Research on the Development and Plugging Capacity of a Honeycomb Porous Lost-Circulation Material

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ABSTRACT: Reducing economic losses and protecting producing strata are important links in the process of oil and gas exploration and exploitation. The key to avoid these problems lies in reducing well leakage accidents in the process of exploitation, in which the correct selection of plugging materials plays a decisive role. In view of the low sealing strength, complex construction, difficulty in unblocking, and high cost of the bridge lost-circulation material (LCM) currently used in plugging, this paper demonstrates the development of a highly elastic honeycomb porous LCM in a targeted manner. Indoor evaluation of the material shows it has good compression resilience and tensile strength: its 50% compression permanent deformation is less than 10% and tensile strength is more than 100 kPa; its retention rate under acidic conditions is more than 97%; it is basically not acid soluble; and at 100 °C aging conditions, the abovementioned performance and properties are maintained in a good manner. Due to the rebound characteristics of the highly elastic honeycomb porous LCM, the material can smoothly enter into different fractures to achieve a good plugging effect under the condition of choosing a suitable size.

1. INTRODUCTION

In recent years, as China’s oil and gas exploration and development efforts continue to increase, the drilling complexity of drilling blocks is also increased, accompanied by more and more frequent well leakage accidents, which not only cause huge economic losses but also seriously damage the production layer and reduce the recovery rate of the reservoir.1−3 Well leakage is the most common complex problem in the drilling construction process and also a technical problem. Efficient plugging material is the key to successful plugging.4,5

According to its mechanism and function, the research on plugging materials at home and abroad can be divided into bridging plugging materials represented by walnut shells and cotton fibers, high water loss plugging materials represented by DTR, temporary plugging materials represented by DF-1, expansion plugging materials, composite plugging materials, and high-temperature plugging materials represented by mica sheets and shells.6−9 At present, the plugging materials for fracture leakage are mainly bridging plugging materials. The so-called bridging plugging is a plugging method of mixing inert materials with different shapes and particles in drilling fluids with different formulas and directly injecting them into the leaking layer. After the materials are injected into the leaking layer, a plugging wall with certain mechanical strength is formed.6−10 Amanullah11,12 has developed a series of bridging granular arc plugging materials with date palm cores, which have good sealing and pressure-bearing capacity for cracks with a width of 2 mm; Mansour13,14 and others have developed a new intelligent plugging material with an anionic shape-memory polymer as the raw material, which can temporarily form a certain shape and return to the original state in a specific environment, but it has certain requirements for the environment. At the same time, its research is not in-depth, and its mechanical strength and chemical stability need to be further improved; Su and others15−17 have synthesized a leakage prevention and plugging agent GSZ-1 by drilling with fiber materials, inorganic mineral materials, ultrafine elastic expansion materials, and deformable materials. This material is applicable to both reservoirs and nonreservoirs. This experiment has strong pertinence, but there is a lack of experiment on compressive strength, which needs to be studied; Wang and others18−20 have developed an expansive plugging material, which expands slowly after entering the crack to fill the crack, so as to achieve the plugging effect. However, the construction of this process is complex and can be used only for specific cracks; Kang et al.21−24 has studied the plugging effect of different types of bridge plugging materials when used alone and...
in combination. The experimental results show that the “rigid + elastic + fiber” composite bridging material has the best plugging effect for millimeter cracks. However, due to the influence of gravity settlement, scouring in the fracture and other factors, it is not easy for this material to stay in large fractures with a large fracture width and a high longitudinal extension, which may lead to the low pressure-bearing capacity of the plugging layer and easy repeated leakage, and poor matching of the particle size to the low pressure-bearing capacity of the plugging layer and fracture width and a high longitudinal extension, which may lead not easy for this material to stay in large fractures with a large gravity settlement, scouring in the fracture and other factors, it is easy repeated leakage, and poor matching of the particle size to the low pressure-bearing capacity of the plugging layer and fracture width and a high longitudinal extension, which may lead not easy for this material to stay in large fractures with a large gravity settlement, scouring in the fracture and other factors, it is easy repeated leakage, and poor matching of the particle size to the low pressure-bearing capacity of the plugging layer and fracture width and a high longitudinal extension, which may lead not easy for this material to stay in large fractures with a large gravity settlement, scouring in the fracture and other factors, it is easy repeated leakage, and poor matching of the particle size to the low pressure-bearing capacity of the plugging layer and fracture width and a high longitudinal extension, which may lead not easy for this material to stay in large fractures with a large gravity settlement, scouring in the fracture and other factors, it is easy repeated leakage, and poor matching of the particle size to the low pressure-bearing capacity of the plugging layer and fracture width and a high longitudinal extension.

