Experimental Analysis of How the Form of Biodegradable Resin Drilling Fluid Additives Affects Filtration Properties and Lost Circulation Prevention Performance

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Keywords

Drilling mud, fluid loss, lost circulation materials, filtration properties, filter cake

ABSTRACT

In well drilling, mud circulating in the wellbore can cause 'Lost Circulation', a phenomenon in which mud is lost into permeable formations. One of the measures against lost circulation is the use of lost circulation materials, but few studies have investigated the use of biodegradable resins as lost circulation materials. The use of biodegradable resins is expected to reduce the environmental impact of well drilling. This study aims to evaluate how the addition of different forms of biodegradable PHBH (Poly(3-Hydroxybutyrate-co-3-Hydroxyhexanoate)) resin as lost circulation materials to drilling mud affects mud filtration properties and lost circulation performance in high-temperature wells. Static filtration tests and pore plugging tests were conducted to evaluate filtration and fluid-loss properties of mud containing PHBH. The tests were carried out to compare the properties of drilling muds containing PHBH in the form of powder, fiber, and pellets. To compare and evaluate filtration properties of a base mud and mud samples containing PHBH, the filtrate volume and the thickness of the formed filter cake were measured using a low temperature and low pressure (LPLT) filter press for shallow wells and a high temperature and high pressure (HPHT) filter press for deeper wells. The results show that the filter cake thickness and filtrate volume were reduced by adding PHBH in different forms to the base mud under both LPLT and HPHT conditions. The addition of PHBH in powder form reduced the filtrate volume and filter cake thickness the most. When using PHBH in powder form, mud with 3.0 wt% PHBH reduced the filtrate volume by up to 31% and the filter cake thickness by 41% compared to the base mud under HPHT conditions. Scanning electron microscope (SEM) observations showed that the diameters of the powder particles varied between about 2 to 40 μm. This particle size distribution is assumed to have contributed to the favorable fluid loss prevention and greater pore-plugging capacity of the powder-based PHBH mud.

1. Introduction

During wellbore drilling, drilling fluid (mud) is circulated to remove rock cuttings generated by the cutting and crushing action of the drill bit that results in fracturing and breaking up of the rock formations being excavated. However, mud circulating in the wellbore can be lost to permeable formations and fractures. Lost circulation often occurs in oil wells in limestone formations, and in geothermal wells drilling fluids are commonly lost to fractured volcanic formations (Okino, 1981).

In addition, lost circulation occurs during drilling in approximately 20-25% of wells drilled worldwide (Economides et al., 1998). According to the U.S. Department of Energy, an average of 10% to 20% of the drilling costs of high-temperature, high-pressure (HTHP) wells were spent on controlling mud loss (Growcock, 2010). Lost circulation can trigger formation collapse, stuck pipe or formation fluid blowout, so early detection and prevention of mud loss is essential. Therefore, it is necessary to detect and prevent the spread of such phenomena in the early stages. One of the measures that have been regularly applied in practice is the use of lost circulation materials (LCMs). Lost circulation materials (LCMs) are used to block the lost circulation layer, and in the past, sawdust, straw, lump clay, brick chips, beans, wood shavings, and rubber shavings have been used. Currently, various mud companies have developed various mud prevention agents, which can be broadly classified into fibrous, granular, and flake types. However, none of them is a definitive choice, and the development of better mud prevention agents is worth considering.

In the present study, a biodegradable resin called PHBH (poly-3-hydroxybutyrate-3-hydroxyhexanoate) was investigated as a mud prevention agent. PHBH decomposes in compost and soil as well as in seawater by the action of microorganisms. Therefore, it might have a low environmental impact when used in the underground environment of geothermal and oil wells. PHBH can also be manufactured in different forms, such as powder, pellets, or fibers. Therefore, a variety of different forms of PHBH can be considered to design an effective drilling fluid. Here we considered PHBH drilling fluid additives in the form of powder, pellets, and fibers.

