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The Evaluation and Application of SmartGel for Deepwater Loss-Circulation Control

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Abstract: In view of the problem that the formation of deepwater wells in the study area leak easily, the mechanism of loss-circulation was studied in depth, and the loss-circulation plugging material SmartGel was developed with guar gum and its derivatives as the main synthetic raw materials. The gel process could be controlled by adjusting the dosage and temperature of gel accelerators. In order to adjust the gelling speed of SmartGel, GelRetarder and GelAccelerant were developed. The extrusion strength of SmartGel increased with the increase in SmartGel dose and decreased with the increase in temperature. As for the plugging performance of SmartGel, the sand bed test confirmed that the pressure capacity of SmartGel in the 80 °C sand bed can reach at least 7 MPa, which can meet the requirements of site construction. The PPT sand tray test and core flow meter simulation pore test showed that SmartGel has good bearing performance. As for the gel-breaking of SmartGel, low-temperature gel-breaking was achieved by adding the biological gel-breaking agent S100. The gel-breaking time was shortened by increasing the dose of S100; the higher the temperature, the more obvious the effect. To facilitate high-temperature gel-breaking, the post-gel-breaking method was adopted since the enzyme gel-breaking agent cannot play a role above 60 °C. The test showed that after adding 5% gel-breaking agent PF-JPC, due to gel-breaking at 80 °C, the SmartGel gel completely reduced the viscosity within 48 h. We successfully used SmartGel + 0.2% GelRetarder to stop the loss-circulation in well A and used a cored well wall to show a good gel-breaking effect.

Keywords: deepwater drilling; unconsolidated formation; loss-circulation material; gel-breaking effect; pressure-bearing capacity

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1. Introduction

Natural or fractured reservoirs, high-permeable sandstone, and cavernous zones might lead to loss-circulation. Fractured reservoirs can greatly contribute to production but will also play a role as a downhole hazard during drilling operations. If a drilling operation encounters a fractured reservoir, a complete loss-circulation without return might occur. The Lingshui block is located in the eastern part of Lingshui Sag in the Qiongdongnan Basin, belonging to the central canyon, which is rich in natural gas resources. However, the water is relatively deep, the geological age of the stratum is relatively new, and the sedimentation rate is relatively high. The complicated sedimentary environment leads to the undercompaction of the deepwater stratum and a narrow pressure window, so it is prone to complicated situations such as loss-circulation and blowout. The lithology of the second member of the Yinggehai Formation in the Lingshui block is mainly gray mudstone, argillaceous siltstone, and gray silty mudstone. Generally, the interface between mudstone and sandstone is prone to produce stress “weak points” of tectonic movement, and there are interface fracture zones between mudstone and sandstone, thus forming more loss-circulation formation [1–3]. In addition, because the formation fractures in the second member of the Yinggehai formation mostly appear in the form of transverse fractures, and sandstone has good permeability, once subjected to hydrostatic pressure, the fractures will be easily pushed open and spread around quickly, resulting in continuous loss-circulation, which greatly increases the difficulty of plugging in drilling [4–6]. Moreover, the formation features in the Yinggehai formation are developed with mainly longitudinal fractures and many thief zones; therefore, loss-circulation occurs frequently. In addition, plugging under pressure before drilling the gas zone and cementing operations are difficult and require a long time resulting from different pore-pressure formations in the same well interval. It is considered that formation loss-circulation is the main factor that affects drilling efficiency. Subsequently, in view of the complex problem that deepwater wells are prone to loss-circulation, ultra-deepwater drilling operators in the western South China Sea conducted research on the borehole loss-circulation mechanism in the Lingshui block and measures to solve loss-circulation were proposed, including developing novel loss-circulation materials, ensuring loss-circulation is handled carefully to secure operation safety for such a harsh deepwater drilling environment. Common plugging materials include bridging plugging materials, high filtration plugging materials, inorganic gel plugging materials, temporary plugging materials, and polymer gel plugging materials [7,8]. Polymer gel plugging technology has a wide range of applications at home, such as rapid gel formation for shallow wells [9], high-temperature gel for deep wells [10–13], gel formation for high salt stratum [14], timing gel formation [15], etc. Abroad, Sweatman et al. [16] developed a polymer gel loss-circulation plugging system (CP), which is formed by crosslinking two polymers. Lecolier et al. [17,18] developed a crosslinked polymer-type bridge plugging material (CACP), which is mainly made of polymer gel and is filled with inert fibers, particles, and other materials for bridging. Polymer hydrogels have been widely used in many fields due to their higher mechanical strength, better stability, lower cost, good biocompatibility, and acceptable biodegradability [19–23]. Due to the low price, good economy, and environmental friendliness of vegetable gum, some scholars have studied the application of vegetable gum drilling fluid in well loss treatment [24–28]. When the gel is used for plugging, two issues are critical: one is gel formation time, and the other is reservoir protection performance. Gel formation time is very important to the result of gel plugging. If gelatinization is too slow, the gel liquid is not gelatinized in the loss-circulation layer, and it will lead to the failure of the plugging operation. If the glue is formed too quickly, it will not only fail to plug the leak but also bring trouble to the drilling operation. Due to the different loss-circulation zones of different wells, the time of gel flow into the loss-circulation zone is not fixed, and the pump speed has a great influence on the loss-circulation, which is limited, so the gel system gel formation time is controlled, and rapid crosslinking glue formation occurs after the flow into the loss-circulation, which has a profound impact on the success of the plugging operation. Reservoir protection is also important, and sometimes even if you succeed in plugging a leak, if the gel does not degrade or break, it cannot achieve the productivity that it should, and the overall plugging effort is a failure.

