Thief-zone plugging mechanism and application of calcite particles in fractured formations

Jiaxue Li^{1,2} · Shuanggui Li³ · Lijuan Pan³ · Wei Gao³ · Jie Sun¹ · Meng Qin¹

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Abstract

Lost circulation in fractured strata during drilling incurs additional costs and leads to difficulties in promoting drilling safety and efficiency. Plugging-while-drilling is a feasible means to address lost circulation in fractured formations. The particle size distribution (PSD) of plugging particles is determined empirically; therefore, it is often not matched with the fracture sealing requirement. This study investigates the lost circulation mechanism of fractured strata and identifies a calcite particle-based material as the preferred plugging agent. The plugging mechanism and the design of PSD and particle concentration are demonstrated. Based on the concentration, a plugging-while-drilling technique was developed for fractured strata. The results show that calcite particles tend to form the filling layer at the fracture inlet, which cuts off the leakage of the drilling fluid into the fracture, eliminating the drilling fluid pressure applied on the fracture surface. Thus, a stable sealing for the fractured formation is achieved, and the pressure-bearing capacity of the borehole wall is increased. The result also reveals the optimal mixing and concentration models for calcite particles with various diameters. The plugging technique based on calcite particles for fractured formations is applied in a field experiment. The results confirm that the technique can improve the chance of lost circulation prevention and thief-zone plugging in fractured strata and remarkably reduce both the event quantity of lost circulation and the volume of circulation loss. The findings of this research lay a theoretical basis to address lost circulation in fractured formations and, thus, have important practical significance.

Keywords Calcite particle · Thief-zone · Sealing while drilling · Fractured formations

Introduction

Multi-point leakoff, which is characterized by a small initial loss of circulation and uncertain leakoff positions, frequently occurs during the drilling of naturally fractured strata. Not only does such a leakoff result in the total loss of circulation, but it can also trigger a cascade of complex issues. For example, suspension of drilling operations to treat lost circulation every time it occurs would consume a large amount of time, reduce the drilling speed, and increase the costs.

Based on the stress cage theory, Aston et al. (2004) developed a “designer mud” (by adding appropriate materials to the mud system) to increase the fracture resistance of the soil while drilling. Sweatman (2004) and Dupriest (2005) proposed a sealing mechanism and mechanical model for leveraging the high closure stress on the two fracture surfaces, to prevent lost circulation of drilling fluids. Song (2006) and Fah (2007)’s experiments demonstrated that a significant increase in the resistance of formation fracture could be achieved by the fracture sealing or plugging mechanism induced by a particle “screen-out” effect resulting from the drilling fluid loaded with an adequate amount of narrow-sized granular materials.

Luo et al. (2011) develop a technique that prevents or stops lost circulation while drilling (plugging-while-drilling) in fractured strata; in this method, high strength non-hydration rigid particles are included as additives in drilling fluid (Jiaxue et al. 2011). Wang and Pu (2014) presented a numerical study of the plugging behavior of granular lost circulation material (LCM) at a particle scale

✉ Jiaxue Li
liji3211979@163.com

¹ China University of Petroleum (Beijing), Karamay, Xinjiang, China

² State Key Laboratory of Heavy Oil Processing in Karamay, Xinjiang, China

³ Sinopec Northwest Petroleum Bureau Engineering Technology Research Institute, Urumchi, Xinjiang, China

using the discrete element method (DEM) with the coarse mesh model (Gui and Pu 2014). Cook John (2016) studied the formation mechanism of mud cake on the thief-zone to improve the bearing capacity of wellbore (Role and of Filter cake in Wellbore Strengthening 2016). Bagherzadeh (2018) revealed the law of fracture and leakage of thief-zone formation based on the principle of hydraulic Fracturing (Bagherzadeh et al. 2018). Chengyuan et al. (2016) constructed a mathematical model of the fracture propagation pressure to account for the fracture plugging based on experiments, and they (2018) developed a stochastic microscale model for the size-exclusion particular-suspension transport in fractured media (Chengyuan and Yili 2016; Chengyuan et al. 2018). Majid (2019) developed durian rind as an LCM for stopping the leakage (Fatihah et al. 2019). Bao (2019) designed a long fracture slot to evaluate the influence of the LCMs type, concentration and size distribution on plugging effect, and announced that suitable wide particle size distribution of LCM formed thick plugging zone inside the fracture, multi-layer seal barrier can withstand the external load together, resulted in high seal integrities (Bao et al. 2019). Zhu (2019) present the one-way coupled CFD–DEM approach to simulate the flow of granular LCM in a vertical fracture, and they studied the effects of particle size distribution (PSD) and concentration on the fracture plugging process through a series of controlled numerical experiments (Zhu et al. 2019).