2. Materials Used

A reference base mud was prepared by adding a thickener and sepiolite to water. Polyanionic cellulose (PAC-HG) was used as a thickener and sepiolite was used as a basic clay mineral in the drilling mud. To test the performance of PHBH additives as lost circulation materials, PHBH-based mud samples were made by adding PHBH of different shapes (fiber, powder or pellets) to the base mud. PHBH is a 100% biomass-derived polymer made by specific microorganisms that are primarily fed vegetable oil. PHBH is a thermoplastic and can be molded and processed in the same way as petroleum-derived thermoplastics (Fukuda, 2020).

The forms of PHBH used in this experiment were fibrous, powder and pellet forms. The fibrous form has a fiber length of 14 mm and a fiber diameter of 20-30 μm, the powder diameter distribution is not known, and the pellet form has a diameter of 2.3-2.5 mm and a height of 3 mm (Figure 1). The general properties of PHBH and PAC-HG are shown in Tables 1 and 2.

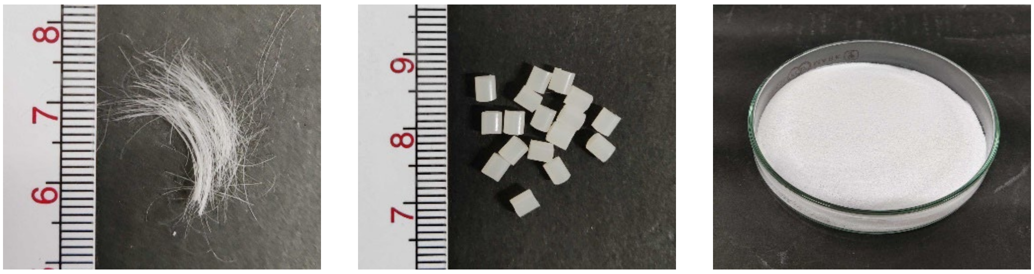

Figure 1: Shape of PHBH specimen. From left to right: fiber, pellets, powder.

Table 1: Properties of PHBH.

PHBH (Fiber, Pellets, Powder)	Specific Gravity (SG)	Melting Point (℃)	Glass-Transition Temperature (℃)
	1.20	145	2

Table 2: Properties of the applied PAC-HG fluid thickener.

PAC-HG	Appearance	Purity	pH	Moisture
	White powder	99% or higher	6.5-8.0	10% or less

3. Mud Rheology Test

3.1 Experimental Procedure: Mud Rheology

In this experiment, polyanionic cellulose (PAC-HG) and sepiolite dissolved in water were used for the base mud. The concentration of each mud additive was 1.5 wt% for sepiolite and 0.4 wt% for PAC-HG. The PHBH mud samples were prepared by adding PHBH of different forms to the base mud, including PHBH powder, fiber, and pellets. The tested concentrations for the powder and pellets were 1.5 wt% and 3.0 wt%. However, the considered fiber concentrations were 0.05 wt% and 0.1 wt% (Table 3). Higher fiber concentrations were not considered since it resulted in the fibers clumping together in the mixed mud. A Hamilton Beach mixer, commonly used as a test mud mixer, was used for the sample preparation.

Table 3: Considered PHBH mud combinations for PHBH powder, fiber, and pellets.

Sepiolite concentration (wt%)		1.5
PAC concentration (wt%)		0.4
PHBH concentration (wt%)	Powder	1.5, 3.0
	Fiber	0.05, 0.1
	Pellets	1.5, 3.0

Viscosity measurements of the base mud and the PHBH mud under ambient and elevated temperature conditions were performed to evaluate their rheological properties. For the viscosity measurements, a VG Meter Model 35 double-cylinder rotational viscometer manufactured by Fann Instrument Company was used, as recommended by API (American

Petroleum Institute) standards. High-temperature conditions were tested at 200°F (93°C), which is the temperature limit of the VG meter. The Model 35 viscometer has 6 speeds (3, 6, 100, 200, 300, and 600 rpm). Samples were put in a sample cup, and the VG meter dial value was read when the sample viscosity resistance and spring torque were balanced at each shear rate.