2. SmartGel Loss-Circulation Technology

2.1. Performance Characteristics of SmartGel

For an aqueous solution such as guar gel, when the concentration exceeds 1%, it will form pasty-like fluid, and its fluidity will become worse. If the concentration is lower than 1%, it will form a jelly, and its strength is too low to be used as a liquid plug. SmartGel is a kind of gel-forming agent with strong elasticity, which takes guar gel and its derivatives as the main synthetic raw materials and is modified quite a few times. The agent is a light-yellow flowable powder, which can form a uniformly dispersed non-viscosifying system in water. After adding the proper amount of GelAccelerant into SmartGel and heating it to an appropriate temperature, the viscosity of the system will be higher and higher until a strong elastic gel is formed. The gelling process can be controlled by adjusting the dosage and temperature of GelAccelerant [29–32]. Figure 1a shows the state before gelling, where the viscosity is equivalent to water; Figure 1b shows the state after gelling, where the low shear rate viscosity LSRV exceeds 2,000,000 cp.

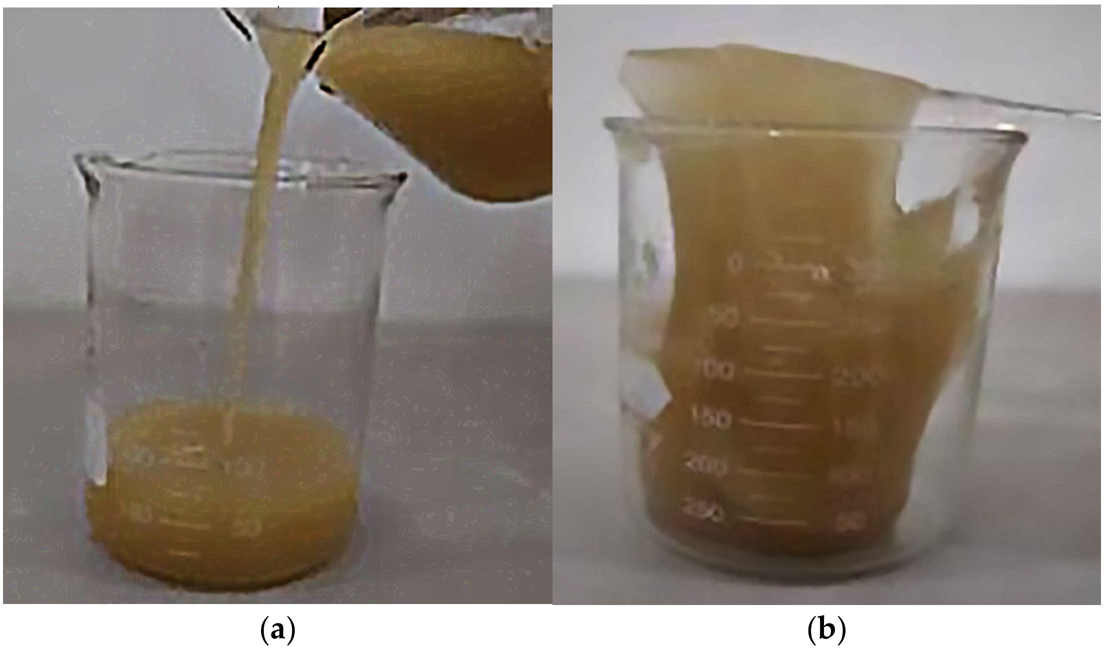

Figure 1. Gelling status: (**a**) before gelling and (**b**) after gelling.

2.2. Gelling Property of SmartGel

SmartGel is guar gel modified product. If it is a general guar gel derivative, such as hydroxypropyl guar gel and carboxymethyl guar gel, it will obviously increase its viscosity after being dissolved in water. When the concentration exceeds 1%, it is not only difficult to prepare gel solution but also prone to form "fisheye" (convex granules). Moreover, if the viscosity is too high, it is difficult to pump, and the