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Experimental Study on Loss-Prevention Performance of Oil-Based Drilling Fluids

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Abstract

Compared to the water-based drilling fluids, lost circulation is more prone to occur when drilling with oil-based drilling fluids and it is difficult to deal with this problem on the drilling site for lack of high-efficiency lost circulation materials. In order to solve this technical problem, the principles of pressure resistance plugging technology of oil-based drilling fluids was firstly investigated according to the force-chain principle of granular matter mechanics, and rigid bridging particles, elastic packing particles and micro fibers could synergistically form fracture tight sealing zones with strong force-chain network to strengthen the lost circulation prevention ability of oil-based drilling fluids. Based on the principle above, novel loss-prevention materials were finally developed for oil-based drilling fluids by optimizing different plugging agents. Experimental results show that novel loss-prevention materials could be compatible with other components of oil-based drilling fluids. The oil-based drilling fluids with high sealing capacity could be optimized by adding novel loss-prevention materials, and it exhibits good rheological behavior with a low PPT filtration of 11.4 mL and excellent lost circulation prevention ability to strengthen the wellbore while drilling.

Key words: Lost circulation; Oil-based drilling fluid; Loss prevention materials; Tight plugging mechanism; Strong force-chain

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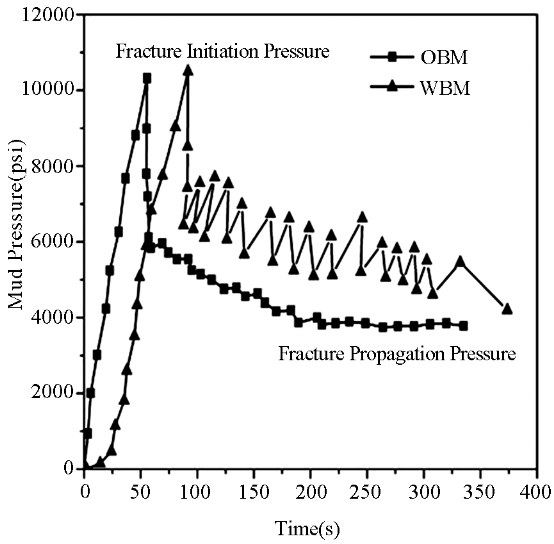
INTRODUCTION

In drilling engineering, lost circulation is one of the most serious problems, and its economic cost is due to the loss of expensive drilling fluid into the formation and nonproductive time spent on regaining mud circulation. Lost circulation treatments can be applied before or after lost circulation occurs. Therefore such applications naturally fall into two categories: preventive treatments and corrective treatments. If untreated, lost circulation may lead to well control issues, poor hole cleaning, wellbore collapse and stuck pipe[1]. Recently, with the promotion of oil and gas development around the world, the exploration scope has been gradually extended to complicated geological reservoirs, such as deep or ultra-deep, unconventional, deep-water reservoirs, oil-based drilling fluids (OBM) have been becoming the best choice become of its excellent performance[2-3]. But, compared to the water-based drilling fluid, lost circulation is more prone to occur when drilling with OBM and it is difficult to deal with this problem on the drilling site for lack of high-efficiency lost circulation materials[4-9].

The DEA-13 Project was designed to understand why lost circulation problems occur more frequently when drilling with OBM. A great deal of experiments were proved that the fracture initiation pressure for water-based drilling fluids (WBM) and oil-based drilling fluids (OBM) were similar, but fracture propagation pressure was much lower for oil-based drilling fluids than it was for water-based drilling fluids[10-12]. This phenomenon was explained by “tip screen-out” used in hydraulic fracturing[13-15]. Moreover, GPRI 2000 joint project demonstrated that circulation materials type, concentration and particle size distribution were key factors to improve the effectiveness of loss-prevention[16-17]. Furthermore, a series of rock mechanics experiments were conducted to further investigate the lost circulation mechanism of OBM. The tests demonstrated that the rock tensile and shear strength were reduced significantly after immersed in OBM for certain time, because of invasion and adsorption of surfactants in OBM, such as emulsifiers, wetting agents[18].