3.2 Experimental Results and Discussion: Mud Rheology

Figures 2 through 4 show the relationship between the fluid shear rate and shear stress, and the shear rate and viscosity when PHBH fiber, pellets, and powder forms were added to the base mud. From Figures 2 to 4, it can be seen that adding PHBH to the base mud had little effect on the rheological properties of the mud. This was found for both room temperature and high temperature conditions.

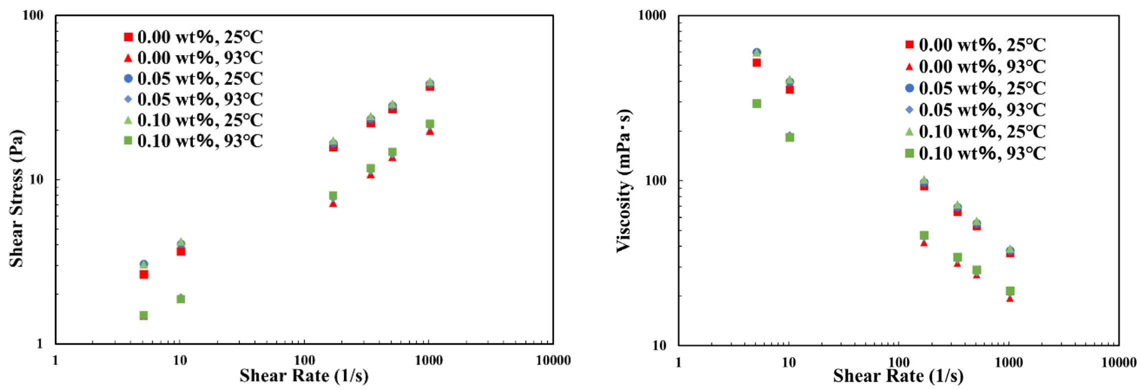

Figure 2: Relationship between shear rate and shear stress/viscosity with PHBH fiber addition.

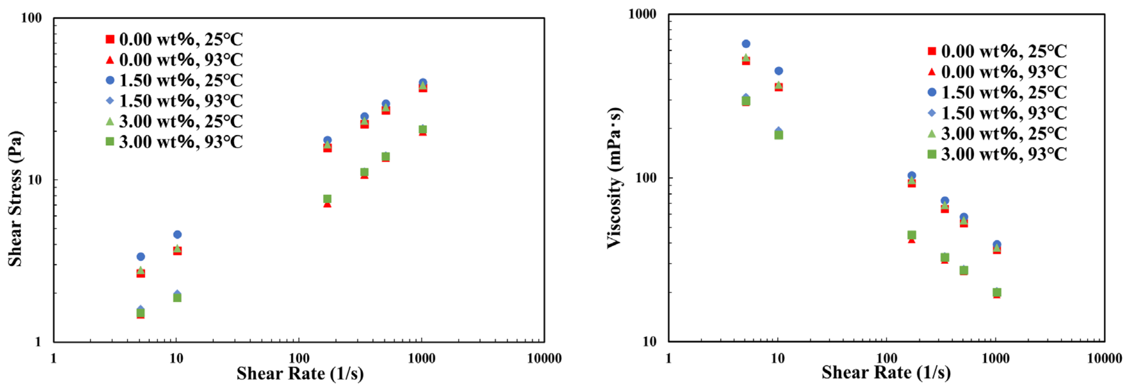

Figure 3: Relationship between shear rate and shear stress/viscosity with PHBH pellet addition.