gel strength after crosslinking is low, so it cannot provide a blocking effect. In contrast, after SmartGel is dissolved in water, even if its concentration reaches 7%, its initial viscosity is still equal to water; therefore, the hydration process is slow, and its viscosity increases slowly [33–35]. The gelling rate can be controlled by adjusting the dosage and temperature of GelAccelerant. In this way, in the process of preparation and pumping, the flow resistance of SmartGel is low, and it can gel quickly after entering the formation, forming a strong elastic gel, which plays a role in plugging the formation.

In order to adjust the gelling rate of SmartGel, gelling rate regulators GelRetarder and GelAccelerant were developed, in which GelRetarder is used to delay the gelling rate, and GelAccelerant is used to accelerate the gelling rate. At a certain temperature, the increasing viscosity rate of the system can be changed by adding the two regulators at the same time and adjusting the dosage ratio. Taking the dosage of 0.2% SmartGel as an example, when the system is heated at a heating rate of 3 °C/minute, and the temperature rises from 25 °C to 50 °C, the variation of its Φ600 reading with time is shown in Figure 2, in which the addition ratio of 0.2% GelRetarder + 0.3% GelAccelerant can obtain a higher viscosity in a short time. Figure 3 shows how the gelation time of SmartGel can be changed by adjusting the dosage of GelRetader and GelAccelerant. It cannot be simply concluded that either longer or shorter gelation time is better, the gelation time must accommodate to well conditions.

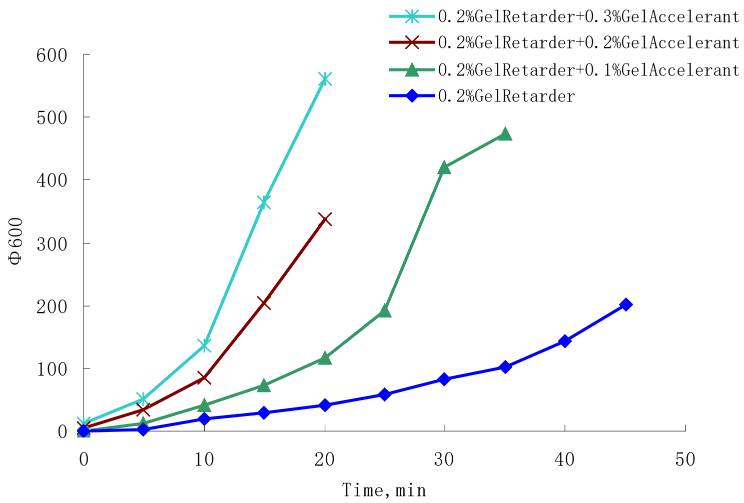

Figure 2. Viscosity variation of 7% SmartGel.