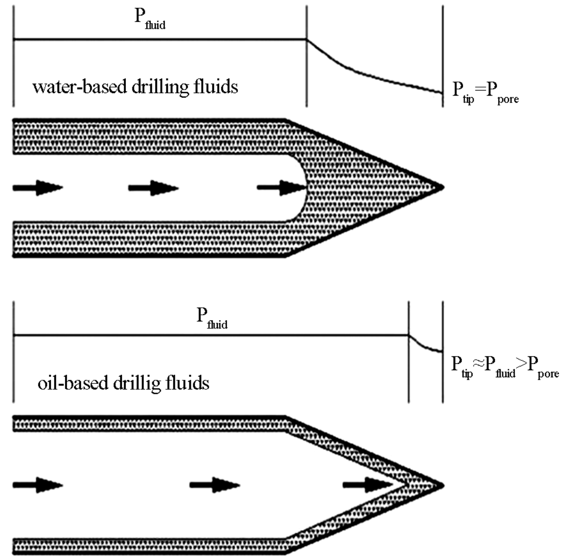


Figure 1
Comparison of Fracturing Test Curves With OBM and WBM[10]

Given that both oil-based drilling fluids and lost circulation are often expensive, the direct economic impact of lost circulation may be substantial. The cost issue is especially relevant for oil-based drilling fluids that are usually more costly than water-based drilling fluids. Inspired by DEA-13 and GPRI 2000 project results, lost circulation prevention method using loss-prevention materials (LPM) may be the best solution for oil-based drilling fluids. In this paper, novel loss-prevention materials were finally developed for oil-based drilling fluids by optimizing different plugging agents, such as rigid bridging particles, elastic packing particles and micro fibers. The oil-based drilling fluids with high sealing capacity were also optimized and evaluated by adding novel loss-prevention materials. Furthermore, the plugging mechanism of novel loss-prevention materials was also investigated according to the force-chain principle of granular matter mechanics.

1. MATERIALS AND METHODS

1.1 Materials

The novel loss-prevention materials were prepared using standard commercial additives, such as calcium carbonate, graphite, asphalt and micro fiber, and the trade names of additives were replaced by generic description. Moreover, the oil-based drilling fluid as base fluid was also prepared using standard commercial additives, and the formulation of the tested drilling fluid are listed in Table 1, and it was weighed to be 1.20 g/cm^3 using API barite.

Table 1
Formulation of Tested Oil-Based Drilling Fluid

Formulation	Base fluid
Density, g/cm^3	1.20
Mineral oil, mL	as required
Emulsifier, % (m/v)	2.0
Wetting agent, % (m/v)	3.0
Viscosifier, % (m/v)	0.5
Organic bentonite, % (m/v)	4.0
CaO, % (m/v)	1.0

1.2 Permeability Plugging Test

Recently, Permeability Plugging Test (PPT) was adopted to evaluate the relative plugging performance of LCM combines or drilling fluids and ceramic discs of different permeability, representing formation pores or fractures, were used as test media in the PPT testing. The filtration volume, testing under high temperature and high pressure for 30 min (for example, 7.5MPa/120℃) was conventionally chosen as experimental parameters to evaluate the loss-prevention ability of drilling fluids[19]. Therefore, the Permeability Plugging Test (PPT) was adapted to optimizing and evaluating novel loss-prevention materials and ceramic discs of representative permeability 10 μm^2 were used as test media in this paper. It is believed that when the permeability of formation reach or exceeds 10 μm^2, heavy fluid loss would occur if untreated[20].

