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Research article

An optimal design for millimeter-wide facture plugging zone

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Abstract

Lost circulation control in millimeter-wide fractures has been a challenge in well drilling all the time. Low pressure-bearing capacity of a plugging zone will result in excessive consumption of lost circulation materials (LCMs) and extra down time. In this study, laboratory experiments were conducted on the plugging of millimeter-wide fractures to evaluate the plugging effects of different types of LCM including rigid granules, elastic particles and fiber. Maximum plugging pressure, total loss volume before sealing and plugging time were taken as the evaluation index of the LCM plugging effect. According to the experimental results, the synergistic plugging mechanisms of different LCM combinations were also analyzed. Experimental results showed that the total loss volume of the plugging zone formed by rigid and elastic particle combination was generally greater than 400 mL, and the maximum plugging pressure of the plugging zone formed by elastic particle and fiber combination was generally less than 6 MPa. In contrast, the plugging zone formed by the combination of the three types of LCMs has the maximum plugging pressure of up to 13 MPa and total loss volume before sealing of 75 mL. In the synergistic plugging process, rigid granules form a frame with high pressure-bearing capacity in the narrower parts of the fractures; elastic particles generate elastic force through elastic deformation to increase the friction between a fracture and a plugging zone to make the plugging zone more stable; fibers filling in the pore space between the particles increase the tightness and integrity of the plugging zone. The experimental results can provide guidance for the optimal design of LCMs used in the field.

Keywords: Millimeter wide; Fracture plugging zone; Optimal design; Pressure bearing capacity; Rigid granule; Elastic particle; Fiber; Material synergy

Naturally fractured formation is one kind of the most commonly encountered formations. Lost circulation, which often causes a series of downhole problems, happens frequently during the drilling of this kind of formations [1]. Drilling fluid loss will lead to the increase of down time and have a negative impact on some important geological work. Researchers and engineers have made a lot of research on the lost circulation prevention and plugging during drilling [2−5]. The bridging method, as a most commonly used method, has always been the focus of attention [6−8]. As the EMW increases along with drilling depth, the plugging zone needs to meet the required pressure-bearing capacity after formed in the fracture, so Xu Chengyuan came up with a sealing strategy to enhance the pressure-capacity of plugging zones [9]. A dual fiber method proposed by Andrade in which the tough fiber formes a bridge and the soft fiber fills the gap, was successfully used in plugging the circulation loss in the fields in southern Mexico [10]. Li Jiaxue proposed a method to form a bridge at the fracture mouth with rigid particles, and calculated the particle size distribution based on the fracture width [11]. Kefi introduced a sealing method with the synergy effects of fibers forming a bridge and particles filling the gaps; he also presented a method to calculate the stiffness of fiber based on fracture width and differential pressure [12]. Jia Lili, Friedheim, Whitfill and Mao Hongjiang summarized the mostly used lost circulation materials (LCM) and predicted LCM development direction in the future [13−17]. Yan Fengming proposed the thought of temporary sealing, which involves forming a tight plugging zone at the fracture mouth with acid soluble materials [18], so the plugging zone could be easily

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removed with acids before production. It can be seen that methods for controlling loss circulation caused by micro fractures have been fairly mature.

Fracture width commonly ranges from several microns to several hundred microns under in situ formation stress [19], but often increases to millimeters as the stress state around the wellbore changes during drilling process, which results in a sharp increase in the rate and the amount of drilling fluid loss. In addition, the dynamic changes of fracture width with the stress state makes the plugging operation difficult. There are several difficulties in plugging fractures of millimeter width: ① LCM can hardly form a seal at the fracture mouth because of the large fracture width and high lost rate, and LCM flows into deep formations easily along with drilling fluid; ② the plugging zone formed by large size LCM is not tight and stable enough; ③ fracture width changes dynamically with pressure variation, so conventional LCM can't adapt to the change, making previously formed plugging zones prone to failure. In order to deal with millimeter fracture lost circulation more efficiently, laboratory experiments were conducted to select plugging materials and optimize the LCM formula.

