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Study on the Elastic-Plastic Properties of Deep Well Complex Fractured Loss Formations and the Performance and Plugging Characteristics of Drilling Lost Circulation Materials

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Abstract: To address issues in deep wells with complex fractured loss formations—such as drilling fluid lost circulation materials having difficulty entering fractures, challenges in controlling plugging locations, and material performance degradation under high temperatures—a ductile-elastic drilling fluid lost circulation material suitable for high-temperature and high-pressure environments has been developed. Through tests of physical and mechanical properties, porous media plugging experiments, and pressure-bearing evaluation, the material's deformation capacity, compressive performance, and plugging behavior characteristics were systematically analyzed. The results show that this ductile-elastic material retains good elastic recovery and compressive stability under high-temperature conditions, capable of forming a stable bridging structure within fractures. Compared to traditional rigid materials, the ductile-elastic material can significantly improve the distribution of plugging locations, enabling effective transfer from the wellbore wall into the fracture interior. Multi-level particle size combinations can enhance inter-particle interlocking, improving the density and pressure-bearing capacity of the plugging layer. These research findings can provide a reference for the design and field application of drilling fluid lost circulation materials in deep wells with complex loss formations.

Keywords: Deep well; fracture-type loss; drilling fluid loss control;Resilience materials; sealing mechanism

1 Introduction

While-drilling lost circulation control is one of the most direct and efficient methods for addressing small- to medium-scale fluid losses in drilling engineering. Owing to its operational

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simplicity, rapid response, and relatively low cost, this technology has been widely applied in drilling through complex formations. Meanwhile, the continuous introduction of lost circulation materials (LCMs) can, to some extent, pre-reinforce the wellbore wall and reduce the risk of subsequent severe losses. However, in deep and complex fractured lost-circulation formations, fractures are usually highly developed, geometrically complex, and characterized by significant scale variations. The fracture aperture and connectivity exhibit strong heterogeneity, which causes the transport and placement of LCMs to be strongly affected by fracture structure and flow-field distribution during the plugging process. As a result, the materials often fail to migrate deeply into the fractures and tend to accumulate prematurely near the wellbore wall, forming "surface plugging". This phenomenon hinders the further migration of LCMs into the fracture interior and ultimately leads to poor overall plugging performance[Error! Unknown switch argument.-Error! Unknown switch argument.].

To address lost circulation in complex fractured formations, extensive studies have been carried out on while-drilling LCMs and related plugging technologies. Early studies mainly focused on rigid particles and mineral-based plugging materials, which achieved sealing through particle bridging and fracture filling. Liu et al. developed a while-drilling loss-prevention material, SMFL, suitable for fractures with widths of 1–2 mm, which improved fracture plugging efficiency and pressure-bearing capacity [Error! Unknown switch argument.]. Zhao et al. proposed a composite plugging system composed of water-swelling materials, rigid particles, and fibers, achieving effective plugging of fractures ranging from 0.05 to 3 mm[Error! Unknown switch argument.]. Wang et al. constructed a low-density while-drilling loss-prevention drilling fluid system, in which rigid–flexible combined LCMs effectively sealed low-pressure fractured reservoirs [Error! Unknown switch argument.]. With further research, it has been gradually recognized that single rigid-particle materials are highly dependent on fracture size and are therefore difficult to adapt to complex multi-scale fracture systems. To improve the adaptability of LCMs to different fracture scales, continuous particle size distributions and multi-stage particle synergistic plugging methods have been introduced. Luo et al. proposed a technical approach combining managed pressure drilling with while-drilling plugging, which enhanced wellbore pressure-bearing capacity and reduced drilling fluid loss [Error! Unknown switch argument.]. Zhou et al. established a basalt fiber plugging system, in which multi-stage fibers synergistically formed a skeleton structure, thereby improving fracture sealing capacity and effectively reducing mud loss**Error! Unknown switch argument.**.