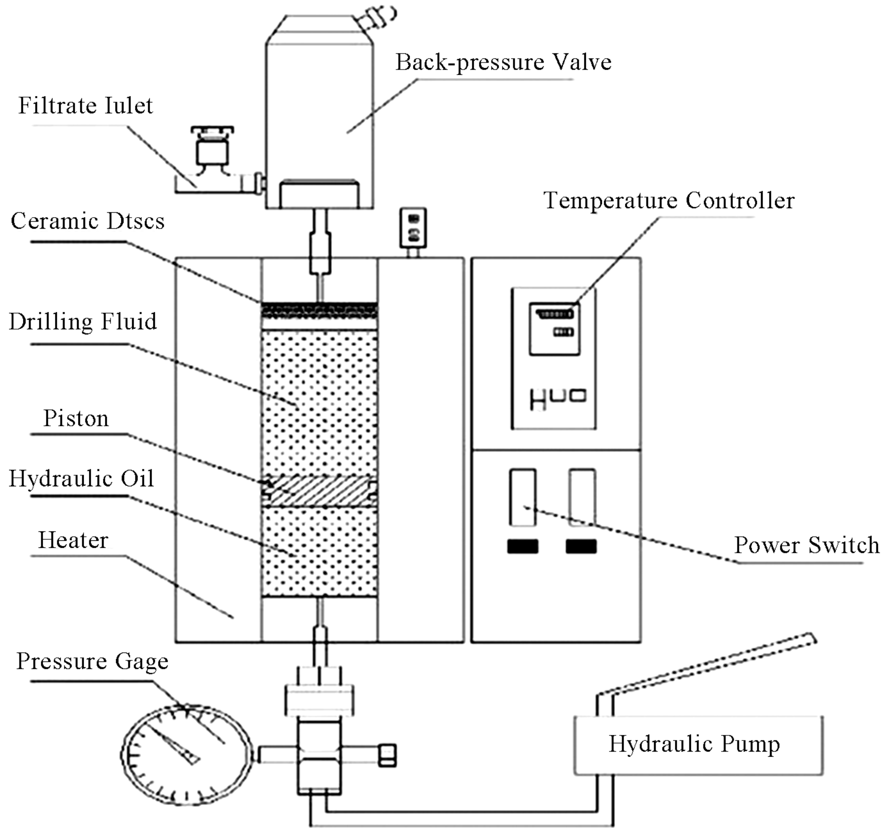


Figure 2
Schematic Diagram of Permeability Plugging Apparatus

1.3 Preparation of Novel Loss-Prevention Materials

Firstly, the particle size distribution (PSD) of calcium carbonate and graphite were analyzed with dynamic light scattering using Mastersizer 3000. Secondly, calcium carbonate, graphite, asphalt and micro fibers were added into the base fluid respectively, and the testing fluids were hot rolled at 120 ℃ for 16 h. The rigid bridging particles, elastic packing particles, softening particles and micro fibers were optimized based on the PPT filtration volume measured under the condition of 120 ℃/7.5MPa. Finally, the novel loss-prevention materials for oil-based drilling fluids were prepared with reasonable size distribution and concentration according to the Ideal Packing Theory.

1.4 Evaluation of Novel Loss-Prevention Materials

The novel loss-prevention materials were reacted with the prepared oil-based drilling fluid and stirred for 30 min. After hot rolling at 120 ℃ for 16 h, the rheological and filtration properties were measured and the compatibility or applicability of novel loss-prevention materials in the oil-based drilling fluids was investigated based on the rheological and filtration properties and plugging ability comparison of fluids with or without novel loss-prevention materials.

The rheological properties of the oil-based drilling fluids were measured using a model ZNN-D6 viscometer. The apparent viscosity, plastic viscosity and yield point were calculated from 600 and 300 rpm dial reading according to the API recommended practice of standard procedures for field testing drilling fluids at 65 ℃[21]. The filtration properties were measured using GGS-71B filtration apparatus at 120 ℃ for 30 min. The plugging ability was also measured using Permeability Plugging apparatus at 120 ℃ for 30 min.

Apparent viscosity (AV) = $\varphi_{600}/2$ (mPa.s)
Plastic viscosity (PV) = $\varphi_{600}-\varphi_{300}$ (mPa.s)
Yield point (YP) = $(\varphi_{300}-PV)/2$ (Pa)
HTHP filtration (HTHP FL) = $2\times FL_{GGS}$ (mL)
PPT filtration (PPT FL) = $2\times FL_{PPT}$ (mL)

2. RESULTS AND DISCUSSION

2.1 Optimization of Novel Loss-Prevention Materials

According to the Ideal Packing Theory, rigid bridging particles, elastic packing particles, softening particles and micro fibers were optimized respectively. Based on the optimization of different plugging agents (particles), the novel loss-prevention materials were finally prepared by adjusting the relative concentration of different plugging agents with the guidance of the Ideal Packing Theory. The candidate formulations are listed in Table 2, and the size distribution curve of NO.1 formulation reaches high coincidence degree with the standard baseline of the Ideal Packing Theory (Figure 3). In order to verify this analysis above, the novel loss-prevention materials of different candidate formulations were added into the base fluid respectively, and the testing fluids were hot rolled at 120 ℃ for 16 h. The PPT filtration volume was measured under the condition of 120 ℃/7.5MPa. As shown in Figure 4, the PPT filtration volume was significantly reduced and the NO.1 formulation exhibits the best plugging performance with the PPT filtration volume of only 12.1 mL. Finally, the optimum formula of novel loss-prevention materials was determined as follows: 1.0% Rigid Particle + 0.5% Elastic Particle +2.5% Micro Fiber + 1.0% Softening Particle.