In 2020, She J.P proposed Cusp catastrophe model for plugging pressure prediction of lost circulation control (She et al. 2020), Wang M.B developed A numerical simulation to study the effect of solid particles on the lost circulation (Wang et al. 2020), and Majzoub M.I developed cross-linked polymers for wellbore strengthening (Salehi et al. 2020), Pouya Tavakolia proposed the method of stabilizing system from the angle of surface tension, and the method of improving wellbore stability by using micro-nano materials (Tavakoli et al. 2020).

However, the PSD and concentration of plugging particles are typically determined through empirical methods or laboratory tests, and the selected particle is often either too large to penetrate fractures and form a sealing pack between the fracture surfaces or is too small to hold its position in the fracture and still function normally. The function of plugging agents is to achieve retention, bridging, and packing in fractures (Tongtai et al. 1997). To this end, we investigated the plugging behavior of calcite particles and proposed a thief-zone mechanism for the formation of a solid sealing pack. Models based on the fracture characteristics of strata were developed to determine the calcite particle size and concentration, which can provide theoretical guidance on the implementation of the plugging-while-drilling technique.

Table 1 Basic properties of calcite particles

Main composition	Particle shape	Mohs hardness	Density (g/cm ³)	Acid dissolution rate (%)
Calcium carbonate	Cubic	3	2.703 (22.5 ppg)	99.0

Table 2 Size of calcite particles

Specifications	A	B	C	D
Size by sieve mesh number	> 20	20–40	40–80	80–200
Size by millimeter	> 0.9	0.9–0.4	0.4–0.2	0.2–0.074

Plugging mechanism of calcite particles

Calcite particle-based plugging agent

Generally, bridging materials for lost circulation in the field are divided into four groups, namely, granular, fibrous and flake materials, and others. Given the features and requirements of the plugging-while-drilling technique, calcite-based plugging particles were identified as the ideal candidate among various options. These plugging agents are characterized by high strength, tolerance to high temperatures, and zero hydration deformation. These agents are not easily dispersed in mud, are easy to identify, and do not interfere with mud logging. Furthermore, crushed calcite particles produce several cubic fragments. Some basic properties of calcite particles are listed in Table 1, while the classification of calcite particles for plugging-while-drilling is demonstrated in Table 2.

A technical requirement of plugging-while-drilling is that the plugging particles must not have any considerable effect on the properties of the drilling fluid. Therefore, the rheology and water-loss performance of the drilling fluid used in the field are tested with the addition of calcite particles. Sample No. 1 is the drilling fluid used in the field (the composition of the drilling fluid was: 4.0% bentonite mud + 0.2% 80A51 (Polymer viscosity improver agent) + 0.2% HV-CMC (another polymer viscosity improver agent) + 5% SPNH (Filtration reducer agent) + 3% SMP-2 (Another filtration reducer agent) + 1% FT-1 (Sulfonated asphalt powder) + 1% RH-1 (Lubricant) + Weighting agent); formulation of Sample No. 2 is Sample No. 1 + 1% Grade-C calcite particles and 2% Grade-D calcite particles; and formulation of Sample No. 3 is Sample No. 1 + 2% Grade-C calcite particles and 3% Grade-D calcite particles.

The experiment results confirm that the addition of calcite particles does not have any significant effect on

the properties of the drilling fluid. Density, viscosity, and gel strength of the drilling fluid undergo only slight increments, thereby securing the implementation of the plugging-while-drilling technique.

Mechanisms behind fracturing plugging by calcite particles

Fractures were divided into natural fractures and drilling-induced fractures, but the leakage caused by drilling-induced fractures is more serious and common. The in situ stress equilibrium breaks when the strata are drilled. Rock in the wellbore is excavated, and the drilling fluids are injected. An excessively large pressure produced by the drilling fluid height and weight leads to the extension and opening of existing fractures in the strata, and if the fracture opening is

large enough, the drilling fluids will leak into the formation along the fracture (Fig. 1).