1. Plugging mechanisms of different kinds of LCM

1) Fibers. Fiber is a common kind of LCM. When added in drilling fluid, fiber longer than the fracture can form a bridge and subsequently capture other fiber, forming a network structure which will enhance the total stability of fracture-plugging zone. Different kinds of fibers play different roles in the process of plugging. Hard fibers can be used to bridge, while soft fibers with low rigidity can intertwine and make the network more dense. But since fibers are low in rigidity on the whole, the maximum plugging pressure formed by fibers only cannot withstand large differentiate pressure. Soft fibers(DTR [20], QP-1) and hard fibers with different stiffness (plastic fibers, animal hair) were used in the experiments in this study (Fig. 1).

2) Rigid granules. Rigid particles, with high stiffness and compressive strength, act as frames in a plugging zone [21]. In field operations, quartz, walnut shells, $CaCO_3$ and broken cuttings are often used as rigid granules. In the process of plugging, rigid granules can bridge in the narrower part of the fracture and subsequent particles will be stopped and accumulate in the fracture. To form a fracture-plugging zone with rigid granules alone, the rigid granules should have different sizes so that the smaller sized granules can fill into the pore space between the larger granules. But the tightness of the fracture-plugging zone formed with rigid granules of different sizes is still not high enough because of the limit of granule shapes and sizes, so fiber and elastic particles are needed to further improve the tightness of the plugging zone. Walnut shells were selected as rigid granules in this paper. According to the granule size selection method, the bridging particle size should be smaller than the fracture width and larger than 0.6 times that of fracture width. Therefore, walnut shells of (8−12) mesh were chosen as the bridging particles in this paper.

3) Elastic particles. The addition of elastic particles will increase the friction between the plugging zone and the fracture surface because of their elastic deformation, thus improving the stability of the plugging zone. However, the plugging zone formed with elastic particles alone has lower maximum plugging pressure and tightness compared with the plugging zone formed with rigid granules alone and fibers alone because of its relatively lower stiffness and flexibility compared with rigid granules and fibers. According to the analysis above, different types of LCM have their advantages and disadvantages. In this study, rigid granules, fibers and elastic particles were used together to fully exploit their advantages and make up their disadvantages on the plugging effect.

2. Laboratory evaluation of plugging effect with LCM combinations

2.1. Experiment design and evaluation method

The objective of the laboratory experiments conducted in this study is to determine the optimal LCM combination and concentration for plugging millimeter-wide fractures and investigate the synergistic plugging mechanisms of different LCM combinations. Core samples with the fracture width of 2 mm were used for experimental evaluation (Fig. 2). To make sure the permeability is comparable the specimen has the same fracture before and after the fracture-plugging process. The experimental temperature was indoor temperature. The formula and the property of the basic fluid are shown in Tables 1 and 2.

Three key indexes were adopted to evaluate the plugging effect of LCM in this study: maximum plugging pressure, plugging time and total loss volume before sealing. Maximum plugging pressure refers to pressure a fracture-plugging zone

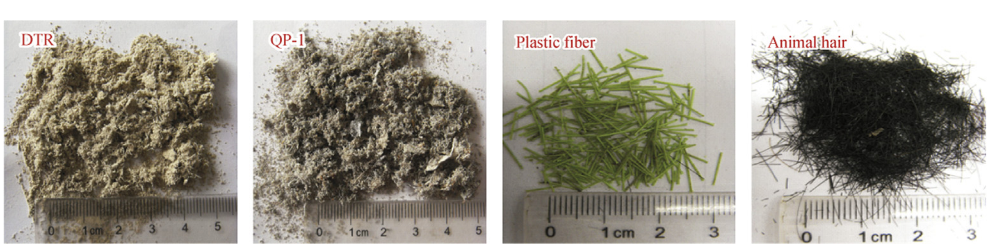

Fig. 1. Fibers and hair used for laboratory evaluation.