Table 2
Candidate Formulations of Novel Loss-Prevention Materials

NO	Rigid particle/%	Elastic particle/%	Micro fiber/%	Softening particle/%
1#	1.0	0.5	2.5	1.0
2#	1.0	0.5	3.0	0.5
3#	1.0	1.0	2.0	1.0
4#	1.5	0.5	2.0	1.0
5#	1.5	1.0	2.0	0.5
6#	2.0	0.5	1.5	1.0

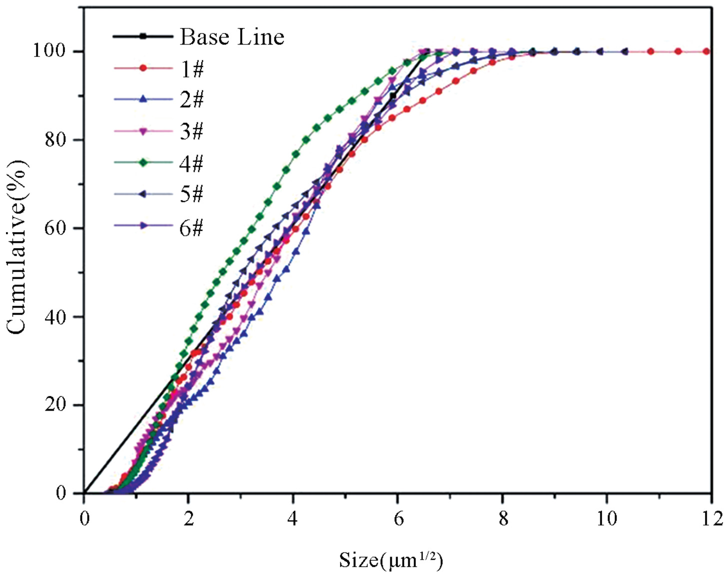


Figure 3
Particle Size Distribution of Candidate Formulations

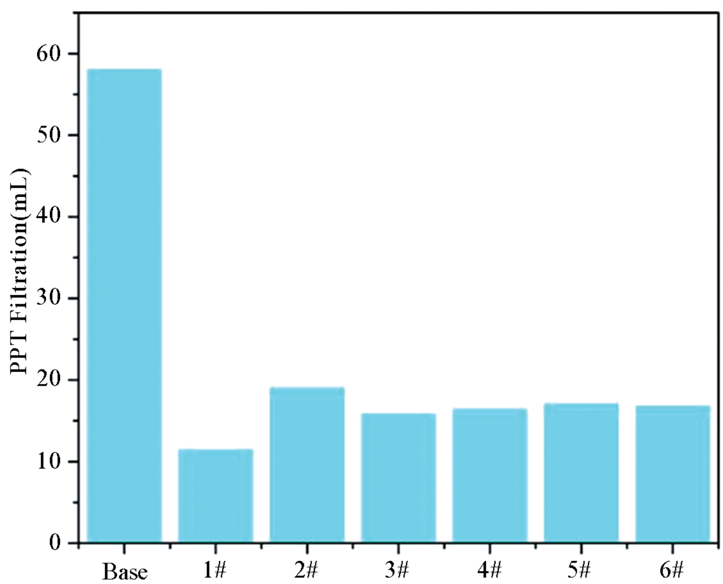


Figure 4
PPT Filtration Volume of Candidate Formulations

2.2 Evaluation of Novel Loss-Prevention Materials

The oil-based drilling fluids were conventionally applied in drilling process of ultra-deep, unconventional and deep-water reservoirs, and the fluid density was mainly from 1.6 to 2.2 g/cm^3. Therefore, the compatibility or applicability of novel loss-prevention materials (NLPM) in the oil-based drilling fluids was investigated based on the rheological and filtration properties, plugging ability comparison of oil-based drilling fluids with or without NLPM. The Formulation of oil-based drilling fluids used in compatibility or applicability tests is listed in Table 3.