In recent years, elastic–tough plugging materials have attracted increasing attention because of their favorable deformability and fracture adaptability. Liu et al. developed a modified mineral-fiber-based oil-based while-drilling plugging material, PSIFIBER, which exhibited good thermal resistance and fracture plugging performance **Error! Unknown switch argument.**. Liu et

al. developed a self-degradable polymer plugging agent with both favorable pressure-bearing capacity and reservoir protection performance **Error! Unknown switch argument.**. Meanwhile, to address the performance degradation of plugging materials under high-temperature deep-well conditions, Dong et al. evaluated the thermal stability of while-drilling LCMs for ultra-deep high-temperature wells and screened plugging systems suitable for environments above 200 °C **Error! Unknown switch argument.**. Xiong et al. pointed out that although high-temperature-resistant plugging materials show promising application potential, they still suffer from elastic attenuation and insufficient structural stability under long-term high-temperature exposure **Error! Unknown switch argument.**.

Overall, existing while-drilling lost circulation control technologies have gradually evolved from single rigid-particle bridging toward rigid–flexible coupling, multi-scale synergistic plugging, and functional composite plugging systems, achieving certain application effects in complex lost-circulation formations **Error! Unknown switch argument.Error! Unknown switch argument.**. Nevertheless, for deep and complex fractured lost-circulation formations, current LCMs still face several challenges, including insufficient deep migration capability, unstable internal supporting structures within fractures, and significant performance degradation under high-temperature conditions. These limitations make it difficult to meet the deep-well engineering requirements for high pressure-bearing capacity, deep fracture sealing, and long-term plugging stability. Therefore, the development of while-drilling LCMs and plugging methods with favorable migration capability, fracture adaptability, and high-temperature stability remains an important research direction.

Numerical simulation serves as a critical method to quantitatively describe the migration, deposition and plugging evolution of lost circulation materials within complex multi-scale fracture networks. The projection-based embedded discrete fracture model (pEDFM) has become a mainstream tool for fractured reservoir flow simulation, which can accurately characterize anisotropic fluid transport behavior inside fractures**Error! Unknown switch argument.**. Combined with two-point flux approximation and mimetic finite difference (TPFA-MFD) discretization, pEDFM can realize high-precision two-phase flow simulation in fractured media with strong heterogeneity**Error! Unknown switch argument.**. To further track fluid flow paths in fractures, a streamline-based solving framework was integrated into the pEDFM algorithm, which greatly improves the computational efficiency of fracture flow simulation**Error! Unknown switch argument.**. Hybrid mimetic finite difference and streamline coupling methods further optimize the numerical stability of two-phase flow calculation for fractured formations**Error! Unknown switch argument.**. The generalized pEDFM framework has also been successfully extended to simulate CO_2 displacement flow behavior in fractured reservoirs, providing a reference for multi-fluid leakage prediction in fractured strata**Error! Unknown switch argument.**. In addition to embedded fracture models, meshless

numerical approaches based on extended finite volume methods avoid grid distortion defects when modeling irregular multi-scale fractures, offering a new technical route for simulating LCM filling in complex fracture geometries[Error! Unknown switch argument.]. Besides the above fracture numerical modeling theories, many scholars have carried out targeted research on drilling fluid loss mechanisms, fracture leakage channel characterization and wellbore stability in fractured loss formations, which provide theoretical support for the development of high-performance elastic-tough plugging materials in this paper[Error! Unknown switch argument.Error! Unknown switch argument.].

2. Experimental Materials and Methods

2.1 Synthesis Method of While-Drilling Lost Circulation Materials

In this study, ultra-high-molecular-weight polyethylene was used as the rigid skeleton and compounded with a styrene–butadiene rubber elastic phase to construct an elastic–tough composite material matrix. Under the action of dispersants and crosslinking auxiliaries, a structurally stable elastic–tough composite matrix was formed. Under certain temperature and mixing conditions, the rigid phase and elastic phase were fully compounded to obtain bulk materials with both high strength and elastic characteristics. Subsequently, the bulk materials were subjected to mechanical shearing and crushing, and irregular particles with particle sizes of 0.1–1 mm were obtained by sieving.

These particles have multi-angular and rough surface characteristics, which are beneficial for enhancing interparticle friction and interlocking. Meanwhile, the rigid–flexible combination inside the material enables it to maintain structural strength under compression while possessing a certain deformation ability, thereby improving its entry capability and plugging stability in complex fractures. The drilling fluid used in the experiments was a field water-based drilling fluid system collected from an offshore block of CNOOC Shanghai Branch. After sampling, the drilling fluid was restored to room temperature and then used in subsequent experiments.