Under such circumstances, the plugging slurry added with calcite plugging agents enters the fracture with the drilling fluids. Then, calcite particles stop moving at certain positions in the fractures and agglomerate for bridging. Therefore, the filling layer formed by the bridging and accumulation of calcite particles stays at the surface, mouth, middle part, and tip of the fracture, which is decided by matching the calcite particle with the fracture sealing requirement (Fig. 2).

In the case of the calcite particle size exactly matching the mouth of the fracture (the intersection of the fracture and borehole wall), the calcite particles bridge at the fracture mouth, forming a filling (sealing) layer that works synergistically with the mud cake. After the filling layer is formed (from the mouth to the tip of the fracture), the drilling fluids in the fracture flow into the strata via the fracture surface, which is associated with the depletion of pressure produced by the drilling fluid's height and weight in the fracture. Moreover, the pressure before the filling layer (from the wellbore to the mouth) is exerted only on the mud cake and the filling layer on the borehole wall, which only tends to break the filling layer and push it inward along the fracture, instead of the fracture surfaces and the opening. Consequently, the fractures tend to close, and the strong closure stress generated by the in situ stress field firmly holds the filling layer from being pushed over by the fluid pressure in the wellbore. In addition, as the filling layer composed of calcite particles has high strength, it can resist a considerably high fluid pressure at the fracture inlet after plugging. Thus, it can tolerate the pressure fluctuations inside the wellbore during drilling. In other words, the filling layer plugging the mouth can firmly seal the fracture and is unlikely to be broken and cause lost circulation (Fig. 3).

According to the stress cage theory, the filling (sealing) layer formed by the bridging and agglomeration of calcite particles has a very low permeability, which can lead to pressure isolation. This method increased the hoop stress around

Fig. 1 Behavior of loss when drilling in the fractured formation

Fig. 2 Sealing position of the calcite particle in the fracture

Fig. 3 Mechanism of flow pressure when plugging layer is deposited at the mouth of the fracture

Fig. 4 Excess pressure with calcite particle plugging the mouth of the fracture

the wellbore, provided the induced fracture is bridged at or close to the wellbore wall (the mouth of the fracture). Given below is an equation for calculating the increase hoop stress (Aston et al. 2004):

$$\Delta P = \frac{\pi}{8} \times \frac{w}{R} \times \frac{E}{1 - \nu^2} \quad (1)$$

where ΔP is the excess pressure within the fracture (the pressure above the minimum principal in situ stress). Further, W is the fracture opening width, R is the fracture radius, E is the Young's modulus of the formation, and ν is the Poisson's ratio of the formation.

This equation explained how the wellbore can bear such high pressures produced by the drilling fluid height and weight after the formation of the fitting layer at the mouth. In other words, the designed PSD and concentration of calcite particles required to seal the mouth of the fracture can endure fluctuations of pressure difference (the difference between the drilling fluid pressure and pore pressure) during the process of drilling, without loss (Fig. 4).

If bridging and plugging of calcite particles occur at some point in the middle or tip section of the fracture, the pressure produced by the drilling fluid height and weight in the fracture space after the filling layer would vanish, while that between the filling layer and the wellbore will continue to

exist. This pressure may easily grow and correspondingly cause the fracture to expand on the account of the pressure fluctuations during the drilling process. Further growth of the fracture opening would compromise the filling layer, originally having achieved plugging at a certain position in the fracture, and lost circulation would recur. It should also be noted that, even if the filling layer can form again, it still might be unstable (Fig. 5).

Particle size distribution and concentration models of calcite particles

Size distribution model for calcite particles

Two types of calcite particles are required for fracture sealing, namely, bridging particles suitable for the mouth of the fracture and accumulating particles with the corresponding size distribution. The first type mainly serves as a bridging agent, acting as a framework for the filling layer. The bridging particle size and the fracture opening must be compatible with each other, for the formation of the filling layer. Bridging of granular plugging materials can be achieved in three forms, namely, single-particle, dual-particle, and multi-particle bridging (Fig. 6), which sufficiently explains the bridging behavior of plugging particles in fractures. The odds of stable bridging in the dual- and multi-particle forms, however, are far less than those in the single-particle form. Furthermore, the filling layers formed by dual- and multi-particle bridging tend to be easily broken under excessive pressure difference between the wellbore and the fracture. Given this, filling layers formed by the dual- and multi-particle forms are probably weak. The surge pressure generated by tripping in and out during drilling, and the high pressure difference adopted in the subsequent plugging treatment after the end of the drilling operation can easily impact the filling layer. Thus, the formed filling layer must have tremendous strength

Fig. 5 Mechanism of the pressure when plugging layer deposited in the middle or tip of the fracture

Fig. 6 Bridging forms of the calcite particles in the mouth of the fracture

to tolerate high pressure differences, and wherever possible single-particle bridging should be pursued in the selection of bridging particles.

