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Experimental investigation on size degradation of bridging material in drilling fluids

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A B S T R A C T

Solid particle size distribution (PSD) of drilling fluids is one of the key factors for the formation damage and lost circulation control. However, particle size degradation occurs during the long-term process of drilling fluid circulation in the wellbore, consequently resulting in severe formation damage. In this study, size degradation experiments of calcium carbonate solids in the period of drilling fluid circulation are conducted to understand the effect of initial particle size, rotation speed, shear time, fluid viscosity, temperature, pH, salinity, and solid concentration on size degradation of bridging material (BM). The size degradation rate of D_{90} is taken as the characterization of particle size degradation. The results show that ① the degree of size degradation sharply increases with increasing solid initial size, rotation speed, and shear time. Under the experimental conditions, size degradation rate of sample with $D_{90} = 44.153$ μm is up to 30%~40% at a rotation speed of 1000 rpm over 30 min; ② there is a critical particle size in the range 15–20 μm for size degradation over 90 min. When the particle size drops to this critical size, no size degradation occurs obviously; ③ size degradation decreases with increasing fluid viscosity; ④ fluid temperature, pH, salinity, and solid concentration have little effect on size degradation. The evaluation criterion of size degradation is established, and an empirical model is developed to calculate the size degradation. Two mechanisms of the formation damage induced by size degradation are revealed. Based on the particle size degradation, the strategy for the optimization of PSD and solid supplement is presented. We believe that this strategy will be of great significance to designing the particle size distribution of BM for drilling fluids in the field.

1. Introduction

Formation damage has become a hot topic in the process of oil and gas exploration and development due to the increasing exploring and developing orientation into deep/ultra-deep and unconventional reservoirs [1]. Under the drilling process, formation damage caused by the invasion of drilling fluids severely obstructs the timely discovery, accurate evaluation, and efficient development of oil and gas reservoirs [2,3]. Correspondingly, formation damage prevention/control (FDP/FDC) is an important counter measure in the exploration, drilling, development, and production of reservoirs [1]. It is the key to design the drilling fluid performances reasonably for effectively implementing FDP/FDC technology, including the optimization of particle size distribution (PSD), determination of solid concentration, and design of drilling-fluid rheological properties [4–7]. Among these performances, the design of optimal solid PSD is the one of the key factors to prevent the formation damage caused by the invasion of drilling fluids, which is supposed to match with the fracture width or pore size distribution [8–12]. Kaeuffer [8] first proposed the "Ideal Packing Theory (IPT)" for the optimal lost circulation material (LCM) based on the principle of the maximum particle accumulation efficiency. Subsequently, IPT was further developed and applied in field [10,13–15]. Abrams [4] developed the rule for optimizing the LCM size in drilling fluids, known as the "1/3 Bridging Rule". Based on the "1/3 Bridging Rule", Luo and Luo [16] further advanced the "Shielding Temporary Plugging Technique", referring that the stable bridge in pore throat of reservoirs would be achieved as long as the particle size is equal to 1/2–2/3 of the average pore-throat diameter of reservoirs. Hands et al. [9] introduced the "D_{90} Rule" that the particle size D_{90} should be equal or close to the maximum pore-throat size or fracture width. Cui and Zhang [17] presented the "Temporary Plugging Fractal Theory" by using the self-similarity of pore-throat size distribution and temporary plugging agent size distribution. Kang et al. [18] launched the "Temporary Shielding Loss Technique" for fractured reservoirs. Nevertheless, when these LCM size optimization theories are applied *in situ*, formation damage issues caused by drilling-fluid loss still occur frequently [19].

In recent years, a significant number of studies have demonstrate that particle size degradation would occur during the long-term process of solid particle circulation with drilling fluids in the wellbore [20–27]. Oort et al. [20] first pointed out that the LCM would go through the size degradation in the process of drilling fluid circulation and experimentally

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verified that the size degradation level of calcium carbonate is significantly higher than graphite and fiber materials. Valsecchi [28] briefly summarized the mechanisms of solid particle size degradation during drilling fluid circulation, including the interactions of solids with fluid, solids with solids, and solids with mechanic boundary. In addition, based on the drilling-fluid loss control, extensive studies on the particle size degradation in the granular LCM have been conducted by experimental and simulating methods [29–31]. Especially, drilling the deep/ultra-deep reservoirs with multi-pressure system, long open-hole section, HTHP in downhole, high-salinity formation fluid, *etc.*, which extremely aggravates the circulation conditions and extends the circulation time, leads to the more significant particle size degradation [32]. Once particle size degrades to a certain extent, some serious issues will be caused that the PSD after degradation would deviate from the one designed initially, and the pore throat or fracture would be barely plugged effectively, resulting in the drilling fluid loss, much deeper invasion of filtrate fluid and particles, and ultimately severe formation damage [28].