2.2 Experimental Methods

Various methods were used to evaluate the material properties and plugging behavior. The pressure-bearing capacity of the lost circulation materials was tested using a fracture simulation device, and the pressure variation characteristics during the plugging process were analyzed. High-temperature aging experiments were conducted to evaluate the thermal stability of the materials at 120–200 °C. Differential scanning calorimetry (DSC) was used to analyze the thermal properties and phase transition behavior of the materials. Static sedimentation experiments were carried out to evaluate the suspension stability of the materials in drilling fluid. Meanwhile, the rheological parameters of the drilling fluid before and after adding the lost circulation materials

were measured to evaluate their influence on the performance of the drilling fluid system. Plugging experiments were conducted in steel fracture models and natural core fracture models to analyze the migration, accumulation, and bridging processes of the materials in fractures.

3. Performance Evaluation of Elastic–Tough While-Drilling Lost Circulation Materials

3.1 Particle Size Distribution of Elastic–Tough While-Drilling Lost Circulation Materials

The prepared lost circulation particles were classified by a standard sieving method, and the mass fractions of different particle size ranges were determined, as shown in Fig. 1, to obtain the particle size distribution curve of the material. For the plugging requirement of fractures with widths of 0.75–1.50 mm, the material gradation was evaluated according to the D90 fracture-width distribution principle. That is, a sufficient proportion of large particles is required to participate in bridging at the fracture entrance, while medium and fine particles are used to fill the pores within the bridging skeleton. The detailed particle size distribution is shown in Fig. 2.

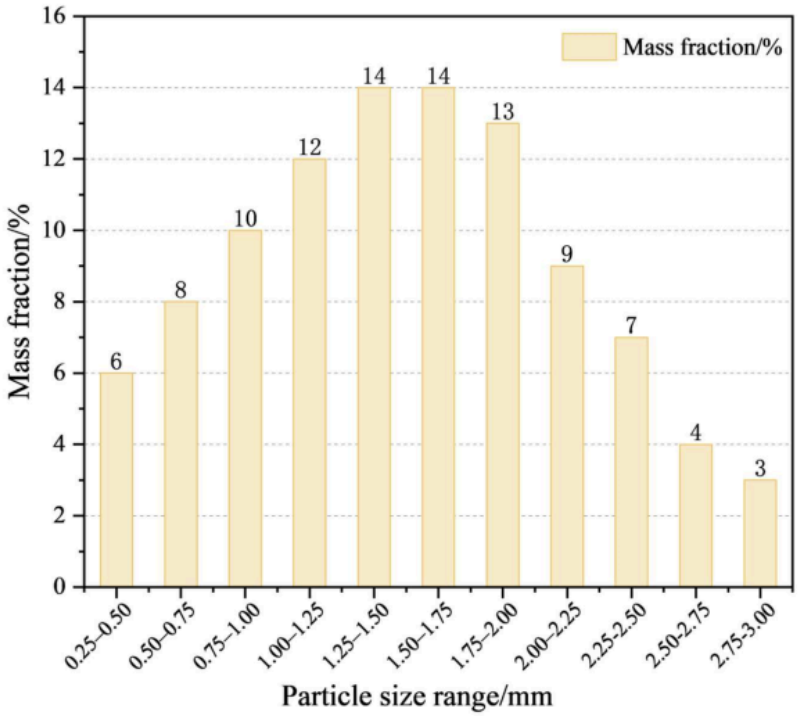


Figure 1. Particle size range of the elastic-tough lost-circulation material (LCM) used while drilling.