Figure 3. Gel after experiment.

2.3. Relative Strength of SmartGel

(1) Experimental materials and devices

Fresh water, SmartGel, 0.2% GelRetarder, a water bath, and a stainless-steel container with a 3 mm hole at the bottom

(2) Experimental procedure

Prepare temporary loss-circulation agent by adding fresh water + SmartGel + 0.2% GelRetarder. Then, put it into a water bath apparatus at 80 °C with stirring, and after the viscosity of the liquid increases and the SmartGel no longer settles, transfer it into a stainless-steel container with a 3 mm hole at the bottom. After keeping it at a certain temperature for 1 h, flush nitrogen into the container from the top. Observe whether there is gel being squeezed out in the bottom hole and take the lowest pressure of gel extrusion as the strength of SmartGel.

(3) Experimental result

The experimental data are shown in Table 1.

(4) Experimental data analysis

According to the experiment results in Table 1, when the dosage of SmartGel increases, the squeezing strength is higher, and the plugging performance is better. It is easy to understand that the extrusion strength increases with the increase in SmartGel dose. It can also be seen from Table 1 that the extrusion strength decreases with the increase in temperature. The reason is as follows: with the increase in temperature, the gel will become thinner, and the extrusion strength will decrease relatively (it is easier to squeeze).

Table 1. Squeeze gel strength of SmartGel.

Dosage of SmartGel	Squeeze Gel Strength of SmartGel, MPa			
	50 °C	60 °C	70 °C	80 °C
4%	0.90	0.80	0.67	0.54
5%	1.10	1.00	0.82	0.67
6%	1.40	1.30	1.10	0.88
7%	1.50	1.42	1.28	1.04

2.4. Evaluation of Plugging Performance of SmartGel

2.4.1. Sand Layer Experiment Set Up

First, add 200 g of 40–60 mesh quartz sand to fill the filtration loss bucket of the loss-circulation plugging apparatus. Prepare 7% SmartGel with tap water, and add 0.2% GelRetarder, transfer the system to a filtration loss bucket, seal it, heat it to 80 °C, and then keep the temperature for 1 h so that SmartGel can be fully gelled in the sand layer. After the SmartGel is gelled, apply pressure of 3.5 MPa to it, and no gel is squeezed out at the outlet. Then, gradually increase the pressure until it reaches 6.7 MPa, no gel is squeezed out, and no filtration flows out. This shows that the bearing capacity of SmartGel in the sand layer at 80 °C can reach at least 7 MPa, which can meet the requirements of downhole conditions [36,37].

2.4.2. Permeable Plugging Tester (PPT) Sand Disc Experiment

Put an abrasive disc with a permeability of 20 darcys into the PPT experiment device. In order to conduct a filed plugging operation, it is the plan to use pure gel, which will be displaced by drilling fluid to the loss-circulation zone. Therefore, prepare 7% SmartGel with tap water, add 0.2% GelRetarder, transfer the system into the filtration loss bucket of the PPT device, heat it to 93 °C in a sealed way, and create heat preservation for 1 h. After heat preservation, apply pressures of 3.5 MPa, 7 MPa, 10.3 MPa, 13.8 MPa, and 15 MPa, respectively, and keep pressure for 30 min; measure the cumulative volume of filtrate or gel flowing out at the outlet. It can be found that during the pressure application, filtration flows out, but no gel is squeezed out. Figures 3 and 4 show the pictures of the gel and abrasive disc taken out after the experiment. Figure 5 shows the experiment measurement result: the fluid loss gradually decreases, indicating that the system has formed efficient plugging at the end face of the core, preventing the solid phase and filtrate from entering the core, thus achieving the effect of pressure-bearing plugging. Figure 3 shows how the gelation time of SmartGel can be changed by adjusting the dosage of GelRetader and GelAccelerant; it cannot be simply concluded that either a longer gelation time or shorter gelation time is better. The gelation time must accommodate to well conditions.

