Core Plugging Experiment. In order to evaluate the plugging performance and pressure-bearing capacity of the plugging agent, a plugging experiment is conducted. The experimental device diagram is shown in Figure 2. This device consists of a drilling fluid pressure control unit, a fluid storage unit, a formation model, a plugging fluid temperature control unit, and an enclosing pressure unit. A fractured core sample that simulates the real form of the formation is fixed in the core holder. The device controls the pressure and temperature of the plugging fluid entering the formation model and controls the pressure loaded on the formation model. The pressure values at different depths of the fracture are measured using pressure transducers, and the flow rate of the plugging fluid is measured using the weighing method.

3. RESULTS AND DISCUSSION

3.1. Determination of the Nano-Film-Forming Plugging Drilling Fluid Formulation. 3.1.1. Optimization of Anti-Slump Agents for the Nano-Film-Forming Plugging Drilling Fluid. The performance evaluation of four anti-slump agents is carried out. Figure 3 shows the relationship between the dosages of different anti-slump agents and the filtrate of the drilling fluid. The filtrate loss of the drilling fluid first decreased with the increase of the anti-slump agent dosage and then leveled off. SMNA-1 has the best filtration effect, and the optimal dosage is 2%.

Pressure-transfer experiments are carried out with shale cores. 2% SMNA-1 is added to the base slurry to test the permeability of shale before and after adding it. The experimental results are shown in Table 3. It can be seen that the permeability reduction rate of the base slurry without SMNA-1 is 44.2%, and the permeability can be reduced by 74.7% after the anti-slump agent SMNA-1 is added. This is because SMNA-1 can form a dense pressure-bearing seal near the wellbore, preventing pressure transmission and filtrate intrusion. The plugging and anti-slump agent SMNA-1 can effectively pack and bond the filter cake through its deformability and cohesiveness. At the same time, it
uses its hydrophobic properties to form a blocking film on the surface of the filter cake to bind free water and enhance the toughness and compactness of the filter cake. Thereby, the plugging and anti-slump ability of the drilling fluid is improved.23

3.1.2. Effect of Modified Nano-SiO2 Particles on the Stability of Shale. As for fracture-bearing hard and brittle shale, the key to wellbore stability is to prevent the transmission of pore pressure; therefore, it is necessary to strengthen the plugging of microfractures. Previous research based on pressure permeability experiments has shown that nanoparticles can block the transfer of drilling fluid pressure to shale formations. When the film-forming plugging agent is used in combination with nano-silica, the nano-plugging agent takes advantage of its excellent deformation adsorption capacity to preferentially adsorb in the pores and fractures on the wellbore surface, thereby forming a film on the wellbore wall. Due to the small particle size and uniform particle distribution of nano-silica, it can effectively block the micropores and microcracks on the membrane, form a dense membrane to prevent the intrusion of the filtrate, and stabilize the well wall and protect the reservoir.24−28 The effect of nanomaterials on the stability of shale is studied. Modified nano-SiO2 is obtained by ultrasonically modifying nano-SiO2 with the silane coupling agent, introducing vinyl functional groups, and copolymerizing with polymerizable monomers under certain temperature and pressure conditions. The ability of modified nano-SiO2 and several other inhibitors to inhibit shale hydration is compared using a linear swelling instrument, as shown in Figure 4. The

Figure 4. Effects of different materials on hydration expansion strain of shale.

displacement sensor is attached on the top surface of the sample, and then the remaining space of the test container is filled with the experiment fluid. The hydration expansion rate of the sample can be recorded using the data acquisition system. After nanomaterials form a protective film on the surface of shale, it can inhibit the hydration expansion caused by surface water absorption and reduce the hydration expansion rate of shale from 45 to 15%.

The performance of the nano-film-forming plugging drilling fluid is evaluated, as shown in Figure 5. Compared with asphalt plugging materials, modified nano-SiO2 can effectively reduce permeability and slow fluid intrusion. Compared with the common polysulfonic drilling fluid system, the permeability reduction rate of the mud cake reached 93% after adding the nano-plugging agent, and the effect on the rheological properties of the drilling fluid is small.