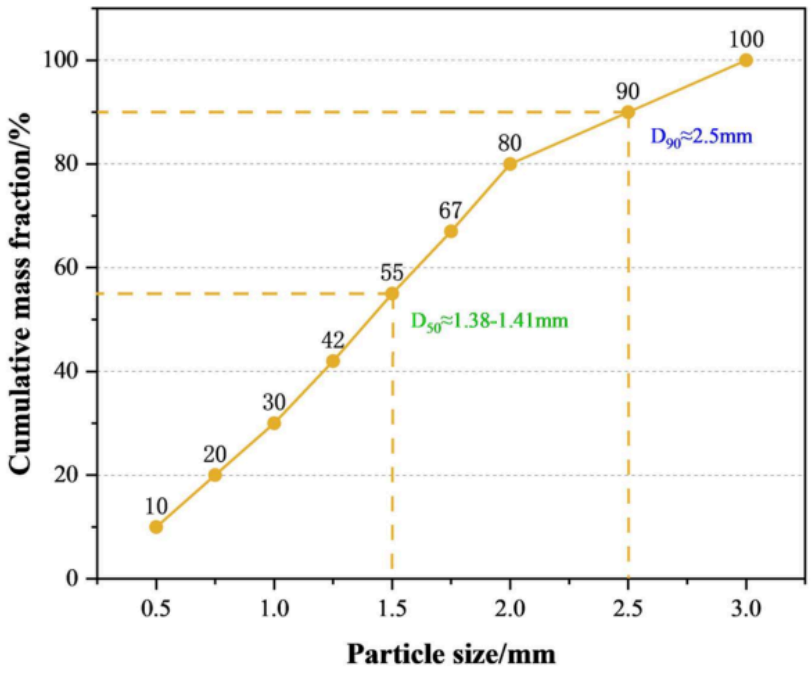


Figure 2. Particle size distribution of the elastic-tough lost-circulation material (LCM) used while drilling.

As shown by the particle size distribution curve, the particle distribution exhibits a unimodal pattern, increasing first and then decreasing. The mass fraction gradually increases with particle size and reaches the main peak in the range of 0.625–1.000 mm, accounting for 41%, followed by a gradual decrease. This indicates that coarse particles in the range of 0.625–1.000 mm are dominant and can preferentially play a bridging role. Medium and fine particles smaller than 0.625 mm account for 36% and can fill the pores among coarse particles, thereby improving the compactness of the plugging layer. A small proportion of coarser particles larger than 1.000 mm, accounting for 19%, can provide bridging and supporting effects under wide-fracture conditions. Overall, the particle system exhibits a reasonable gradation of coarse, medium, and fine particles. This gradation can simultaneously satisfy the requirements of entrance bridging and internal filling in medium-width fractures, which is conducive to forming a stable and compact plugging structure and is suitable for plugging fractures with widths of 0.75–1.50 mm.

3.2 Analysis of Compression–Recovery Performance

The uniaxial compression–recovery performance of the elastic–tough lost circulation particles was tested using an electronic universal testing machine. Three representative particle size ranges, namely 0.500–0.625 mm, 0.750–0.875 mm, and 1.000–1.125 mm, were selected for loading–unloading tests under a flat-plate indenter. The loading rate was set to 1 mm/min, and the

maximum compression displacements were set to 30%, 50%, and 70% of the initial particle height, respectively. After holding for 10 s, the samples were unloaded. The initial particle height, compressed height, and recovered height after unloading were recorded, and the compression ratio, recovery ratio, and residual deformation ratio were calculated accordingly.

To evaluate the influence of high temperature on the elastic characteristics of the materials, the particles were aged at 120 °C, 160 °C, and 200 °C for 16 h, respectively, and then subjected to the same tests. Each experiment was conducted five times in parallel, and the average value was used as the final result. The experimental results of the recovery ratio are shown in Fig. 3, and the residual deformation ratio results are shown in Fig. 4.