Figure 4. Abrasive disc after experiment.

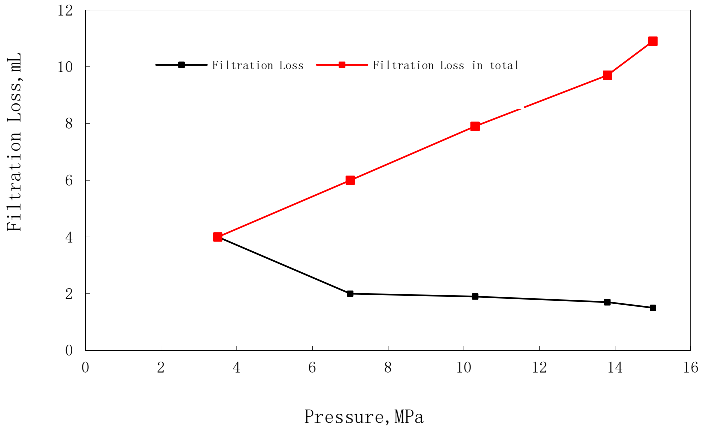

Figure 5. Result of PPT sand disc pressure bearing.

2.4.3. Experiment Results of Simulated Porosity by Core Flow Meter

Drill a perforated hole along the axis of the sandstone core to simulate the downhole situation and evaluate the bearing capacity of SmartGel. The core diameter is 2.45 cm, the core length is 6.15 cm, and the simulated pore diameter is 3.5 mm, as shown in Figure 6. Prepare 0.2% GelRetarder + 7% SmartGel with clean water in a beaker, and then put the perforated core into the beaker to completely immerse it. Then, seal the beaker and place it in an incubator, and keep the beaker at a constant temperature of 80 °C for 1 h so that the SmartGel can be fully gelled. After taking it out, remove the gel from the core surface (the gel cake is left at the end) and place it in the core holder. The core displacement experiment should be carried out at 80 °C. As shown in Figure 7, the maximum breakthrough pressure of gel can reach 0.63 MPa, indicating that it has acceptable pressure-bearing performance.

Figure 6. Perforated core.

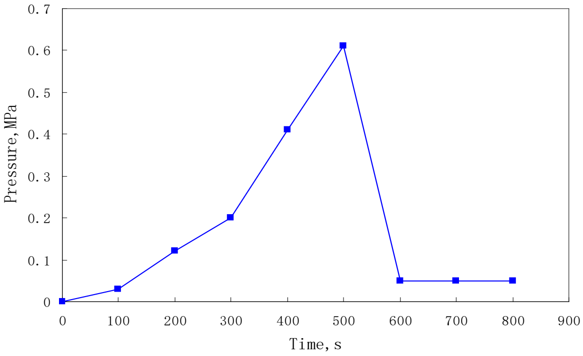

Figure 7. Results from core displacement experiment.

2.5. *Evaluation of Gel-Breaking Performance of SmartGel*

2.5.1. Gel-Breaking Performance of SmartGel at Low Temperature

During the preparation of SmartGel, add a certain amount of biological gel breaker S100 into the system in advance. After it is pumped into the formation by the mud pump, S100 will gradually degrade the SmartGel at the formation temperature until the SmartGel is completely broken and drained out, which saves the gel-breaking procedure and reduces the risk of reservoir damage caused by SmartGel. Formation damage might occur due to loss-circulation remedial treatments during loss-circulation control. The reason for conducting the gel-breaking experiment is to find out how the gel-breaking time of SmartGel affects reservoir protection during loss-circulation plugging. As shown in Figure 8, at 50 °C and 60 °C, the gel-breaking time of 3.5% SmartGel decreases with the increase in S100 dosage, and the effect becomes more obvious with the increase in temperature, as shown in Figure 9. Therefore, with the increase in S100 dosage and temperature, the shorter the gel-breaking time, the easier it is for the hydrocarbon to flow back from the reservoir.