Therefore, in view of the fact that the existing plugging materials cannot meet the requirements of simple construction, strong pressure-bearing performance, and applicability to all kinds of cracks at the same time, starting from the plugging mechanism of bridge plugging materials and aiming at good crack matching, a highly elastic honeycomb porous plugging material is developed. The material has good compression resilience and can enter all kinds of cracks adaptively, which provides a feasible choice for plugging construction.

2. MATERIALS AND METHODS

2.1. Experimental Materials. Glycerin polyester, industrial grade, Jining Huakai Resin Co., Ltd.; TDI, triethylenediamine, silicone oil, industrial grade, Shanghai McLean Biochemical Technology Co., Ltd.; glycerin, analytical grade, Shandong Youso Chemical Technology Co., Ltd.; trimethylpropane, analytical grade, Shandong Youso Chemical Technology Co., Ltd.; stannous octoate (T9), industrial grade, Shandong Baiqian Chemical Co., Ltd.

2.2. Experimental Instruments. JJ-1 precision timing electric stirrer, Changzhou Ronghua Instrument Manufacturing Co., Ltd.; MOD. ZNN-D6 six-speed rotational viscometer, Qingdao Haitongda Special Instrument Factory; XGRL-4 high temperature roller heating furnace, Qingdao Haitongda Special Instrument Factory; HY-20080 microcomputer-controlled electronic universal material tester, Shanghai Hengyi Precision Instrument Co., Ltd.; medium-pressure sand bed filtration instrument, Shenzhen Tiansu Measurement and Testing Co., Ltd.; DJ-6 fracture plugging simulation experiment device, Jingzhou Tallinn Electromechanical Co., Ltd.

2.3. Material Preparation. The highly elastic honeycomb porous lost-circulation material (LCM) is polymerized by one or more polyols and diisocyanates under the conditions of initiators and catalysts and formed under the action of foaming agents and surfactants.

There are two main methods for synthesizing highly elastic honeycomb porous LCMs, namely, one-step method and two-step method. In this paper, a one-step foaming process was used; the experimental temperature was controlled at 25°C, and the stirring speed was 3100 rpm. 53.2% glycerol polyester with a hydroxyl value of 65 and 8.6% trimethylpropane polyester with a hydroxyl value of 31.0% were weighed to which 34.3% TDI, 0.17% triethylenediamine, 0.1% stannous octoate (T9), and 0.9% silicone were poured in, closed, and pressurized to 0.7 MPa, and the slurry was slowly stirred until it turns white then stop stirring. The foaming reaction subsided. Due to the use of high-efficiency catalysts such as organotin, the reaction rate was fast, and the temperature during the exothermic reaction was high. It did not need to be heated and aged after foaming. Porous products with relatively uniform cells can also be obtained under certain conditions. The main formula is shown in Table 1.

Table 1. Foaming Formula of Highly Elastic Honeycomb Porous LCM

| raw material                              | quality/portion | country |
|-------------------------------------------|-----------------|---------|
| glycerol polyester (hydroxyl value: 65)  | 53.2            | CHN     |
| trimethylolpropane polyester (hydroxyl value: 310) | 8.6            | CHN     |
| TDI                                       | 34.3            | CHN     |
| foaming agent                             | 2.73            | CHN     |
| triethylenediamine                        | 0.17            | CHN     |
| stannous octoate (T9)                     | 0.1             | CHN     |
| silicone                                  | 0.9             | CHN     |

2.4. Experimental Methods. 2.4.1. Suspension Performance. Its density was tested by the mass-volume method. The suspension ability of the material was improved by adjusting the material density.