Table 3
Formulation of Oil-Based Drilling Fluids

Formulation	OBM-1	OBM-2	OBM-3
Density, g/cm^3	1.60	1.80	2.20
Oil/water, v/v	90/10	90/10	90/10
Mineral oil, mL	As required	As required	As required
26%wt $CaCl_2$, mL	As required	As required	As required
1# Emulsifier, % (m/v)	3.0	3.0	3.0
2# Emulsifier, % (m/v)	4.0	4.0	4.0
Rheology control agent, % (m/v)	1.2	1.0	1.0
Filtrate reducer, % (m/v)	3.0	3.0	3.0
Organic bentonite, % (m/v)	4.0	3.5	3.0
CaO, % (m/v)	4.0	4.0	4.0

2.2.1 Rheological and Filtration Properties

Rheological and filtration properties of different fluids were measured at 65 ℃ before and after adding 5.0% (m/v) NLPM (Table 4) after hot rolling at 120 ℃ for 16 h. It could be seen from Table 4 that adding NLPM would not have adverse effect on rheological and emulsion properties of oil-based drilling fluids of different density, and it is beneficial to decrease the HTHP filtration volume on the contrary. Therefore, the novel loss-prevention materials could be alternatives to conventional or standard plugging additives in oil-based drilling fluids.

Table 4
Effect of NLPM on Rheological and Filtration Properties of Drilling Fluids

Formulation	Test condition	AV/mPa.s	PV/mPa.s	YP/Pa	HTHP-FL/mL
OBM-1	Before aging	47.0	34.0	13.0	-
	After aging	37.5	30.0	7.5	8.5
OBM-1 + 5%NLPM	Before aging	40.5	29.0	11.5	-
	After aging	32.5	26.0	6.5	6.4
OBM-2	Before aging	50.0	37.0	13.0	-
	After aging	42.5	35.0	7.5	6.7
OBM-2 + 5%NLPM	Before aging	49.0	36.0	13.0	-
	After aging	36.5	29.0	7.5	5.9
OBM-3	Before aging	89.0	72.0	17.0	-
	After aging	61.5	53.0	8.5	5.1
OBM-3 + 5%NLPM	Before aging	94.0	76.0	18.0	-
	After aging	72.0	62.0	10.0	3.3

2.2.2 Plugging Ability

The Permeability Plugging Test and Fracture Plugging test were adopted to evaluate the plugging ability of oil-based drilling fluids before and after adding 5.0% (mv) NLPM (Table 4) after hot rolling at 120 ℃ for 16 h. Results of permeability plugging tests are shown in Table 5 and Figure 5. It could be seen from Table 5 and Figure 5 that adding NLPM could be beneficial to form tight sealing zones to lower the PPT filtration volume, spurt loss and static filtration rate and significantly improve the plugging ability of oil-based drilling fluids. What's more, the screen mesh of shale shakers in the drilling site is no more than 150, and the novel loss-prevention materials would not be removed from the drilling fluids. It means that the novel loss-prevention materials could keep its effective concentration in the drilling fluids to improve loss-prevention ability of oil-based drilling fluids while drilling.

Table 5
Results of Permeability Plugging Tests for Drilling Fluids

Formulation	PPT filtration/mL	Spurt loss/mL	Static filtration rate/(mL/min^2)
OBM-1	4.6	0.54	0.30
OBM-1 + 5%NLPM	3.6	0.28	0.28
OBM-2	5.2	0.89	0.29
OBM-2 + 5%NLPM	3.8	0.45	0.26
OBM-3	5.4	0.88	0.34
OBM-3 + 5%NLPM	4.0	0.47	0.27