The modified nano-SiO2 particles are added to the drilling fluid base slurry (4.0% bentonite slurry) in different proportions (0.5, 1, 1.5, 2%) to investigate their rheology and fluid loss properties, as shown in Figure 6. With the increase of the dosage of nano-SiO2, the apparent viscosity and plastic viscosity increase gradually, and the fluid loss decreases gradually. When the addition exceeds 1%, the fluid loss curve tends to be flat, and the viscosity begins to increase significantly. Therefore, the optimum addition amount of modified nano-SiO2 is 1%.

On the basis of the commonly used polysulfonic acid drilling fluid in the Hasan area and previous researchers’ research on the polysulfonic acid drilling fluid, modified nano-SiO2 particles and the inlaid film-forming anti-slump agent SMNA-1 are added.29,30 Through laboratory tests, the formula of the film-forming plugging drilling fluid is determined to be 3% bentonite + 0.2NaOH + 0.2% KPAM + 3% SMP + 1% PB-1 + 2% SMNA-1 + 2% lubricant SMLUB-1 + 1% modified nano-SiO2 particles.

3.2. Determination of the Formula of the Bridging Cross-Linking Plugging Agent. The bridging cross-linked plugging agent formulation is determined by changing the

Figure 5. Evaluation of the plugging effect of nano-SiO2.

Figure 6. Effect of different additions of modified nano-SiO2 on the performance of drilling fluids.
compounding ratio of the four preferred plugging materials. Table 4 shows the pressure-bearing capacity of the four plugging materials at different ratios. When adding 8–10% granular material, 3–5% fiber material, 2–4% elastic material, and 0.5–1% cementing material, the plugging agent has the best pressure-bearing capacity.

The plugging agent formulation is evaluated using a high-temperature and high-pressure plugging and anti-spitting simulation evaluation device as shown in Figure 2. A plugging agent is injected into the simulated core, and the plugging agent is pressed into the leakage channel under the action of pressure. Continuous pressurization is carried out, and the change of the leakage volume with time is measured. It is compared with the control group of the base liquid without the plugging agent to judge the plugging effect of the leakage plugging agent. The performance of the bridging cross-linked plugging agent is shown in Table 5. Figures 7–9 show the pressure-bearing capacity of the bridging cross-linked plugging agent under different fracture widths. The evaluation experimental results show that the above plugging formulation can effectively seal 1–3 mm cracks, the pressure-bearing capacity is greater than 10 MPa, and the anti-return liquid capacity is greater than 4 MPa.

### Table 4. Pressure-Bearing Capacity of the Four Plugging Materials in Different Ratios

| experiment number | granular materials, % | elastic materials, % | fiber material, % | bonding material, % | pressure-bearing capacity, MPa |
|-------------------|-----------------------|----------------------|------------------|---------------------|-------------------------------|
| 1                 | 3                     | 2                    | 5                | 0.5                 | 9                             |
| 2                 | 3                     | 4                    | 8                | 0.5                 | 11                            |
| 3                 | 3                     | 6                    | 10               | 0.5                 | 12                            |
| 4                 | 5                     | 6                    | 5                | 1.0                 | 13                            |
| 5                 | 5                     | 4                    | 8                | 1.0                 | 17                            |
| 6                 | 5                     | 2                    | 10               | 1.0                 | 17                            |
| 7                 | 8                     | 6                    | 5                | 1.5                 | 16                            |
| 8                 | 8                     | 2                    | 8                | 1.5                 | 17                            |
| 9                 | 8                     | 4                    | 10               | 1.5                 | 14                            |

### Table 5. Performance of the Bridging Cross-Linked Plugging Agent

| crack width, mm | thickness of the filter cake, cm | weight of the filter cake, g | forward pressure-bearing capacity, MPa | anti-return liquid capacity, MPa |
|-----------------|---------------------------------|-------------------------------|----------------------------------------|---------------------------------|
| 1               | 1.0                             | 376                           | 16.0                                   | 5.5                             |
| 2               | 1.5                             | 459                           | 17.0                                   | 4.5                             |
| 3               | 2.0                             | 583                           | 11.0                                   | 4.0                             |

Figure 7. Pressure-bearing capacity of the plugging agent when the crack width is 1 mm.