Although the size degradation phenomenon in drilling fluid circulation has been extensively studied, pointing out that size degradation would lead to the formation damage, few of these studies revealed the mechanisms of size degradation inducing the formation damage. In addition, it is one of the priority issues to prevent the drilling fluid loss by taking the FDP measures. However, because of the size degradation, the classical bridging theories mentioned above could not work well, resulting in the drilling fluid loss frequently. Thus, it is urgent to put forward the optimization strategy for FDP, which allows for the particle size degradation.

In this study, first, size degradation experiments of calcium carbonate solids are carried out by simulating the changes in flow conditions during the drilling fluid circulation. Then, the effect of multi-factor conditions on the size degradation is analyzed, and the evaluation criterion of size degradation is established. After that, an empirical expression between the size degradation rate and external factors is developed based on the experimental results, and the mechanisms of particle size degradation during the period of drilling fluid circulation are summarized briefly. Furthermore, two mechanisms of the formation damage induced by size degradation are revealed. Finally, the particle size optimization and supplementary strategy for drilling fluids considering size degradation are explored, expecting to better guide the field in optimal PSD of drilling fluids for FDP.

2. Material and methods

2.1. Materials

Calcium carbonate is widely used as bridging material (BM) and weight additive in drilling fluids owing to its high hardness, high acid-soluble rate, and high economic benefit to plug the pore throats or fractures for preventing the formation damage caused by the drilling-fluid loss and adjust the drilling-fluid density. Calcium carbonate material with a purity of 98% and different PSDs, hardness of 2.7–3.0, density of 2.6–2.7 g/cm^3, acid-soluble rate of 99.5%, and spherical shape are taken as experimental samples (Fig. 1). Table 1 lists the eigenvalue values of the selected samples.

Table 1
The size eigenvalues of selected samples.

Samples	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	D_{aver}(μm)
$CaCO_3$–1	1.004	7.386	16.435	8.216
$CaCO_3$–2	1.626	12.646	27.765	14.368
$CaCO_3$–3	2.060	17.534	44.153	22.337
$CaCO_3$–4	13.659	85.937	201.431	91.237
$CaCO_3$–5	134.643	287.957	510.447	301.352

2.2. Argument of experimental conditions

Considering the long-term circulation, high temperature in the borehole, and violent change in fluid flow regime in drilling fluid circulation, experimental conditions including initial particle size, rotation speed, shear time, fluid viscosity, temperature, pH, salinity, and solid concentration are simulated to determine their effect on size degradation. Table 2 lists the set conditions for simulating experiments.

(1) Initial particle size (D_{90})

Five calcium carbonate with different initial size is adopted to reveal the effect of particle size on the size degradation. Additionally, under the *in situ* conditions, the static fracture width and the most of the largest pore-throat radius of the reservoirs are generally <50 μm. Thus, the 1/2–2/3 Bridging Rule could be met by using the $CaCO_3$–3 sample with D_{90} = 44.153 μm [16]. In addition, formation fines generally refer to the fine-grained material with particle size <37 μm (or 44 μm), and fine migration is one of the important factors causing formation damage. Therefore, $CaCO_3$–3 sample would be a good choice to be used to analyze the effect of external conditions on size degradation.

(2) Rotation speed (N)

The rotation speed of drill bit and drill string is relatively low, mainly in hundreds of revolutions per minute (rpm) during the circulation of drilling fluids in the borehole. Besides, the flow conditions are extremely complex, when the drilling fluids are pressurized, leading to the sharp turn in flow direction. Thus, the rotation speed definitely has a great effect on size degradation. For this reason, experimental rotation speed is set to 600, 800, 1000, 1200, and 1400 rpm. Considering the effect of other experimental conditions on size degradation, the rotation speed is set to 1000 rpm.

(3) Shear time (t)

Generally, the circulation period of drilling fluids is estimated conservatively to be >120 min. Considering the process of first one cycle of drilling fluids, experimental shear time is set to 30, 60, 90, 120, and 150 min. Moreover, drilling fluids will generally reach the midpoint between the wellhead and pay zone after 30 min circulation. Before the drilling fluids reach the pay zone, size degradation should be taken into account to determine whether it is necessary to supplement BM in time. Based on this and considering the effect of other experimental conditions on size degradation, shear time is set to 30 min.

Fig. 1. Calcium carbonate material with various size ranges ((a) $CaCO_3$-1; (b) $CaCO_3$-2; (c) $CaCO_3$-3; (d) $CaCO_3$-4 (e) $CaCO_3$-5).