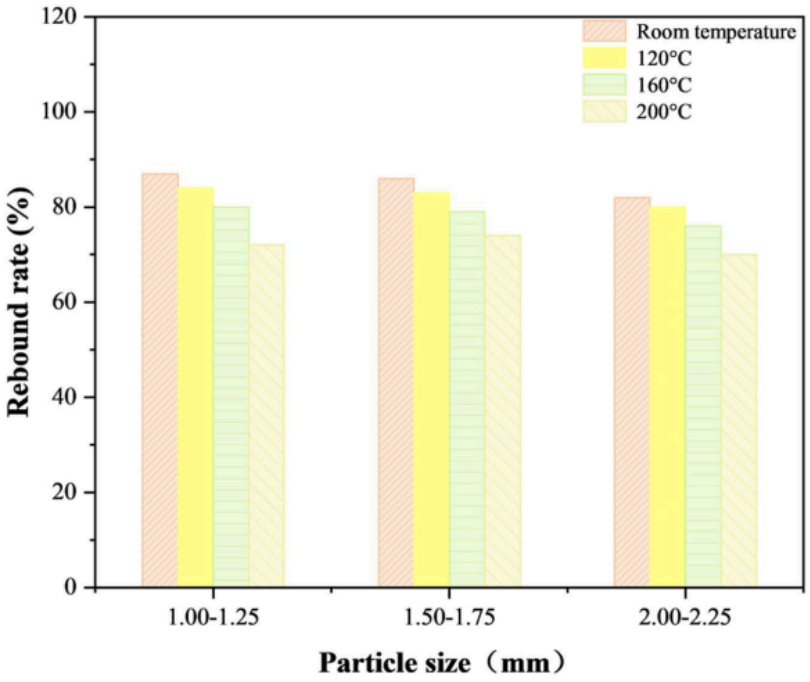


Figure 3. Elastic recovery rate of the elastic-tough lost-circulation material (LCM) used while drilling at different temperatures.

The recovery ratio results show that the lost circulation particles with different particle sizes all exhibited high elastic recovery ability at room temperature, with overall recovery ratios ranging from 82% to 87%. This indicates that the composite material possessed a favorable elastic structure under ambient conditions. With increasing temperature, the recovery ratio of the particles showed an overall decreasing trend and decreased to 70%–74% at 200 °C, suggesting that high temperature induced a certain softening effect on the elastic phase of the material. Nevertheless,

the particles still maintained relatively high recovery ability.

In terms of the particle size effect, the recovery ratios of particles with different sizes did not show a simple monotonic variation. The medium-sized particles ranging from 0.750 to 0.875 mm exhibited relatively better recovery stability under high-temperature conditions. In particular, at 200 °C, their recovery ratio was slightly higher than that of the smaller and larger particles. This indicates that particles within this size range may form a more reasonable structural matching between the rigid skeleton and the elastic phase, enabling effective deformation under compression while maintaining good recovery ability after unloading.

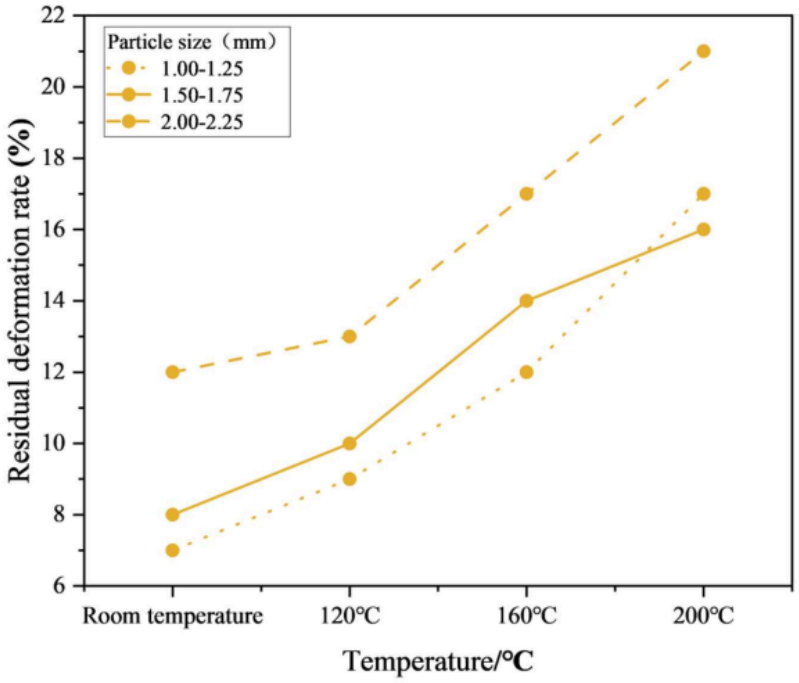


Figure 4. Residual deformation rate of the elastic-tough lost-circulation material (LCM) used while drilling at different temperatures.

The residual deformation test results show that the recovery ratios of lost circulation particles with different particle sizes were 88%–93% at room temperature, indicating excellent elastic recovery ability and a stable elastic crosslinked structure of the material. With increasing temperature, the residual deformation ratio increased, whereas the recovery ratio decreased. At 200 °C, the recovery ratio decreased to 79%–84%, suggesting that although high temperature exerted a certain softening effect on the elastic phase, the material still maintained relatively high elasticity.