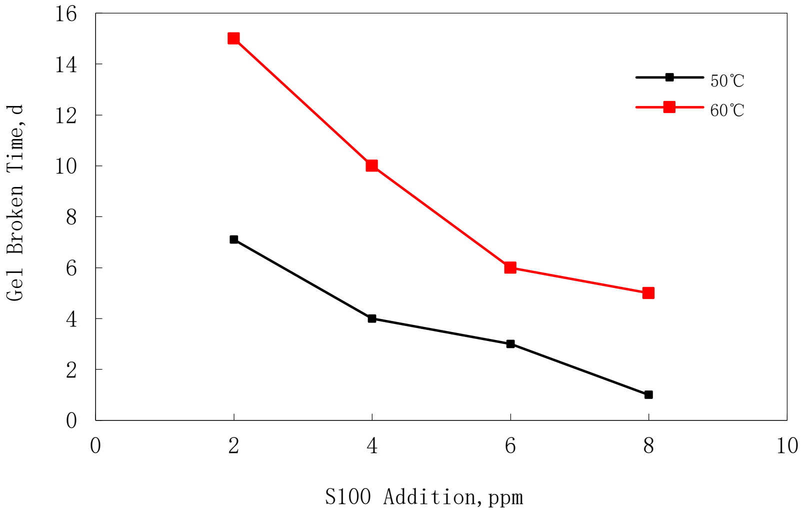

Figure 8. SmartGel gel-breaking time curve.

Figure 9. After gel-breaking.

2.5.2. Gel-Breaking Performance of SmartGel at High Temperature

Due to the restriction of the temperature resistance of biological enzymes, the enzyme will be inactivated above 60 °C, so when the temperature is higher than 60 °C, the oxidative gel-breaking method or post-gel-breaking method can be selected. However, as a shielding temporary loss-circulation agent that can be used to protect the reservoir, the following requirements must be met when the gel-breaker is added in advance: (1) the addition of a gel breaker cannot affect gelling time and gelling strength; (2) the half-life period of the gel breaker shall be as long as possible so that the gel-breaking time can be controlled. The gel must not be broken within 2 days, and after the application, the gel must be broken thoroughly to prevent the reservoir from being polluted; (3) the residual produced after the gel is broken shall be as low as possible to ensure good storage and preservation performance.

Based on the above requirements, it is quite challenging to choose a suitable pre-gel breaker. Because the gel can be used in non-reservoir and reservoir formations, it is not necessary to break the gel for non-reservoir conventional oxidative gel-breakers, making it difficult for them to meet the requirements, while biological enzyme gel-breakers find it difficult to work at high temperatures. Therefore, it is obviously a very challenging problem to choose an enzyme-like chemical agent which can react with guar gel, especially as a pre-gel-breaker. Based on the above difficulties and the degradability of guar gel, the presented method is a simple and easy way to break gel. According to the experiment results of the post-gel-breaking experiment with PF-JPC in the laboratory, after adding 5% PF-JPC, the gel was broken at 80 °C, the viscosity of SmartGel was completely reduced within 48 h, and its viscosity was almost equal to that of water. Figure 10 is a picture of the broken gel.

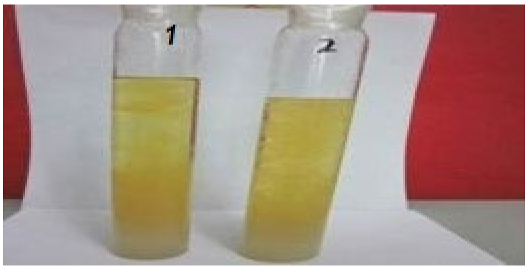

Figure 10. Gel-breaking after 48 h.