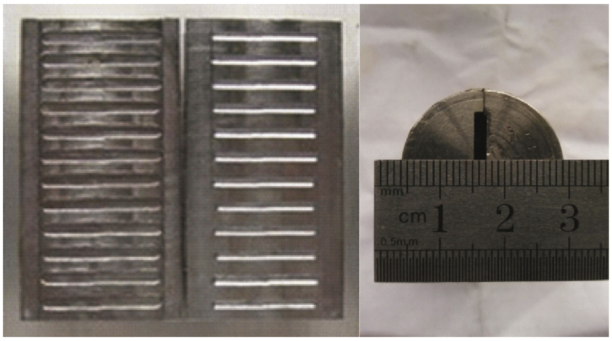

Fig. 2. Steel core samples with the fracture width of 2 mm.

can withstand before it becomes unstable and breaks. Under a certain pressure point, if the loss rate keeps at more than 50 mL/s and lasts for more than 10s, then the previous pressure point is taken as the maximum plugging pressure. Plugging time is defined as the interval from applying the initial pressure point to reaching the maximum plugging pressure. The loss volume before the maximum pressure point is reached is taken as the total loss volume before sealing.

The test procedures are as follows: ① the drill-in fluid added with special LCMs was injected into the fluid container, the initial pressure point was set at 1 MPa for 30 s and then the fluid outlet was opened; ② the drill-in fluid loss and fracture-plugging process was simulated by applying the flowing pressure in increments of 0.5–1 MPa; ③ the pressure at which the plugging zone broke was recorded and the previous pressure point was taken as the maximum plugging pressure. The drill-in loss volume at each pressure point was measured and the cumulative loss volume when the maximum plugging pressure was reached was taken as the total loss volume before sealing.

2.2. Evaluation of fibers

Fibers were used firstly to plug fractures to determine the optimal proportion of soft fibers and hard fibers. The concentration of different types of fiber combinations are shown in Table 3.

Experimental results in Table 4 show that soft fibers can form a plugging zone in a short time, but the maximum plugging pressure of the plugging zone formed by soft fibers is unsatisfactory because of the high flexibility of soft fibers. Experimental results in Table 5 show that the plugging effect was improved when hard fibers were used to form the plugging zone with soft fibers together. The maximum plugging pressure increased to 4.5 MPa and the total loss volume reduced to 350 mL, indicating that the plugging effect can be improved with the combination of soft and hard fibers.

Table 1
Basic fluid formula.

Material	Tap water	Bentonite	HV-CMC
Content	–	6%	0.5%

Table 2
Property parameters of the basic fluid.

Parameter	Apparent viscosity (mPa s)	Plastic viscosity (mPa s)	Yield point (Pa)	Density (g/cm^3)
Value	38.5	27	11.5	1.04

Table 3
Fiber formula for plugging fractures of 2 mm wide.

Formula Number	DTR	QP-1	Plastic fiber	Animal hair
#1	2.5%	/	/	/
#2	/	2.5%	/	/
#3	2.5%	1.5%	/	/
#4	2.5%	1.5%	0.2%	/
#5	2.5%	1.5%	0.3%	/
#6	2.5%	1.5%	/	0.2%
#7	2.5%	1.5%	/	0.3%
#8	2.5%	1.5%	0.2%	0.2%

Table 4
Experimental results of plugging fractures of 2 mm wide with DTR and QP-1.

Formula number	Maximum plugging pressure (MPa)	Plugging time (s)	Total loss volume before sealing (mL)	Remarks
#1	1.0	10	550	Steel core samples
#2	1.0	12	510	
#3	2.5	7	715	

2.3. Evaluation of the combination of rigid granules and elastic particles

The plugging effect of rigid granule and elastic particle combination with different concentration was evaluated. The results are shown in Table 6. It can be seen that when the concentration of rigid granules was less than 3.0%, the plugging zone formed was not effective with low pressure-bearing capacity and high loss volume. When the rigid granule concentration increased to 7.0%, the maximum plugging pressure rose to 9 MPa while the total loss volume was still larger than 420 mL. The plugging effect of this combination was best

Table 5
Experimental results of plugging fractures of 2 mm wide with soft and hard fibers.

Formula number	Maximum plugging pressure (MPa)	Plugging time (s)	Total loss volume before sealing (mL)	Remarks
#4	3.5	10	550	Steel core samples
#5	3.5	10	485	
#6	2.5	7	380	
#7	3.0	5	410	
#8	4.5	6	350	

Table 6
Experimental results of plugging fractures of 2 mm wide with the combination of rigid and elastic particles.