Figure 8. Pressure-bearing capacity of the plugging agent when the crack width is 2 mm.

Figure 9. Pressure-bearing capacity of the plugging agent when the crack width is 3 mm.

3.3. Analysis of the Wellbore Strengthening Mechanism. “Preventive” wellbore strengthening and “remedial” wellbore strengthening are widely used wellbore strengthening methods; this paper proposes a wellbore strengthening technology that combines these two methods. As shown in Figure 10, before loss of circulation occurs, nanofilm-forming plugging agents are employed as a “preventive” wellbore strengthening method. Bridging cross-linked lost circulation agents are employed as a “remedial” wellbore strengthening method after lost circulation occurs.
The mechanism of the nano-film-forming plugging drilling fluid to strengthen wellbore is shown in Figure 11a. Under the action of pressure difference, nanoparticles with a small particle size and uniform distribution are pressed into the micropores and microcracks on the rock surface, reducing the intrusion of the filtrate and forming a physical plugging layer. In addition, the Si–OH on the surface of the modified nano-silica reacts with the Si–OH on the shale surface and produces strong chemical adsorption, which thickens the hydration film and increases the repulsion force of the hydration film. The formation of chemical seals in fractures can alter the pore pressure and tangential stress around the wellbore in shale formations, and the hydration swelling caused by surface water absorption can be suppressed after nanomaterials form a protective film on the surface of shale.

The mechanism of the bridging cross-linking plugging agent strengthening the wellbore is shown in Figure 11b. The bridging and cross-linking plugging agent is added to allow high-strength particles of different particle sizes to bridge the cracks. The fiber material is filled between the particles, and the chemical cross-linking consolidation material tightly cements and solidifies the particles, fibers, and the rock body; stops the propagation of the fracture; and eventually cures the losses.

4. CONCLUSIONS

(1) Aiming at the problems of lost circulation and wellbore instability in the Hasan area, the countermeasures for wellbore strengthening are proposed by analyzing the existing lost circulation technology and drilling fluid technology. The formula of the bridging and cross-linking plugging agent is determined through optimization experiments: well slurry + 8–10 granular materials + 3–5% fiber material + 2–4% elastic material + 0.5–1% cementitious material. The formula of nano-film-forming plugging drilling fluid is determined: 3% bentonite + 0.2NaOH + 0.2% KPAM + 3% SMP + 1% PB-1 + 2% SMNA-1 + 2% lubricant SMLUB-1 + 1% modified nano-SiO₂ particles.

(2) The formulations of the bridging glue-linked plugging agent and nano-film-forming plugging drilling fluid are evaluated by pressure-transfer experiments and a high-temperature and high-pressure plugging simulation and evaluation device. The results show that the bridging cross-linked plugging agent has good pressure-bearing capacity and anti-returning ability, and the nano-film-forming plugging drilling fluid has low filtration loss performance and good rheological properties.

(3) The mechanism of wellbore strengthening is analyzed. The nanoparticles in the nano-film-forming plugging drilling fluid are pressed into the micropores and microfractures on the rock surface under the action of pressure difference, forming a protective film on the shale surface and inhibiting the hydration swelling caused by water absorption on the surface. The chemical cross-linked cementing material in the bridging and gluing plugging agent tightly glues and cures the particles, fibers, and the rock body, thus plugging the cracks and improving the pressure-bearing capacity of the wellbore.

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Figure 11. Diagram of the wellbore strengthening mechanism: (a) nano-film-forming plugging drilling fluid and (b) bridging cross-linking plugging agent.
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Notes
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