3. Application of SmartGel Loss-Circulation Material in Exploration Well A

3.1. Basic Conditions

Water depth of well location: 1500 m.

Drilling layer: Yinggehai Formation (2392~3226 m).

Lithology: Grey mudstone, grey silty mudstone and argillaceous siltstone.

Depth of casing shoe: 2865.38 m.

F.I.T @casing shoe: 1.65 g/cm^3.

Density of drilling fluid: 1.21 g/cm^3.

Drilling ECD: Max. 1.26 g/cm^3.

Back reaming ECD: Max. 1.24 g/cm^3.

Formation pore pressure: 1.20 g/cm^3.

Temperature: 60 °C.

Formula of drilling fluid: 0.2% $NaCO_3$ (sodium carbonate) + 0.17% citric acid + 3% PF-1 (polyamine, Shale inhibitor) + 0.8% PF-2 (coating agent) + 3% PF-3 (coating lubricant) + 2% PF-4 (fluid loss reducer) +2% PF-5 (borehole stabilizer) + 9% NaCl (potassium chloride) + 0.1% NaOH (sodium hydroxide).

The drilling fluid properties are shown in Table 2.

Table 2. Drilling fluid properties.

Density	**1.21 g/cm^3**
Funnel viscosity	66 s
Yield point (YP)	15 Pa
Plastic viscosity (PV)	30 cP
Filtration loss	3.6 mL/30 min

3.2. Loss-Circulation

When normal backreaming comes to 3010 m, the pump pressure decreases, and the weight on the hook increases, accompanied by pump and torque spike, and the return flow of the EKD monitoring system decreases. Stop the pump to observe the rapid decline of the annular level, close the BOP, fill the riser with the booster pump, open the BOP, and fill the annulus with drilling fluid through the booster pump. The loss-circulation rate should be approximately 160 m^3/h. If the loss-circulation rate is too high, the annular level will not be visible. It was decided to close the BOP in time to ensure the safety of well control and avoid the greater risk caused by damage to the riser.

3.3. Analysis of Causes of Loss-Circulation

As shown in Figure 11, the comprehensive mud logging diagram and data while drilling show that the density of this well section is greatly reduced. Judging from the return of mud logging cuttings, the lithology of 3012~3018 m is muddy siltstone, and the bearing capacity of the formation is low. During the drilling of this well section, the density of drilling fluid was 1.21 g/cm^3, and then it was gradually increased to 1.25 g/cm^3, which was measured from the shale shaker. The target formation was uncovered and drilled to the coring formation, and there was no loss-circulation. When reaming back to this formation, the borehole was irregular, which caused the torque to increase and the pump pressure to increase due to an annular jam, resulting in loss-circulation.

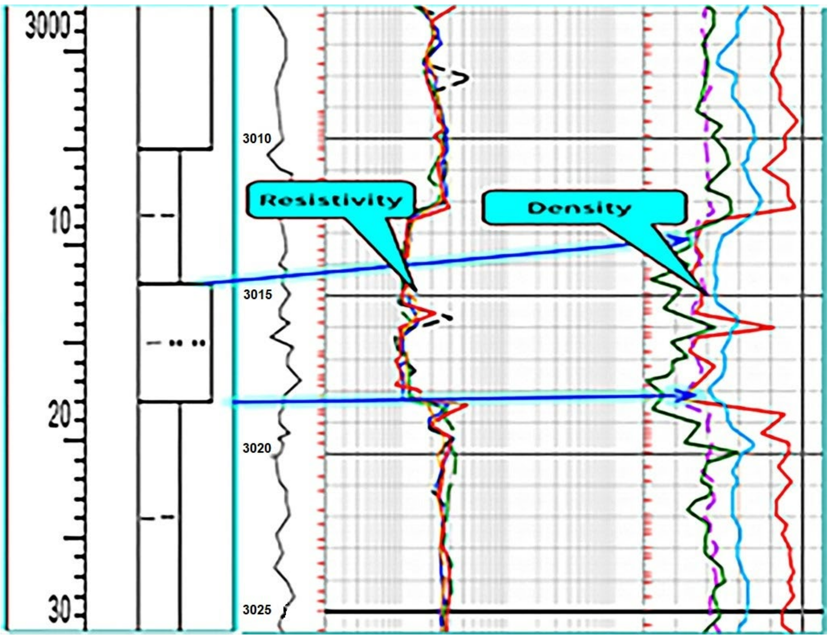

Figure 11. Mud logging diagram.