Experiment number	CR	CE	Maximum plugging pressure (MPa)	Plugging time (s)	Total loss volume before sealing (mL)	Remarks
1	3.0%	5.0%	–	–	1400	Steel core samples
2	3.0%	7.0%	–	–	1400	
3	3.0%	9.0%	3	<100	735	
4	5.0%	5.0%	3	<100	600	
5	5.0%	7.0%	5	<100	420	
6	5.0%	9.0%	6	<100	625	
7	7.0%	5.0%	8	<100	700	
8	7.0%	7.0%	9	<100	605	
9	7.0%	9.0%	9	<100	550	
10	7.0%	7.0%	10	20	350	Natural core samples

Table 7
Experimental results of plugging fractures of 2 mm wide with the combination of elastic particles and fibers.

Experiment number	CE	CF	Maximum plugging pressure (MPa)	Plugging time (s)	Total loss volume before sealing (mL)	Remarks
1	5.0%	4.0%	4	<100	720	Steel core samples
2	7.0%	4.0%	4	45	620	
3	9.0%	4.0%	5	40	690	
4	5.0%	4.5%	4	20	415	
5	7.0%	4.5%	6	15	175	
6	9.0%	4.5%	6	20	350	
7	5.0%	5.0%	5	20	400	
8	7.0%	5.0%	5	20	265	
9	9.0%	5.0%	6	15	380	
10	7.0%	4.5%	9	10	215	Natural core samples

Note: No hard fiber is added in 4.0% of fiber materials.

Fig. 3. Plugging zone formed with the three types of LCMs.

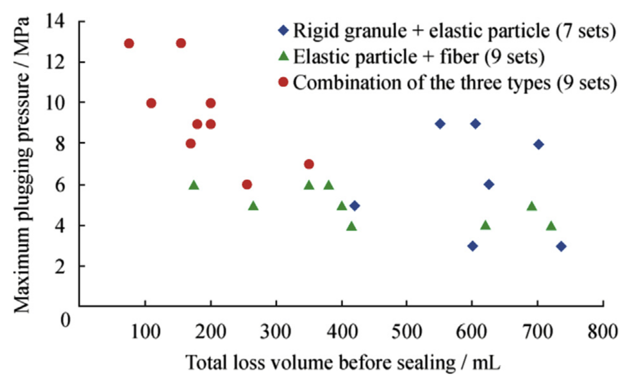

Fig. 4. Plugging effect of different combinations of LCMs.

when the concentration of rigid and elastic particles was 7.0% and 9.0% respectively.

2.4. Evaluation of the combination of elastic particles and fibers

The plugging effect of the combination of elastic particles and fibers with different concentration was evaluated. From Table 7 we can see that the plugging time and total loss volume before sealing with the fiber concentration of 4.0% are larger than that with the fiber concentration of 4.5% and 5.0%. When the fiber concentration increased from 4.5% to 5.0%,

Table 8
Experimental results of plugging fractures of 2 mm wide with three types of LCM combination.

Experiment number	CR	CE	CF	Maximum plugging pressure (MPa)	Plugging time (s)	Total loss volume before sealing (mL)	Remarks
1	3%	5%	4%	7	<100	350	Steel core samples
2	3%	7%	4.5%	10	7	200	
3	3%	9%	5%	10	8	255	
4	5%	5%	5%	9	10	180	
5	5%	7%	4.5%	13	5	75	
6	5%	9%	4%	9	20	200	
7	7%	5%	5%	10	15	110	
8	7%	7%	4%	8	15	170	
9	7%	9%	4.5%	13	12	155	
10	5%	5%	5%	10	5	42	Natural core samples
11	5%	7%	4.5%	13	2	30	
12	7%	5%	5%	12	5	95	

Note: No hard fiber is added in 4.0% of fiber materials.