At the microscale, calcite particles present themselves as cubes. The geometric analysis of fractures and plugging particles concludes the following selection principles for bridging particles: The particle size of the first-grade particle (bridging particle) must lie within the particle diameter ranges shown in Fig. 7a and b. If the calcite particle diameter of the first-grade exceeds that specified in Fig. 7a, the particles are too large to penetrate fractures and can only seal the fracture inlet to some extent by packing on the borehole wall. Meanwhile, if this diameter is less than that in Fig. 7b, bridging particles will simply flow through the fracture, instead of bridging at the fracture inlet. This principle can be expressed as follows:

Fig. 7 Diameter of the bridging particles vs. effective opening of the fracture inlet

$$\sqrt{3}d_1 \geq D \geq d_1 \quad (2)$$

or

$$D \geq d_1 \geq 0.6D \quad (3)$$

and $d_{1\max} = D$ $d_{1\min} = 0.6D$

where D is the effective opening width of the fracture inlet in m, and d_1 is the diameter of the first-grade calcite particle (the bridging particles) (in m).

After bridging the fracture with first-grade calcite particles from the inside, we should use the second-grade particles to fill the remaining space after plugging with the first-grade particles. Since the particle size of the first-grade is $(0.6–1.0)D$, the maximum fracture space that should be sealed by the second-grade particle is $0.4D$. Therefore, in accordance with the same bridging model used for the first-grade particle, the criterion is

$$\sqrt{3}d_2 \geq 0.4D \geq d_2, \quad (4)$$

and the particle size of the second-grade should satisfy

$$0.4D \geq d_2 \geq 0.23D, \quad (5)$$

where d_2 is the second-grade calcite particle diameter (in mm).

Similarly, we have the diameters of the third- and fourth-grades of calcite particles, as expressed below:

$$0.17D \geq d_3 \geq 0.10D, \quad (6)$$

$$0.07D \geq d_4 \geq 0.04D, \quad (7)$$

where d_3 is the diameter of the third-grade rigid particle (in mm), and d_4 is the diameter of the fourth-grade rigid particle (in mm).

In laboratory tests, the simulated fracturing opening is, in most cases, relatively large, which requires four grades of particles for mixing. Nonetheless, the fracture opening underground is limited, and the drilling fluid contains small-sized impurities of rock cutting and weighting materials. Therefore, PSDs of the three grades should be enough to characterize the calcite particles.

Concentration model for calcite particles

In most cases, the concentration of plugging particles is determined empirically. Nevertheless, for calcite particles, the applicable particle concentration can in fact be estimated mathematically.

Under the pressure produced by the drilling fluid height and weight, the fracture expands and forms a flow channel for lost circulation. To stop the fracture from expanding further, after a certain volume of drilling fluids has already leaked into it, the calcite particles (added into the drilling fluid for plugging-while-drilling) should form a solid seal prior to filling the fracture space with the drilling fluids. Thus, further drilling fluid leakoff can be prevented, and the fracture expansion can be stopped. In contrast, if a filling layer fails to form prior to filling the fracture space entirely with the drilling fluid, the pressure originating from the fluid height and weight and imposed on the fracture cannot be isolated, and the stress concentration at the fracture tip will lead to the continued extension of the fracture. Therefore, the drilling fluid, with a volume equal to that of the fracture space, should have sufficient concentration of particles from each of the three grades to form the firm filling layer and enable plugging-while-drilling.

Let the height, length, and opening width of the fracture be H , L , and D , respectively. The fracture can be approximately observed as a cuboid (Fig. 8). Hence, its volume is

$$V = HLD. \quad (8)$$

Assuming that k_1 layers of calcite particles with diameters of $0.6D–D$ are uniformly distributed along the fracture width and height to form a solid filling layer, the volume of the first-grade calcite particle (based on the median diameter of the bridging particle) can be calculated as

Fig. 8 Thief-zone plugging behavior of calcite particles

$$V_1 = k_1 \frac{H}{0.8D} (0.8D)^3 \quad (9)$$

Hence, the concentration of the first-grade calcite particle is

$$C_1 = \frac{V_1 \rho_R}{V} = \frac{k_1 H (0.8D)^3 \rho_R}{0.8D H L D} = 0.64 k_1 \rho_R D L^{-1} \quad (10)$$

where V_1 is the required volume of the first-grade calcite particle, m^3 ; C_1 is the concentration of the first-grade calcite particle, kg/m^3 (mass of calcite particles divided by volume of drilling fluids); ρ_R is the density of the calcite particle (in kg/m^3); and k_1 is the number of effective plugging layers of calcite particles, usually 3 or 4.