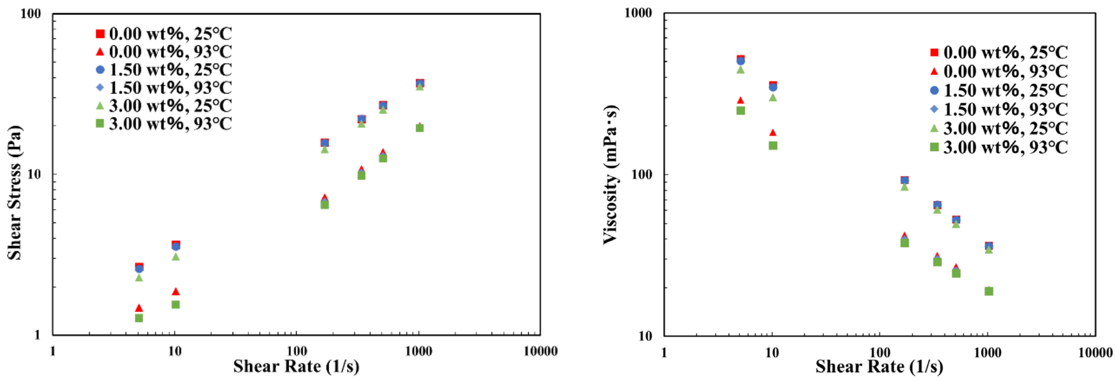

Figure 4: Relationship between shear rate and shear stress/viscosity with PHBH powder addition.

4. LPLT/HPHT Filtration Testing

4.1 Experimental Procedure: Filtration Test

The evaluation of filtration properties is done through the measurement of filtrate volume and filter cake thickness using a filter press according to API (American Petroleum Institute) standards. In this study, filtration tests were conducted under low temperature and low pressure (LPLT) conditions and high temperature and high pressure (HPHT) conditions. Under LTLP conditions, the tests were conducted at room temperature and a pressure of 100 psi; under HTHP conditions, the temperature was 200°F and the pressure was 500 psi. The temperature limit of the VG meter is 200°F. The preparation method for the samples used in the LPLT and HPHT tests was the same as that of the rheological tests. The conditions of the LPLT/HPHT filtration tests according to API standards are shown in Tables 4 and 5 below.

Table 4: API standard for LPLT filtration test.

Pressure	100 psi (690 kPa)
Time	30 minutes
Inside diameter of cell	3 in (7.62 cm)
Height of cell	2.5 in (6.4 cm)
Filtration area	7.1 in² (45.8 cm²)
Filter paper	Whatman No.50
Wire mesh under filter paper	60～80 mesh

Table 5: API standard for HPHT filtration test.

Preparation	Stir for 10 minutes
Pressure	500 psi (3.447 MPa)
Preheating	Less than 1 hour
Time	30 minutes
Filtration area	3.5 in² (22.6 cm²)
Filter paper	Whatman No.50
Wire mesh under filter paper	60～80 mesh

4.2 Experimental Results and Discussion: Filtration Test

Figures 5 and 6 show the changes in total filtrate volume and thickness of filter cake when PHBH of different shapes (powder, pellets, and fiber) were added to the base mud with a PAC concentration of 0.4 wt% and a sepiolite concentration of 1.5 wt% under LTLP/HTHP conditions.

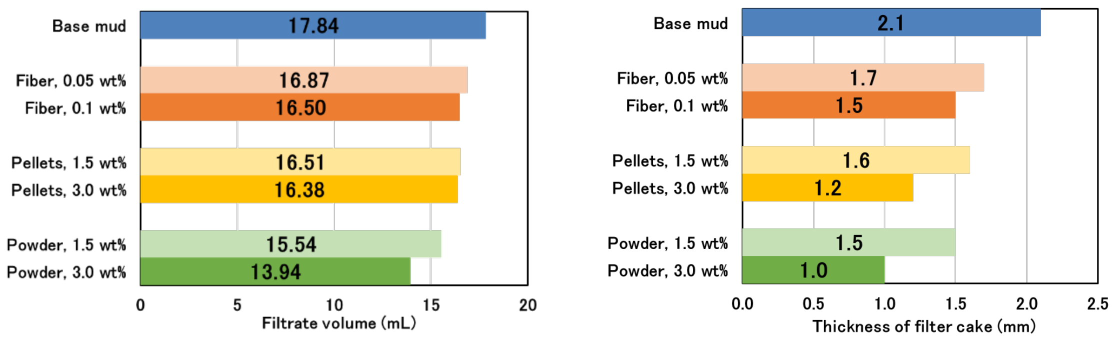

Figure 5: Comparison of filtration properties under LTLP conditions.