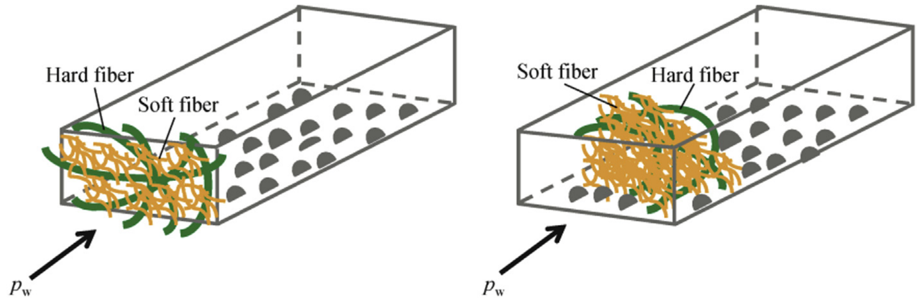

Fig. 5. Fracture-plugging zone formed with fibers.

the plugging effect didn't improve much. Therefore, for the combination of elastic particles and fibers, the best plugging effect was achieved with 7.0% elastic particles and 4.5% fibers. Under this condition, the maximum plugging pressure was 6 MPa and the total loss volume before sealing was 175 mL.

2.5. Evaluation of the combination of rigid granules, elastic particles and fibers

Orthogonal experiment method was adopted to evaluate the effect of different LCM concentration on the plugging effect. The experimental results of plugging the fracture with the combination of rigid granules, elastic particles and fibers are listed in Table 8. It can be seen that the combination of the three types of LCM can improve the plugging effect greatly. The maximum plugging pressure reached 13 MPa and total loss volume before sealing dropped to 30 mL. The optimal concentration of rigid granules, soft fibers, hard fibers and elastic particles is 5%, 4%, 0.5% and 7% respectively. Fig. 3 shows the plugging zone formed in the fracture with the combination of the three types of LCM.

According to a comparison analysis of the plugging effects achieved with different LCM combination (Fig. 4), we can see that the rigid and elastic particle combination without fibers had the maximum total loss volume before sealing and the fiber and elastic combination without rigid granules had the lowest maximum plugging pressure. The combination of the three types of LCM had the best plugging effect. Further analysis will be made in the next section to figure out the underlying mechanisms of synergistic plugging with LCM combination.

3. Synergistic plugging mechanism of LCM combinations

3.1. Plugging mechanism of soft and hard fibers

Fiber, a kind of flexible and elastic material, functions in improving the stability of the fracture-plugging zone. In the sealing process, firstly, hard fibers with relatively high bending strength flow into the fractures, and some of them bridge at the fracture plane because the fiber length is larger than the fracture width. Then, the soft fibers in the drilling fluid are captured by the bridged hard fibers. Soft fibers intertwining with each other form a tight plugging zone like a fiber grid structure, which can reduce the effective cross section area of fractures and reduce drilling fluid loss to filtration gradually so that the pressure propagation in the fractures decreases. Moreover, when the increasing positive pressure difference is larger than the yield strength of the hard fibers, the whole fiber grid structure will be pushed into the fractures and becomes much tighter, which makes the bridging and packing of other plugging material particles easier (Fig. 5).

3.2. Plugging mechanism of the combination of rigid granules and elastic particles

In the plugging process, elastic particles can block at the narrower part of the fractures, detain the rigid particles and prompt the particle bridging. After the initial bridging of rigid granules, the elastic particles are easier to catch, then deform and fill in the inter-space of rigid particles, as is shown in Fig. 6. Eventually a plugging zone would be formed through continuous bridging and filling. As the rigid particles have high strength and small deformation, the plugging zone formed by the combination of rigid and elastic particles has higher pressure-bearing capacity. However, intermittent loss commonly occurs due to the lack of fiber grid structure and the plugging zone is weak in integrity. Also the plugging zone needs more time to become stable and has a bigger leakage volume than the drilling fluid with fibers.

3.3. Plugging mechanism of the combination of elastic particles and fibers

Elastic particles and fibers have good deformability. In the plugging process, fibers can quickly form a network structure

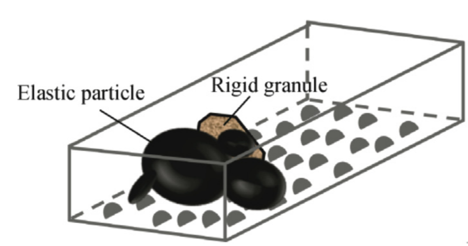

Fig. 6. Fracture-plugging zone formed by the combination of rigid and elastic particles.