From the perspective of particle size, the larger particles exhibited the highest recovery ratio at room temperature. However, the medium-sized particles ranging from 0.750 to 0.875 mm showed the smallest decrease in recovery ratio. At 200 °C, their recovery ratio reached 84%, which was higher than that of the larger particles (83%) and smaller particles (79%). This indicates that particles within this size range achieved an optimal structural matching between the rigid skeleton and the elastic phase. Under high-temperature conditions, they retained both favorable deformation–filling ability and recovery ability after unloading, thereby helping to maintain a more durable plugging effect.

4. Evaluation of the Plugging Performance of the Elastic–Tough While-Drilling Lost Circulation System

4.1 Effect of Elastic–Tough While-Drilling Lost Circulation Material Dosage on the Rheological Properties of Drilling Fluid

The rheological test results are shown in Table 1. As indicated by the results, with the dosage of elastic–tough lost circulation material increasing from 5% to 20%, the dial readings of the drilling fluid at different rotational speeds all showed an increasing trend, suggesting that the addition of particles enhanced the structural strength and viscous characteristics of the system. The apparent viscosity (AV) increased from 41 mPa·s to 52 mPa·s, while the plastic viscosity (PV) increased from 32 mPa·s to 39 mPa·s. The overall increase was relatively moderate, indicating that the incorporation of the lost circulation material did not significantly deteriorate the flow performance of the system, and the drilling fluid still maintained good pumpability.

The yield point (YP) increased from 18 Pa to 26 Pa with increasing material dosage, indicating enhanced structural strength of the system, which is beneficial for improving the carrying capacity of the drilling fluid and maintaining wellbore circulation stability. Meanwhile, the low-shear readings at 6 r/min and 3 r/min increased significantly, suggesting that the low-shear suspension capacity of the system was improved. This is important for preventing the sedimentation of lost circulation particles in the wellbore and achieving uniform transportation during while-drilling plugging operations. Overall, although the rheological properties of the system were enhanced at a dosage of 20%, they remained within an acceptable range. This indicates that the elastic–tough lost circulation material still exhibited good flow adaptability and engineering application feasibility.The detailed rheological data under different LCM dosages are listed in Table 1.

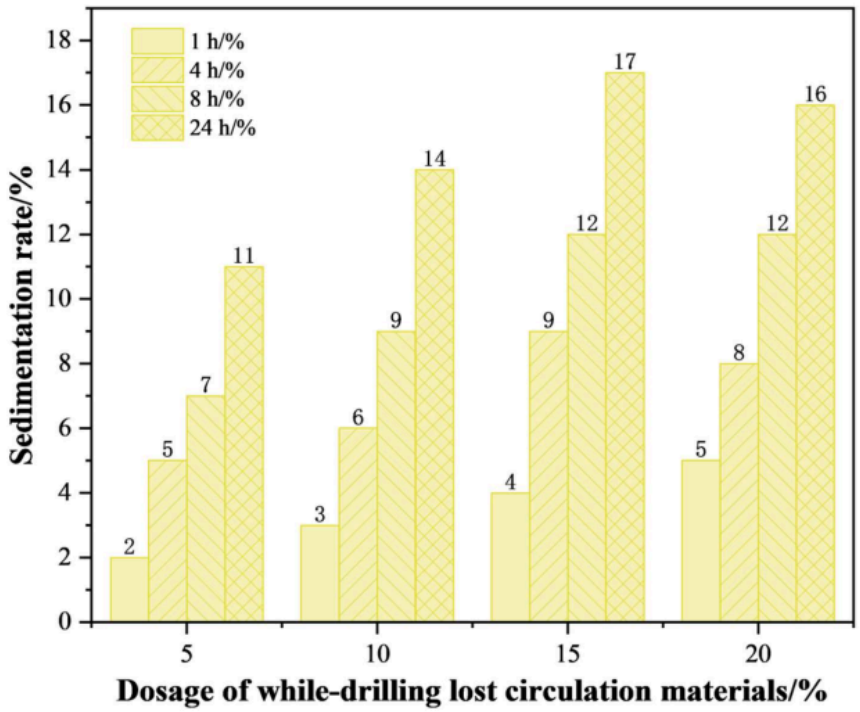
Table 1. Effect of the concentration of lost-circulation material (LCM) used while drilling on the rheological properties of drilling fluid.