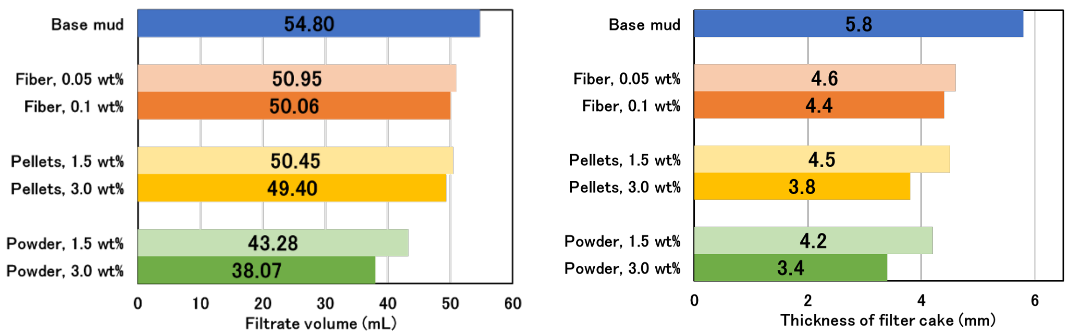

Figure 6: Comparison of filtration properties under HTHP conditions.

Under both LTLP and HPHT conditions, the addition of PHBH, in any form, decreased the filtrate volume and reduced the filter cake thickness. From Figure 5, PHBH mud with the addition of 3.0 wt% PHBH powder reduced the filtrate volume by up to 22% and the filter cake thickness by 52% compared to the base mud. From Figure 6, PHBH mud with the addition of 3.0 wt% PHBH powder reduced the filtrate volume by up to 31% and the filter cake thickness by 41% compared to the base mud. In both LTLP and HPHT conditions, the filtrate volume was the lowest when the powder form PHBH was added, which can be inferred to have quickly closed the pore spaces of the filter paper, and thus had the greatest plugging effect. From the above, it can be concluded that the powder form results in the best filtration properties.

5. Pore Plugging Test

5.1 Experimental Procedure: Pore Plugging

In the filtration test, the powder form that had the best filtration properties was compared to the base mud to evaluate lost circulation prevention performance. The filtration test was conducted by replacing the filter paper in the HTHP filtration tester with a ceramic disc with a nominal pore size of 20 μm that simulates a lost circulation zone. Afterwards, the lost circulation prevention performance was evaluated by analyzing the cross section of the formed filter cake by scanning electron microscopy (SEM). The test conditions are shown in Table 6.

Table 6: The conditions used in the HPHT filtration test.

Preparation	Stir for 10 minutes
Pressure	300 psi (2.0685 MPa)
Preheating	Less than 1 hour
Time	30 minutes
Filtration area	3.5 in² (22.6 cm²)
Filter paper	Fann ceramic disk
Pore diameter	20 μm

5.2 Experimental Results and Discussion: Pore Plugging

The results of the HPHT filtration test simulating a lost circulation zone are shown in Table 7 below. From Table 7, PHBH mud with the addition of 3.0 wt% PHBH powder reduced the filtrate volume by up to 20% and the filter cake thickness by 2.8% compared to the base mud. SEM images of a cross section of the mud wall after the test are shown in Figures 7 and 8.8

Table 7: Results of the HPHT filtration test.

	Filtrate volume	Thickness of filter cake
Base mud	94.96 ml	7.0 mm
Powder, 3.0 wt%	75.80 ml	6.8 mm