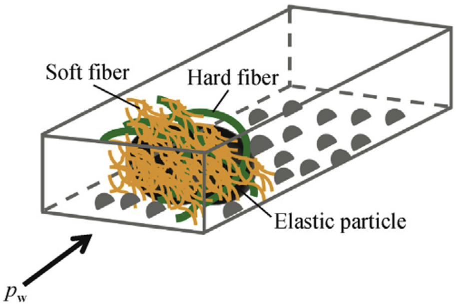

Fig. 7. Fracture-plugging zone formed by the combination of fibers and elastic particles.

in the fracture and elastic particles would fill in pores of the network (Fig. 7). Therefore, the combination of elastic particles and fibers can plug the fracture quickly. The fracture-plugging zone formed with this combination has high tightness and integrity. However, because of lack of rigid bridging particles, the friction between the fracture face and the plugging zone is relatively low. With the increase of differential pressure, the plugging zone would be pushed deep into the fracture.

3.4. Plugging mechanism of the combination of three types of LCM

The combination of rigid granules, elastic particles and fibers can improve the plugging effect greatly thanks to the synergistic effect of the three kinds of materials. The underlying mechanisms of their synergy effect are as follows: rigid granules are essential for the maximum plugging pressure, they can sustain the great stress exerted by the confining stress and fluid pressure because of their high compressive strength over fiber and elastic particles. However, rigid granules themselves have no resilience and cannot ensure the tightness of the plugging zone. These factors will have a negative effect on the plugging effectiveness. Fiber materials have higher aspect ratio compared with particle materials. They can fill into the pore space between particles and increase the tightness of the plugging zone. Therefore, fibers play an important role in reducing the permeability of the fracture-plugging zone and minimizing the total loss volume before sealing. Elastic particles with higher resilience can increase the friction between the fracture face and the plugging zone further through elastic deformation. According to the experimental results and plugging mechanism analysis, with the combination of rigid granules, elastic particles and fibers, the best plugging effect for fractures of 2 mm wide can be achieved (Fig. 8). The effect of different LCMs on plugging is listed in Table 9.

Table 9
Influence of LCMs on plugging effect.

	Rigid granule	Elastic particle	Soft fiber	Hard fiber
Maximum plugging pressure	[fx1]	fx2	/	[fx3]
Total loss volume before sealing	/	[fx3]	[fx1]	fx2
Stability of Plugging zone	fx2	[fx1]	[fx1]	fx2
Plugging efficiency	[fx3]	[fx3]	fx2	[fx1]

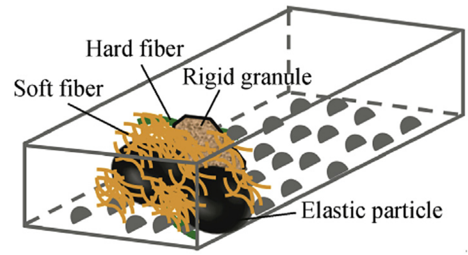

Fig. 8. A fracture-plugging zone formed by the combination of rigid granules, elastic particles and fibers.

4. Conclusions

1) The optimal formula for plugging fractures of 2 mm wide is: the base carrier fluid +5% rigid granule +4% soft fiber +0.5% hard fiber +7% elastic particle.
2) For plugging millimeter-wide fractures, the optimal LCM selection is the combination of rigid granules, elastic particles and fibers.
3) Rigid granules have a main effect on the maximum plugging pressure. Elastic particles can increase the friction between the fracture plane and the plugging zone and improve the stability of the plugging zone. Fibers play an important role in reducing the total loss volume before sealing.
4) The type, combination and concentration of LCMs are vital for the effective plugging of millimeter-wide fractures.