Increase dosage/%	600 rpm	300 rpm	200 rpm	100 rpm	6 rpm	3 rpm
0 (Basal plasma)	82	50	41	30	8	6
5	86	53	44	32	9	7
10	91	57	47	35	11	8
15	97	61	50	37	13	9
20	104	65	53	40	15	11

4.2 Evaluation of the Suspension Stability of Elastic–Tough While-Drilling Lost Circulation Materials

Figure 5. Long-term settling rate of the lost-circulation material (LCM) used while drilling in drilling fluid.

As shown in Fig. 5, with the dosage of lost circulation material increasing from 5% to 20%, the height of the sedimentation layer showed an overall increasing trend, indicating that the suspension stability of the system decreased under higher dosage conditions. This may be attributed to the fact that, at low dosages, the lost circulation particles were relatively uniformly dispersed in the drilling fluid, and the system maintained a stable structure, resulting in a slower sedimentation process. However, as the dosage increased, interparticle interactions became stronger, which promoted local aggregation or flocculation. Consequently, the equivalent particle size increased, thereby accelerating particle sedimentation.



4.3 Evaluation of the Plugging Performance of While-Drilling Lost Circulation Materials in Simulated Fractures

(1) Plugging Performance in a 1 mm Fracture

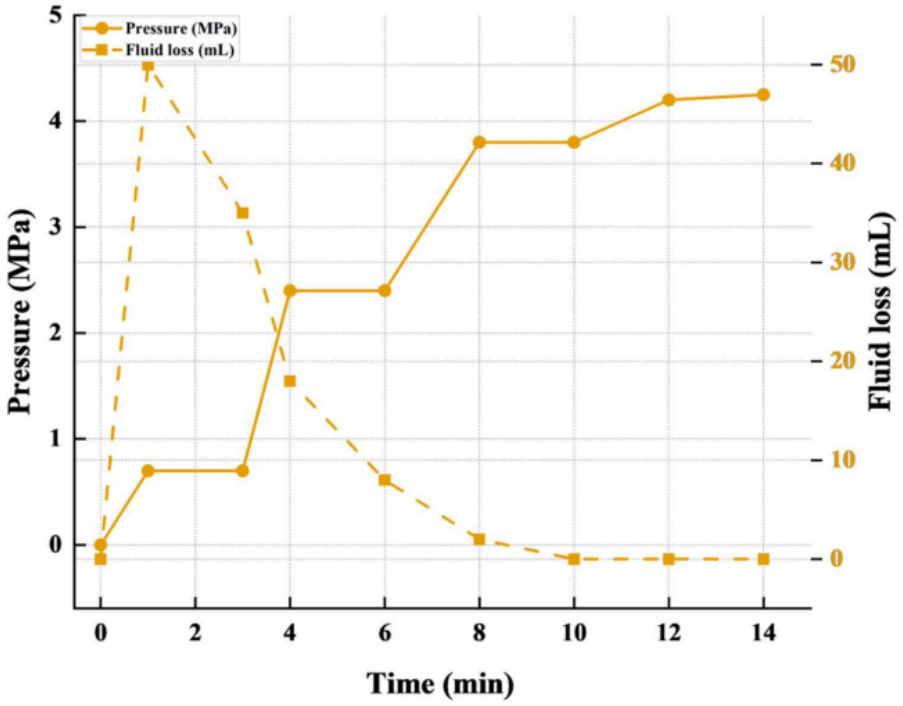


Figure 6. Pressure sealing and fluid loss behavior of a 1-mm fracture.

The experimental results for the 1 mm fracture show that the while-drilling lost circulation materials could rapidly deposit within the fracture and form a compact plugging structure. As shown in Fig. 6, the pressure-bearing capacity of the fracture increased rapidly at the initial stage of the experiment, reaching approximately 3 MPa at 1 min and about 7 MPa at 5 min. Meanwhile, the fluid loss reached a peak value of approximately 42 mL at 1 min and then decreased rapidly, approaching nearly zero at 5 min. As shown in Fig. 7, the fracture plugging photographs further confirmed that the materials were uniformly and continuously deposited within the fracture, thereby ensuring the overall pressure-bearing capacity.