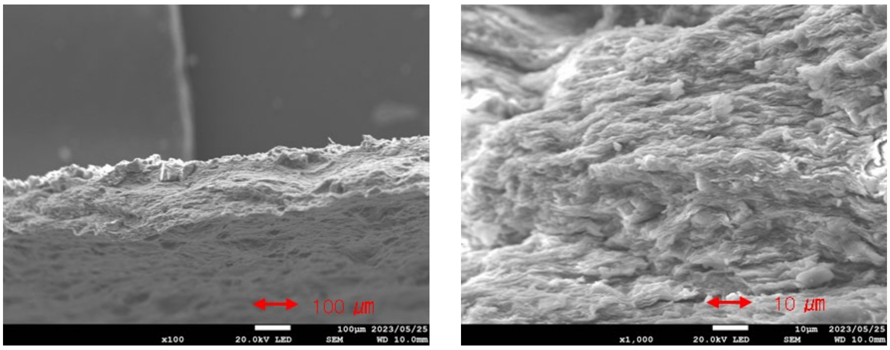

Figure 7: SEM image of a filter cake cross-section formed by the base mud (100× enlargement on the left, and 1,000× enlargement on the right).

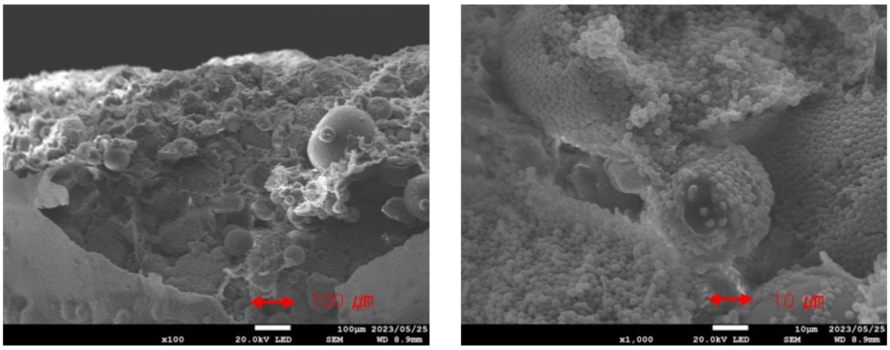

Figure 8: SEM image of mud wall formed when 3.0 wt% powder was added to the base mud (100× enlargement on the left, and 1,000× enlargement on the right).

The results of the SEM images suggest that single and agglomerated particles of about 2 µm in size improve lost circulation prevention performance by plugging the pore in the filter cake. Next, the shape and composition of the sepiolite and PHBH particles were examined by SEM and EDS (energy dispersive X-ray spectroscopy), respectively (Figures 9–12).

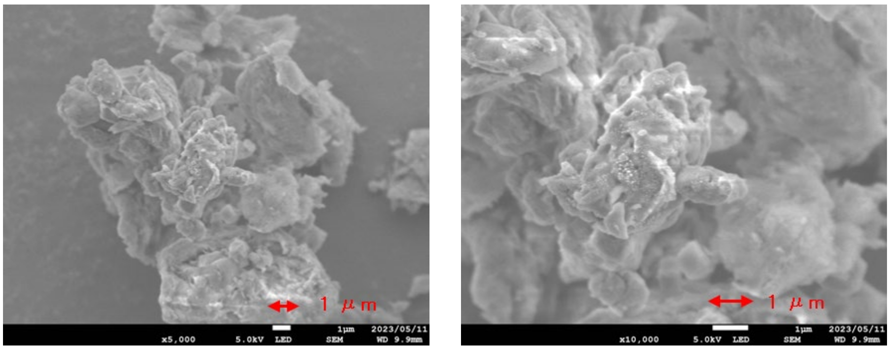

Figure 9: SEM image of sepiolite particles (5,000× enlargement on the left, and 10,000× enlargement on the right).

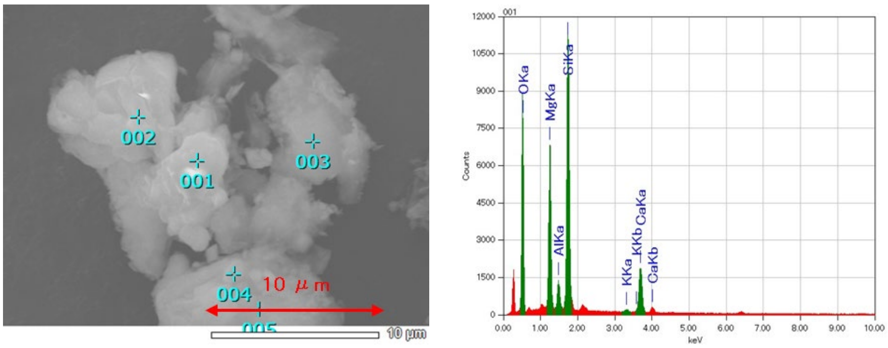

Figure 10: Elemental analysis of sepiolite particles (Spectrum 1) (SEM image on the left, and elemental analysis results on the right).