For the second-grade calcite particle, the randomness of particles of each grade entering the fracture should be considered. Specifically, a portion of the second-grade calcite particles enters the fracture prior to the bridging of the first-grade particle, and these smaller particles cannot fulfill their purpose due to the lack of pre-existing particle bridging. Only after successful bridging of the first-grade particle can smaller rigid particles fill and plug the fracture space. Hence, it is assumed that only k_2 of the second-grade particle enters the fracture, and each bridging particle demands four smaller particles of the next grade to fill its surrounding. With this explanation as the background, the concentration of the second-grade particle can be expressed as

$$C_2 = \frac{4k_1 H (0.32D)^3 \rho_R}{k_2 0.8D H L D} = \frac{0.164 k_1 D \rho_R}{k_2 L} \quad (11)$$

Similarly, the calcite particle concentrations of the third- and fourth-grades can be written as

$$C_3 = \frac{4^2 k_1 H (0.135D)^3 \rho_R}{k_2^2 0.8D H L D} = \frac{0.05 k_1 D \rho_R}{k_2^2 L} \quad (12)$$

$$C_4 = \frac{4^3 k_1 H (0.055D)^3 \rho_R}{k_2^3 0.8D H L D} = \frac{0.01 k_1 D \rho_R}{k_2^3 L} \quad (13)$$

where C_2 is the concentration of the second-grade calcite particles in kg/m^3 (mass of calcite particles divided by the volume of drilling fluids); C_3 is the concentration of the third-grade in kg/m^3 (mass of calcite particles divided by

volume of drilling fluids); C_4 is the concentration of the fourth-grade, in kg/m^3 (mass of calcite particles divided by volume of drilling fluids); and k_2 is the effective coefficient of the accumulating calcite particles, usually 0.4–0.

Based on these equations, all particle concentrations can be determined grade by grade Table 3.

Laboratory testing and field application

Laboratory testing

The apparatus used in the laboratory testing was a modified DL-type lost circulation testing device (Fig. 9). A stainless-steel fracture model was used to simulate the fracture of the strata. The simulated fracture opening was 2.0 mm, the fracture height was 2.5 cm, and the fracture length was assumed to be 1.0 m. The value of coefficients k_1 and k_2 was set to 4.0 and 0.3. The calcite particle consumption for each grade, which was calculated using the presented estimation model, is listed in Table 4. The fracture simulator was placed at the bottom of DL-type lost circulation testing device and the plugging slurry through the fractures from top to bottom in the experiment.

Then, the corresponding plugging formulations can be derived from the results presented in Table 4, which are 15-kg Grade-A calcite particle, 11-kg Grade-B calcite particle, 12-kg Grade-C calcite particle, and 8-kg Grade-D

Fig. 9 DL-type lost circulation testing device and fracture simulators

Table 3 Drilling fluid properties with rigid particles

Experiment number	Density (g/cm ³)	Plastic viscosity (mPa.s)	Yield point (Pa)	Gel strength (10 s/10 min) (Pa)	FL-API (mL)	FL-HTHP (mL)	Kf
No. 1	2.23 (18.6ppg)	64	5.0	2.5/7.5	1.5	8.0	0.0612
No. 2	2.23 (18.6ppg)	71	5.5	3.0/8.0	1.5	7.6	0.0699
No. 3	2.24 (18.7ppg)	77	5.5	3.0/8.0	1.5	8.5	0.0699

Table 4 PSD and concentration of calcite particles for 2-mm fracture plugging

Plugging grade	Size distribution (μm)	Concentration		Specifications of calcite particles
		(kg/m^3)	lb/bbl	
First-grade (bridging) particles	2000–1200	13.8	4.83	Grade-A
Second-grade particles	800–460	11.8	4.14	Grade-B
Third-grade particles	340–200	12.0	4.21	Grade-C
Fourth-grade particles	140–80	8.0	2.8	Grade-D