(2) Plugging Performance in a 2 mm Fracture

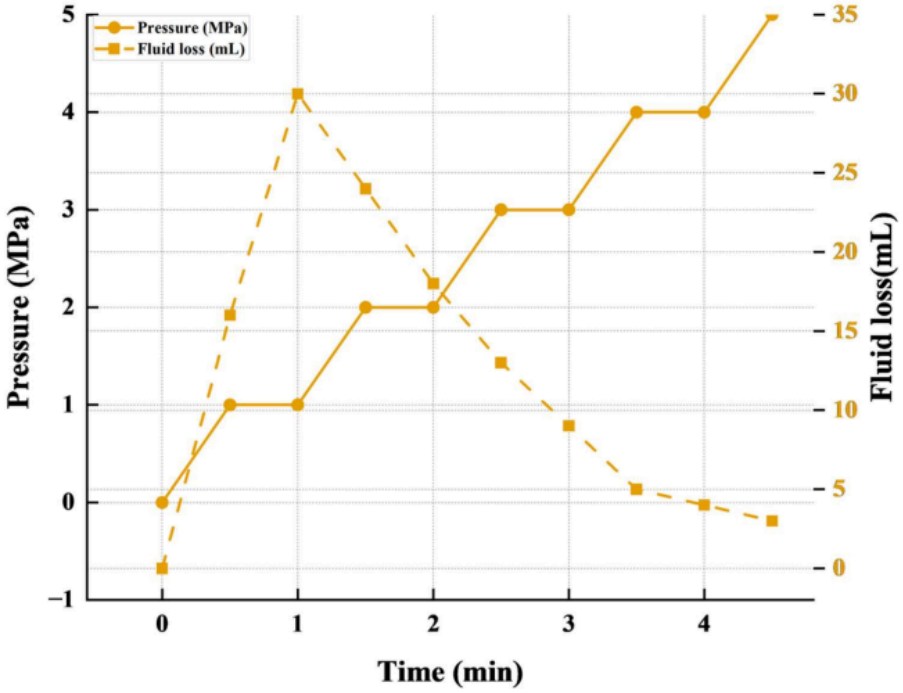


Figure 7. Pressure sealing and fluid loss behavior of a 2-mm fracture.

The experimental results for the 2 mm fracture show that the while-drilling lost circulation materials could form an effective plugging structure in wider fractures. As shown in Fig. 8, the pressure-bearing capacity of the fracture increased rapidly at the initial stage of the experiment, reaching approximately 2 MPa at 1 min and about 5 MPa at 4 min. Meanwhile, the fluid loss reached a peak value of approximately 30 mL at 1 min and then decreased rapidly, approaching nearly zero at 4 min. As shown in Fig. 9, the fracture plugging photographs show that the materials were uniformly and continuously deposited within the fracture, indicating a favorable overall plugging effect.

5. Conclusions

(1) The developed elastic–tough while-drilling lost circulation material exhibited obvious multi-stage particle size gradation characteristics. Coarse particles could achieve bridging at the fracture entrance, while medium and fine particles could fill the pores within the plugging layer, thereby forming a stable and compact bridging-plugging structure. The material is suitable for plugging fractures with widths of 0.75–1.50 mm.

(2) The compression–recovery experiments showed that the material possessed good elastic recovery ability and high-temperature stability. Although the recovery ratio decreased with

increasing temperature, the material still maintained relatively high elasticity at 200 °C. Among the tested particles, those with a particle size of 0.750–0.875 mm exhibited better comprehensive stability.

(3) The rheological evaluation results indicated that the addition of the lost circulation material improved the structural strength, carrying capacity, and low-shear suspension capacity of the drilling fluid system. At a dosage of 20%, the system still maintained good flowability and pumpability, satisfying the requirements of while-drilling lost circulation control operations.

(4) The fracture plugging experiments demonstrated that the elastic–tough lost circulation material could rapidly enter the interiors of 1 mm and 2 mm fractures and form stable bridging-plugging layers. Under the 1 mm fracture condition, the pressure-bearing capacity increased to 7 MPa, and the fluid loss rapidly decreased from a peak value of 42 mL to nearly zero. Under the 2 mm fracture condition, the pressure-bearing capacity reached 5 MPa, and the fluid loss decreased from 30 mL to nearly zero. These results indicate that the material has good deep plugging capability and pressure-bearing stability.

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