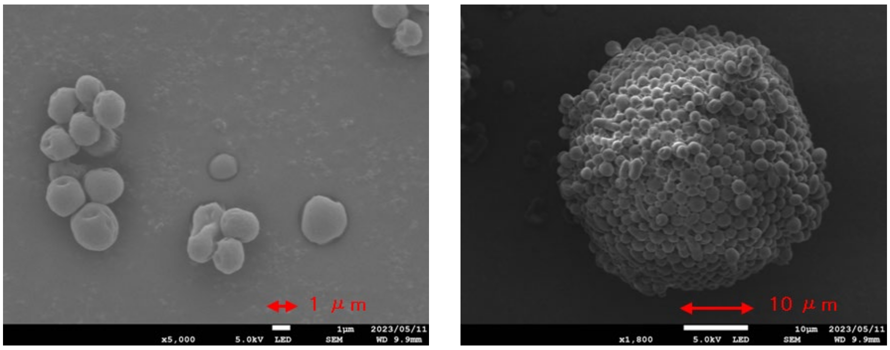

Figure 11: SEM image of PHBH powder particles (5,000× enlargement on the left, and 1,800× enlargement on the right).

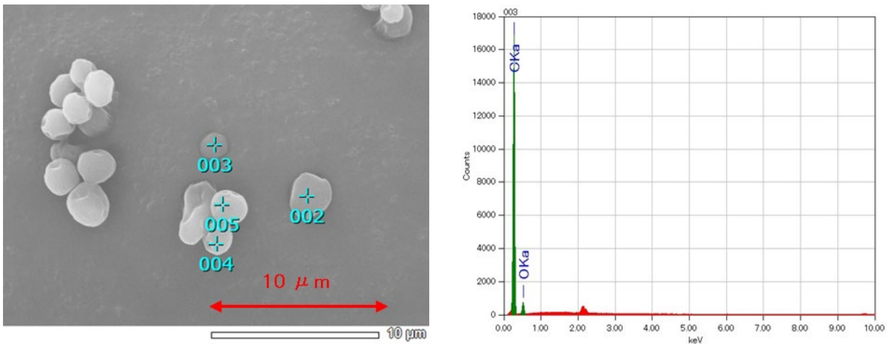

Figure 12: Elemental analysis of PHBH powder particles (Spectrum 3) (SEM image on the left, and elemental analysis results on the right).

From Figures 9 to 12, needle-like crystals of sepiolite, and single (2 µm) and aggregated (40 µm) particles of PHBH were observed in the shape. Figures 10 and 12 confirm that the particles could be identified as sepiolite, which is mainly composed of silica, and PHBH, which is mainly composed of carbon. Figures 13 and 14 show the results of elemental analysis of the filter cake when 3.0 wt% of PHBH powder was added to the base mud.

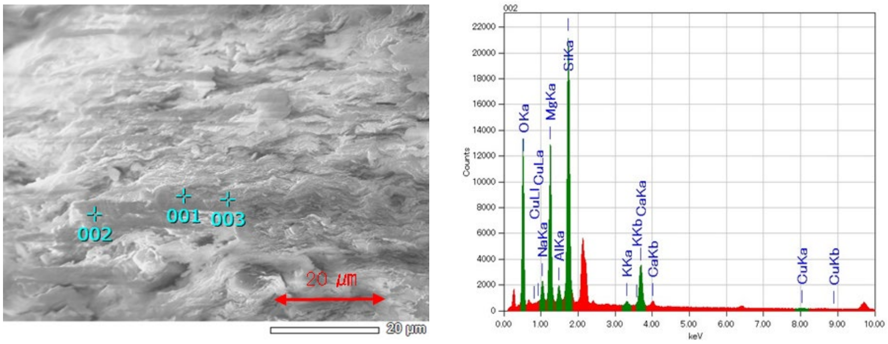

Figure 13: Elemental analysis of a filter cake cross-section formed by the base mud (Spectrum 2) (SEM image on the left, and elemental analysis results on the right).