References

[1] Xu Tongtai, Liu Yujie, Shen Wei. Plugging technology in drilling engineering. Petroleum Industry Press; 1997.
[2] Liu Yanqiang, Xu Tongtai, Yang Zhenjie, Gong Zhimin. Recent progress on preventing and treating lost circulation domestic and overseas. Drill Fluid Complet Fluid 2010;27(6):80–4.
[3] Zhang Xiwen, Sun Jinsheng, Yang Zhi, Shan Wenjun. Lost circulation control in fractured formations. Drill Fluid Complet Fluid 2010;27(3):29–32.
[4] Zhang Xiwen, Li Shuang, Zhang Jie, Sun Jinsheng, Yang Zhi. Research progress on lost circulation materials and lost circulation control technology. Drill Fluid Complet Fluid 2009;26(6):74–6.
[5] Xue Yuzhi, Liu Zhendong, Tang Daixu, Hou Yegui, Song Zhaohui, Liu Congjun. Study on the formulation of lost circulation control fluid and the laws of lost circulation control for fractured formations. Drill Fluid Complet Fluid 2009;26(6):28–30.
[6] Zhang Peiyuan. Progressive bridge plugging technology for lost circulation. Drill Fluid Complet Fluid 2010;27(2):67–9.
[7] Guo Hongfeng, Bu Zhenshan, Qin Changqing. Bridging techniques and the study on bridge materials. Pet Drill Tech 2000;28(5):39–40.
[8] Vickers SR, Hutton AP, Main R, Twynam AJ, Jackson G. Drilling highly fractured limestone reservoir: Is it a particle bridge too far?. Paper 134485, SPE Annual Technical Conference and Exhibition. 2010.
[9] Xu Chengyuan, Kang Yili, You Lijun, Li Daqi, Chen Fei. High-strength, high-stability pill system to prevent lost circulation. IPTC 2013: International Petroleum Technology Conference. 2013.
[10] Andrade AV, Torres L, Bermudez R, Bedino H, Carrillo N, Vargas C, et al. Fiber technology simply and effectively cures total losses in

Southern Mexico without knowing size of fractures. Paper 150844, SPE Latin America and Caribbean Petroleum Engineering Conference. 2012.
[11] Li Jiaxue, Huang Jinjun, Luo Pingya, Yang Li, Lu Yi. Plugging mechanism and estimation models of rigid particles while drilling in fracture formations. Acta Pet Sin 2011;32(3):509−13.
[12] Kefi S, Lee JC, Shindgikar ND, Brunet C, Vidick B, Diaz NI. Optimizing in four steps composite lost-circulation pills without knowing loss zone width. Paper 133735, IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. 2010.
[13] Jia Lili, Tian Lufei, Liu Zhen, Shi Yunzhong, Tian Lei. Research progress of lost circulation materials. Mater Res Appl 2011;5(1):14−6.
[14] Friedheim JE, Arias-prada JE, Sanders MW, Shursen R. Innovative fiber solution for wellbore strengthening. Paper 151473, IADC/SPE Drilling Conference and Exhibition. 2012.
[15] Whitfill DL, Hemphill T. All lost-circulation materials and systems are not created equal. Paper 84319, SPE Annual Technical Conference and Exhibition. 2003.
[16] Mao Hongjiang. Lost circulation and countermeasures in geological and mining exploration drilling. Northwest Geol 2010;43(3):141−6.
[17] Zhang Hongli, Guo Yan, Wang Zhilong. Lost circulation materials in China. Spl Oil Gas Reservoir 2004;11(2):1−2.
[18] Yan Fengming, Kang Yili, Sun Kai, Zhang Jinshun, Wang Hongwei, Du Chunchao. The temporary sealing formula for fractured-Vuggy carbonate reservoir. Pet Drill Tech 2012;40(1):47−51.
[19] Majidi R, Miska SZ, Yu M. Modeling of drilling fluid losses in naturally fractured formations. Paper 114630, SPE Annual Technical Conference and Exhibition. 2008.
[20] Fan Gang. Research and application of DTR plugging agent in the oil drilling. West-China Explor Eng 2006;18(7):100−1.
[21] Kageson-loe NM, Sanders MW, Growcock F, Taugb K, Horsrud P, Singelstad AV, et al. Particulate-based loss-prevention material−the secrets of fracture sealing revealed!. Paper 112595 SPE Drill Complet 2009;24(04):581−9.