2.4.2. Characterization of Skeleton Structure. The produced highly elastic honeycomb porous LCM was subjected to electron microscopy and conventional photography to observe the skeleton structure of the highly elastic honeycomb porous LCM under microscopic and macroscopic conditions.

2.4.3. Temperature Resistance. The LCM after aging at 100°C was sieved, washed, and dried, and the compressive resilience and tensile strength before and after aging were tested with an HY-20080 microcomputer-controlled electronic universal material tester to experimentally evaluate its temperature resistance. The test samples were three. The drilling fluid formula is as follows: fresh water + 15% sodium formate + 0.3% sodium hydroxide + 0.3% sodium carbonate + 2.0% MU1-5-3C + 5% A600 + 0.5% viscousifier VIS-B + 3.0% lubricant SLIP-W.

2.4.4. Acid Solubility Test. A certain amount of earth acid was poured into the test tube according to the proportion, and the weighed LCM was placed into the test tube and heated for 1 h at 90°C. The experimental materials were taken out and put into the oven at 100°C for 4 h, then they were put at room temperature for 12 h, weighed again, and the acid solubility was calculated.

2.4.5. Evaluation of the Plugging Performance. 2.4.5.1. Sand-Bed Plugging Experiment. The configured oil-based drilling fluid with a certain concentration of highly elastic honeycomb porous LCM was put into a pressure roller furnace at 100°C for aging and removed after aging for 16 h. Dried quartz sand of a certain mesh was weighed and poured into the medium-pressure sand bed filter loss apparatus to lay flat and compact, then 400 mL of oil-based drilling fluid was slowly poured in, closed, and pressurized to 0.7 MPa, and the slurry filtration loss was observed.

2.4.5.2. Fracture Plugging Experiment. The effect of different concentrations of reticulated foam LCM on the plugging effect of different simulated fractures was evaluated indoors using a fracture sealing simulator and a simulated irregular fracture mold sheet. After aging (16 h at 100°C), 400 mL drilling fluid was added with different concentrations of highly elastic cellular porous LCM, and fracture plugging experiments were conducted for fracture widths of 1 and 2 mm.
3. RESULTS AND DISCUSSION

3.1. Suspension Performance. Because the actual density of the highly elastic honeycomb porous LCM becomes smaller after foaming and expansion, it is difficult to suspend in the drilling fluid to play a plugging role. Therefore, it is necessary to use some density modifiers to assist the material itself to increase its density to achieve the effect of being suspended in the drilling fluid. The main density adjuster used was barium sulfate with a density of 4.3 g/cm$^3$, and it was supplemented with aluminosilicate cement to increase the strength of the honeycomb porous LCM.

It can be seen from Table 2 that when the weighting agent is 1.8% of the main weighting agent and 1.2% of the auxiliary weighting agent, the highly elastic honeycomb porous LCM is in good condition, but the density still does not meet the suspension requirements. When the main density regulator is added at a certain amount and when the auxiliary regulator aluminosilicate cement is added, the density increases accordingly. However, the prepared honeycomb-shaped porous LCM is easy to collapse during the initiation process, and the generated mesh is not full and appears shrunken. When the auxiliary regulator aluminosilicate cement is added in a certain amount, and the main regulator barium sulfate is increased, it is also prone to collapse. After repeated experiments, the optimum amount of density regulator for the highly elastic honeycomb porous LCM is +3.6% main regulator + 1.2% auxiliary regulator, and the density of the resulting leakage LCM is 1.12 g/cm$^3$.

Table 2. Density Adjustment of the Highly Elastic Honeycomb Porous LCM

| Adjusting Agent | Density/g/cm$^3$ | Porous Material Mesh Results |
|-----------------|-----------------|----------------------------|
| +1.8% main + 1.2% auxiliary | 0.92 | Uniform pore network |
| +1.8% main + 1.6% auxiliary | 1.21 | Easy collapse |
| +2.4% main + 1.2% auxiliary | 1.06 | Uniform pore network |
| +3.6% main + 1.2% auxiliary | 1.12 | Uniform pore network |
| +4% main + 1.2% auxiliary | 1.23 | Easy collapse |

3.2. Skeletal Structure Characterization. Scanning electron microscopy and conventional photography were used to observe the skeleton structure of the highly elastic honeycomb porous LCM under micro- and macro-conditions.