Table 5 PSD and concentration of calcite particles for 1.0-mm fracture plugging

Plugging grade	Size distribution (μm)	Concentration		Specifications of calcite particles
		(kg/m^3)	lb/bbl	
First-grade (bridging) particles	1000–600	7.92	2.78	Grade-B
Second-grade particles	400–230	5.91	2.07	Grade-C
Third-grade particles	170–100	6.0	2.10	Grade-D

calcite particle per 1 m^3 drilling fluid. The seal testing of the plugging fluid prepared according to the presented formulation was tested using the 2-mm-wide fracture model on the DL-type lost circulation testing device, and the results show that the cumulative loss of the plugging fluid was approximately 33 mL, and the filling layer can tolerate pressures of up to 3.5 MPa (Fig. 10). Tight packing of particles was observed in the fractures, and the plugging was successful.

Similarly, the simulated fracture opening is 1.0 mm, the fracture height is 2.5 cm, and the fracture length is assumed to be 1.0 m. Set the values of coefficients k_1 and k_2 to 4.0 and 0.3, respectively. The calcite particle consumption for each grade, which was calculated using the presented estimation model, is listed in Table 5.

The plugging formulations for the fracture width of 1.0 mm are 10-kg Grade-B calcite particle, 6-kg Grade-C calcite particle, and 6-kg Grade-D calcite particle per 1 m^3 . Similarly, the plugging fluid prepared with respect to this formulation was tested using the 1.0-mm fracture model on the DL-type lost circulation testing device. The result shows that 14 ml of plugging fluid was lost, the filling layer endures pressures of up to 3.5 MPa (Fig. 11), and numerous particles are closely packed inside the fracture.

Field application

The plugging-while-drilling testing with calcite particles was successfully implemented in a well located in the Piedmont structure of the Tarim Basin in northwestern China. The target layer of this well develops multiple fractures, causing severe lost circulation during drilling. Statistics of an adjacent well show that the fracture width in this area is generally 1 mm, the fracture height is 0.01 m,

Fig. 10 Cumulative losses of the drilling fluid when plugging a 2.0-mm fracture

and the fracture length is 1.0 m. The plugging formulations are 10-kg Grade-B calcite particle, 6-kg Grade-C calcite particle, and 6-kg Grade-D calcite particle per 1 m^3 . The target layer of this well with the thickness of about 400 m is the main thief-zone in this area. The plugging-while-drilling technique was used for the drilling process, in which the total concentration of calcite particles of Grades B, C, and D is kept within 30 kg per 1 m^3 . The plugging does not interfere with the drilling process, and the loss of circulation is far less than that in the adjacent well. Moreover, a large amount of time was saved on drilling (Table 6). Overall, the plugging-while-drilling practice has achieved good performance.

Table 6 Fluid loss and drilling period in the test well and its adjacent well

Well name	Well section (m)	Section length (m)	Fluid losses (m ³)	Time of sealing	Drilling period (days)
Adjacent well No. 1	4771–5194	423	524	3	46
Adjacent well No. 2	4757–5081	324	1127.3	10	87
Test well with calcite particles	4685–5071	386	109.6	0	14

Fig. 11 Cumulative losses of the drilling fluid when plugging 1.0-mm fracture

Conclusions

- (1) Calcite-based LCM is characterized by its high strength, lack of hydration and deformation, high-temperature resistance, and limited effects on the drilling fluid properties. Thus, it satisfies the requirement for plugging-while-drilling.
- (2) Calcite particles form the filling layer at the fracture inlet and isolate the drilling fluid inside the fracture from the wellbore. Thus, the fracture fluid pressure applied on the fracture surface is eliminated, preventing further expansion of the fracture. Moreover, the particles achieved the stable sealing of fracture, which enhanced the pressure-bearing capacity of the borehole wall.
- (3) The particle size of the first-grade calcite particles (bridging particles) is 60–100% of the fracture inlet opening, that of the second-grade particles is 23–40% of the fracture inlet opening, and that of the third-grade particles is 10–17% of the fracture inlet opening.
- (4) The calcite particle concentration was calculated based on the assumption that the working fluid for the plugging-while-drilling technique, with a volume identi-

cal to that of the fracture space, shall have a sufficient amount of rigid particles of different grades to form a stable filling layer.

- (5) The proposed particle size and concentration models for calcite particles were validated in both laboratory and field applications. The developed models makes up for the defect of designing calcite particles as LCM by experience and can provide a theoretical foundation for the application of the plugging-while-drilling technique and eliminate the disadvantages of empirical methods.

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