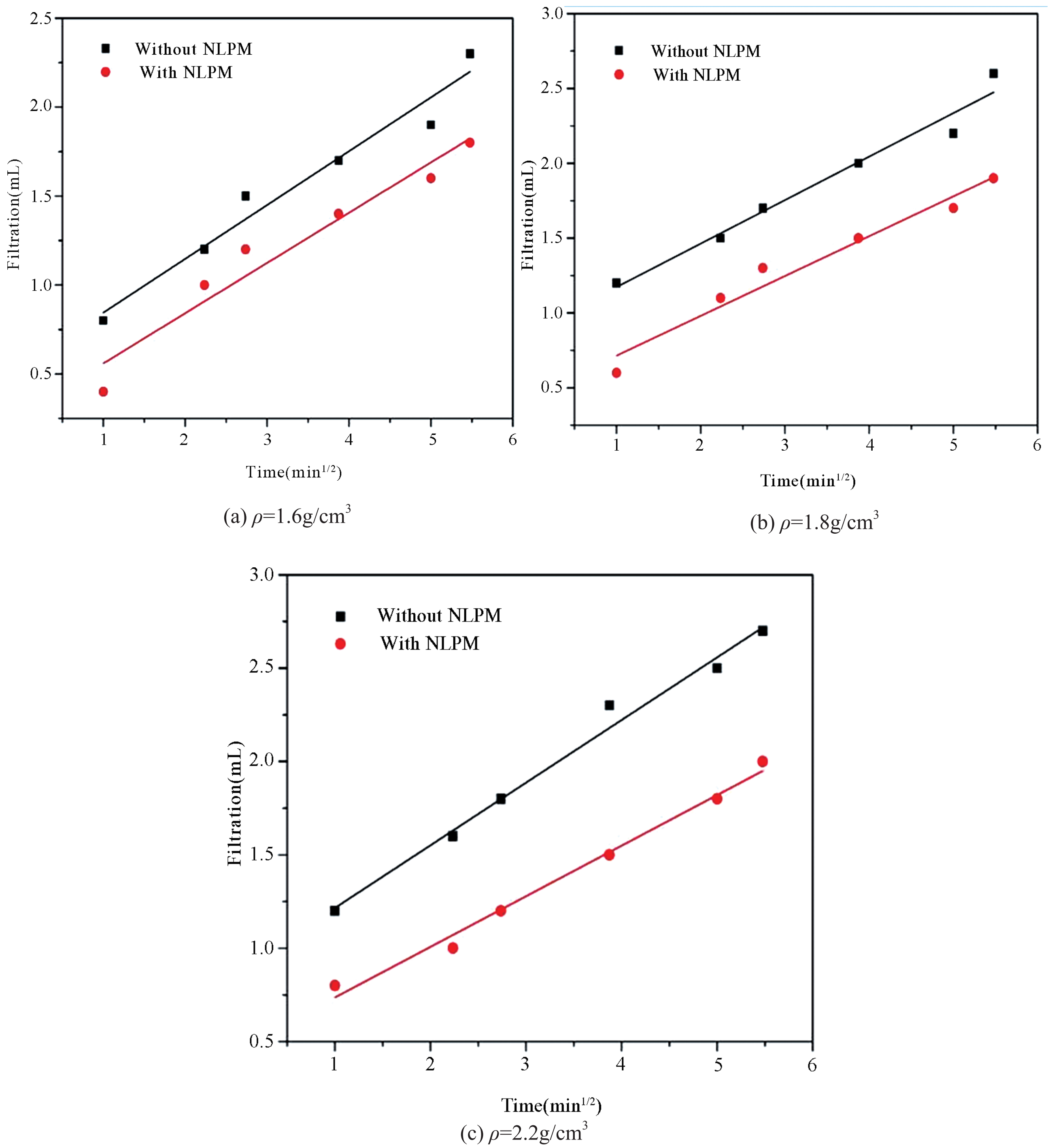


Figure 5
Relationship of PPA Filtration With Square Root of Time

Figure 6 presented the SEM images of aloxite discs before and after test. It could be concluded from Figure 6 that the different components of novel loss-prevention materials, rigid bridging particles, elastic packing particles, softening particles and micro fibers with reasonable size distribution and concentration, could act synergistically to quickly form pore or fracture sealing zones with strong force-chain network to strengthen the lost circulation prevention ability of oil-based drilling fluid.