It can be seen from Figure 1 that the skeleton structure of the highly elastic honeycomb porous LCM is obvious under macroscopic conditions. The uniform mesh size is 1 mm. When the amount of organosilicon as a surfactant is doubled and tripled, porous materials with 0.5 and 0.3 mm pore diameters can be obtained. Observation under 50X magnification of an electron microscope shows that there is still a rich skeleton structure inside, and the inner wall of the cell is complete and smooth, which shows that the high-elastic honeycomb porous LCM has a good opening effect. The rich skeleton structure can make it play a better role of skeleton support at the bottom of the well. At the same time, the good open-pore structure can play the role of filtering and accumulation, so that the large particles can be densely accumulated before the foam, which has a good plugging effect.

3.3. Temperature Resistance. 3.3.1. Compression Rebound Capability. The 50% compression set rate of the highly elastic honeycomb porous leakage LCM is used as an index to characterize the compression rebound rate of the highly elastic honeycomb porous leakage LCM before and after aging. Referring to the Chinese national industry standard GB/T 6669-2008 “Determination of Compression Settlement of Flexible Foamed Polymer Materials”, the experiment evaluates the compression resilience performance of the highly elastic cellular porous LCM before and after aging. It can be seen from Figure 2 that the 50% compression set rate of sample 1 before aging is 10%, and it is still 10% after aging. The 50% compression set rate of the other two groups of samples before and after aging is about 10%. The compression rebound rate of the highly elastic honeycomb porous LCM before and after aging is greater than or equal to 90%.

It shows that the material has good compression resilience, can still retain a strong resilience at 100 °C temperature, and can quickly recover to complete the plugging task after adaptive compression enters the fracture.

3.3.2. Tensile Capacity. For the determination of the tensile strength of the highly elastic cellular porous LCM, refer to the Chinese national industry standard GB/T 6344-2008 “Determination of the Tensile Strength and Elongation at Break of Flexible Foamed Polymer Materials”. It can be seen from Figure 3 that the tensile strength of the highly elastic honeycomb porous LCM before and after aging has little change, and the anti-strength is above 100 kPa. The highly elastic honeycomb porous LCM with high tensile strength can overcome the interference of multiple downhole pressures, and combined with strong compression resilience, it can effectively enter the fracture, which is more conducive to the plugging effect.
3.4. Material Acid Solubility. The acid solubility of the highly elastic honeycomb porous LCM is related to whether it can still exert its own performance under acidic conditions and resist the dissolution of various substances at the bottom of the well.

The mass comparison of the three groups of samples before and after acid dissolution is shown in Figure 4.

It can be seen from Figure 4 that the quality of the highly elastic honeycomb porous LCM before and after acid dissolution has little change, the loss rate is extremely low compared with that before acid dissolution, and the acid dissolution retention rate is above 97%. It can be seen that the highly elastic honeycomb porous LCM is basically insoluble in acid, can resist acid corrosion from various aspects at the bottom of the well, and can still exert its own performance under strong acid conditions to complete fracture plugging.

3.5. Material Plugging Ability. 3.5.1. Sand-Bed-Plugging Capacity. Based on the sand-bed-plugging evaluation device, 2, 4, and 6% of high-elastic honeycomb porous LCM with a size of 4 mm were added to the drilling-fluid-based slurry, and the plugging slurry was aged. In the experiment, 20−40 mesh quartz sand was used for the sand-bed-plugging experiment.

It can be seen from Figure 5 that under the condition of the original base slurry performance, the greater the amount of highly elastic honeycomb porous LCM added, the better the plugging performance. With the increase of the added concentration of the highly elastic honeycomb porous LCM, the instantaneous leakage of the plugging slurry decreases gradually. Compared with 4% addition, the 6% highly elastic honeycomb porous LCM has better performance in the instantaneous fluid loss. The synthetic highly elastic honeycomb porous LCM can well improve the plugging performance of the drilling fluid, and adding 6% of the highly elastic honeycomb porous LCM can achieve plugging in a short time.