The field operators first obtained formation pore pressure of 1.20 g/cm^3 through pressure monitoring while drilling, and then, in order to balance the wellbore pressure, reduced drilling fluid density in the riser from 1.26 g/cm^3 to 1.21 g/cm^3 by circulation to reduce loss-circulation rate.

3.4. Plugging and Gel-Breaking Effect

(1) Formula for plugging drilling fluid: fresh water + SmartGel + 0.2% GelRetarder;
(2) Close the choke valve, open the upper annulus blowout preventer, gradually increase the pump rate to 2850 L/min for circulation with 228 L/min as an increment, and observe the wellbore stability for loss-circulation;
(3) Formation pressure test: 1.13 m^3 of accumulated drilling fluid is pumped, the pump pressure is 0.13 MPa~0.41 MPa, the pump pressure drops to 0.13 MPa after stopping the pump, and the pressure is released and flow back 0.5 m^3;
(4) Plugging is successful and normal circulation is established;
(5) When drilling reaches target depth, the measured circulating temperature at the bottom is 73 °C, and the static temperature is 78 °C. At the end of drilling, the drilling fluid with a dosage of 5% PF-JPC is added for circulating gel-breaking, and then the rotary sidewall coring tool is run to perform sidewall coring. From the results of coring, there is no gel on the surface, which proves that the gel-breaking effect is good.

4. Conclusions

(1) There are many interbedded layers between mudstone and sandstone in the second member of the Yinggehai Formation in the Lingshui block, and there is an interface fracture zone between mudstone and sandstone; many layers of loss-circulation are formed, which is prone to cause loss-circulation.

(2) SmartGel has a high viscosity and good plugging effect, which can effectively plug loss formation. Based on the degradability of guar gel, after gel-breaking treatment is adopted at 80 °C, the viscosity of SmartGel gel can be completely eased within 48 h, and its viscosity is similar to water, with a good gel-breaking effect, which can effectively protect the reservoir.

(3) The gel process could be controlled by adjusting the dosage and temperature of gel accelerators. In order to adjust the gelling speed of SmartGel, GelRetarder and GelAccelerant were developed.

(4) The extrusion strength of SmartGel increases with the increase in SmartGel dose and decreases with the increase in temperature.

(5) As for the plugging performance of SmartGel, the sand bed test confirms that the pressure capacity of SmartGel in the 80 °C sand bed can reach at least 7 MPa, which can meet the requirements of site construction. The PPT sand tray test and core flow meter simulation pore test show that SmartGel has good bearing performance.

(6) As for the gel-breaking of SmartGel, low-temperature gel-breaking is achieved by adding the biological gel-breaking agent S100. The gel-breaking time is shortened with the increasing dose of S100, and the higher the temperature is, the more obvious the effect is. During high-temperature gel-breaking, the enzyme gel-breaking agent does not play a role above 60 °C; therefore, the post-gel-breaking method is adopted. The test shows that after adding 5% gel-breaking agent PF-JPC, causing gel-breaking at 80 °C, the SmartGel gel completely reduces the viscosity within 48 h.

(7) After successful plugging, drilling was successfully completed with a drilling fluid density of 1.21 g/cm^3, and no loss-circulation occurred afterwards. According to the core results obtained after gel-breaking, there was no gel residual on the core surface, indicating that the SmartGel loss-circulation agent has a good application effect and can improve deepwater drilling to a certain extent.

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