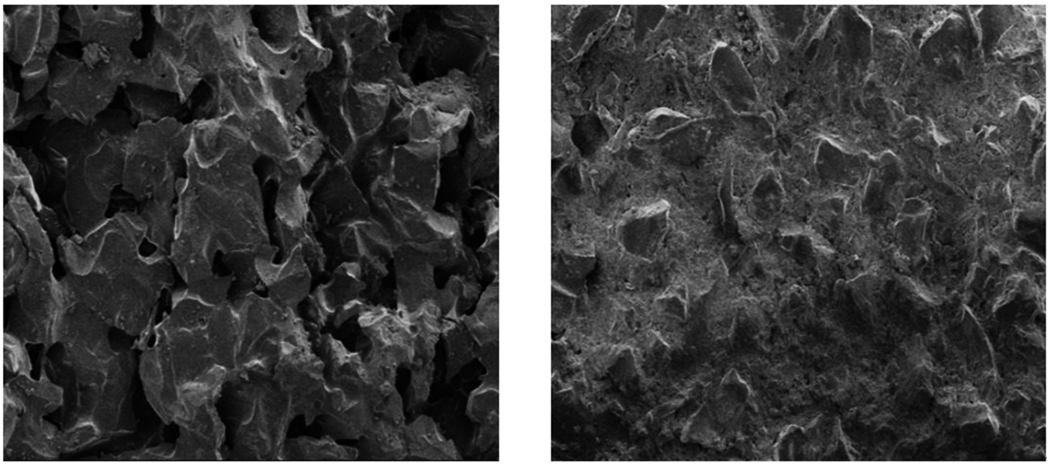


Figure 6
SEM Photographs of Aloxite Discs: Before Test (Left), After Test (Right)

3. PLUGGING MECHANISM OF NOVEL LOSS-PREVENTION MATERIALS

According to the force-chain principle of granular matter mechanics, fracture plugged zone is a typical granular matter system that consists of different types of lost circulation materials (LCM), which is intrinsically multi-scale, micro-scale particles, meso-scale force chains and macro-scale granular matter. In-between the micro-scale particles and macro-scale granular matter, the meso-scale, force chains, acts as the key factor that determines mechanical properties of granular matter systems[22].

Tight pressure-resistance plugging principles indicates that different types of lost circulation materials (LCM), rigid bridging particles, elastic packing particles, softening particles and micro fibers with reasonable size distribution and concentration, could cooperate with each other to form fracture sealing zones with strong force-chain network to strengthen the lost circulation prevention ability of oil-based drilling fluid. Firstly, the coarse rigid particles could plug or bridge the fracture or pore throats to establish coarse-particle framework of fracture sealing zones and the elastic particles could be deformable under fluid pressure or formation pressure to fill the voids between the coarse particles. What’s more, the fiber materials are also necessary to improve the pressure-resistance stability of fracture sealing zones. Along with the formation of fracture tight sealing zones, fluid loss would be reduced to fluid filtration, and then softening particles are incorporated to produce a tight filter-cake to reduce fluid loss. Finally, the fracture tight sealing zones with strong force-chain network could be formed to enhance the formation pressure-resistance ability, thus strengthening the wellbore.

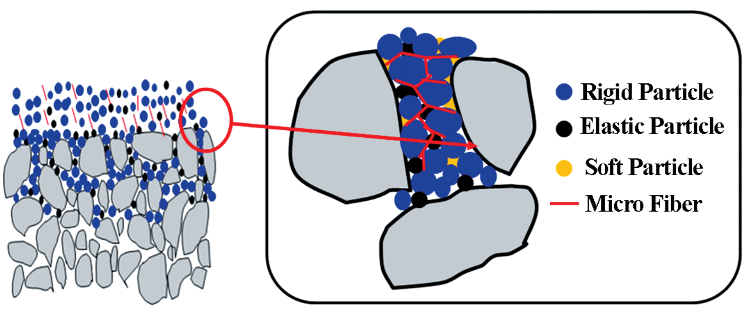


Figure 7
Schematic Diagram of Tight and Pressure-Resistance Plugging Mechanism

CONCLUSION

In order to solve serious lost circulation problems of oil-based drilling fluids, the novel loss-prevention materials for oil-based drilling fluids were successfully developed based on the optimization of rigid bridging particles, elastic packing particles, softening particles and micro fibers. The plugging mechanism of novel loss-prevention materials was also investigated. It is concluded that rigid bridging particles, elastic packing particles, softening particles and micro fibers could cooperate with each other to form fracture tight sealing zones with strong force-chain network to strengthen the lost circulation prevention ability of oil-based drilling fluid. What's more, the novel loss-prevention materials could be compatible with other components of oil-based drilling fluids, and it is alternatives to conventional or standard plugging additives in oil-based drilling fluids.

Nomenclature

AV	Apparent Viscosity
DEA	Drilling Engineering Association
GPRI	Global Petroleum Research Institute
HTHP	High Temperature and High Pressure
LCM	Lost Circulation Material
NLPM	Novel Loss-Prevention Material
OBM	Oil-Based Drilling Fluids
PPT	Permeability Plugging Test
PV	Plastic Viscosity
SEM	Scanning Electron Microscopy
WBM	Water-Based Drilling Fluids
YP	Yield Point

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