3.5.2. Fracture Plugging Effect. 3.5.2.1. Material Size. Because the simulated fractures involved in this experiment have two specifications of 1 and 2 mm widths, if the size of the highly elastic honeycomb porous LCM is too small or too large, it will inevitably cause different degrees of leakage or sealing. Different sizes of highly elastic honeycomb porous LCM were used in the study. 400 mL of drilling fluid was taken after aging (16 h aging at 100 °C) with 6% high elastic honeycomb porous LCM of different widths and tested and screened for selecting the size of the best matching material suitable for fracture widths of 1 and 2 mm.

It can be seen from Table 3 that the optimal highly elastic honeycomb porous leakage LCM corresponding to a 1 mm width fracture is a highly elastic honeycomb porous leakage LCM with a cutting size of 2 mm; the simulated fracture plugging experiment with a width of 2 mm should use a size of 4 mm highly elastic honeycomb porous LCM.

3.5.2.2. Fracture Plugging Experiment. It can be seen from Figure 6 that when the 2 mm highly elastic honeycomb porous LCM is used to conduct the simulation plugging experiment on the simulated fracture with the width of 1 mm, the plugging
slurry can well complete the plugging task, the overall leakage is less than 10 mL, and the pressure is up to 4.5 MPa.

It can be seen from Figure 7 that the 2 mm fracture simulation plugging experiment was carried out by using 4 mm highly elastic honeycomb porous LCM. The plugging barrier can bear a pressure of up to 5 MPa, and the leakage was 26.5 mL, which is larger than 1 mm fractures. The pressure borne by the plugging barrier meets the needs of fracture plugging.

Because the highly elastic honeycomb porous LCM has good compression resilience, it can exert its resilience after entering the fracture under a certain pressure and restore the original shape to quickly fill the fracture to achieve plugging. It can be seen from the plugging results that the plugging agent can bear a pressure of up to 4.5 MPa under the fracture model of 1 and 2 mm, which can effectively improve the leakage plugging ability of the fracture.

3.6. Leakage Plugging Mechanism Analysis.

(1) Skeleton infiltration: it can be seen from the fracture plugging experiment that when the pressure is less than 3 MPa, the filtration loss is more serious, but when the pressure increases to 4–5 MPa, the filtration loss is reduced, indicating that the mesh foam plugging material plays a role in blocking, filtration and so on. Due to its elasticity, it can be squeezed into the cracks or voids under the action of the bottom hole pressure difference, forming a filter screen at the cracks. At the same time, the skeletons are closely packed at the cracks, which play the role of blocking the leakage channels.

(2) Capture effect: from the sand-bed-sealing experiment, we can find that 0 and 2% of honeycomb porous materials added contrasts with the results of the experiment, the filtration volume is decreased significantly; this is because the material has a reticular structure, so it is easy to capture other types in the bottom hole plugging material to form a three-dimensional sealing isolation layer, which can improve the retention ability of plugging material in the cracks and improve the plugging success rate.

(3) Improve the pressure-bearing capacity: the filling material is continuously accumulated in the filter screen, and the plugging area is long. A large number of elastic mesh plugging materials block the partition wall to cooperate with each other, bear the external load, and improve the dense pressure-bearing capacity of the plugging layer. The specific synergistic effect is shown in Figure 8.

4. CONCLUSIONS

(1) A highly elastic honeycomb porous plugging material which can be well suspended in a low-density drilling fluid under the condition of maintaining good performance is prepared. It is stably and uniformly suspended in the drilling fluid and exerts good plugging performance.

(2) The 50% compression set rate and tensile strength of the highly elastic honeycomb porous plugging material before and after aging (100 °C, 16 h) change less than 10%, which indicates that the material has good temperature resistance. At the same time, it is basically insoluble in acid, which means that it can resist the reaction of various acidic substances at the bottom of the well and improve the success rate of plugging.

(3) The optimum amount of highly elastic honeycomb porous plugging material in a low-density drilling fluid is 6%. Sand-bed experiments and fracture experiments show that the material can reduce the instantaneous fluid loss and can adapt to fractures of different widths.

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Notes

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