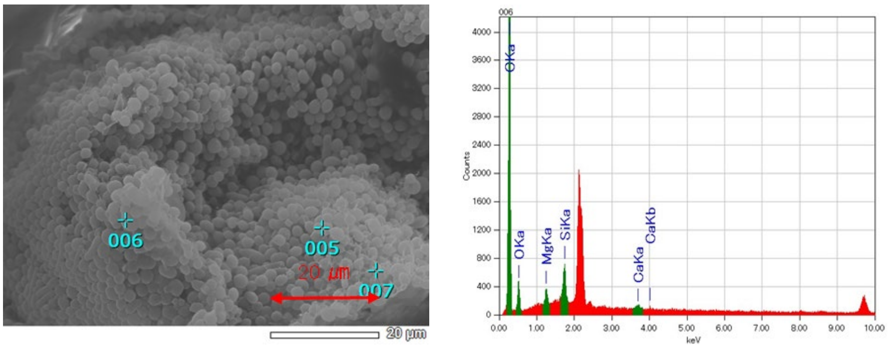

Figure 14: Elemental analysis of a filter cake cross-section formed when 3.0 wt% of PBHB powder was added to the base mud (Spectrum 6) (SEM image on the left, and elemental analysis results on the right).

Figure 13 show that the filter cake formed by the base mud is mainly composed of silica, which is consistent with the sepiolite in the base mud. On the other hand, the mud wall created by adding PHBH powder to the mud fluid shows 2 μm particles mainly composed of carbon, suggesting that the observed particles were PHBH.

Figure 15 shows a cross-section of the ceramic disk after the filtration tests. From Figure 15, it was observed that the PHBH powder was distributed within the pore space of the ceramic disk. This suggests that the addition of PHBH powder plugged the pore space and prevented lost circulation.

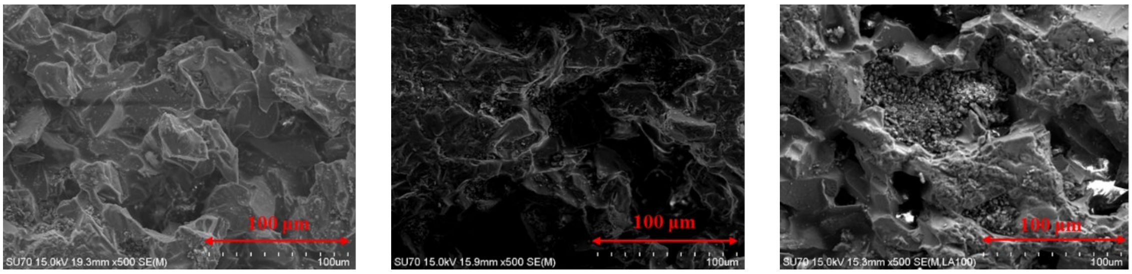

Figure 15: SEM images of ceramic disk. From left to right: ceramic disk only, after the base mud filtration test, and after the 3.0 wt% PHBH powder filtration test.

6. Conclusions

The test results show that addition of PHBH to a base drilling fluid did not significantly affect the rheological properties of the fluid, independent of the shape/form of the PHBH material. Notably, the filter cake thickness and filtrate volume decreased with the addition of PHBH under both LPLT (low temperature and low pressure) and HPHT (high temperature and high pressure) test conditions. This applied to all shapes/forms of PHBH considered. The addition of PHBH, therefore, improves fluid filtration properties. Moreover, PHBH powder gave the best filtration performance.

In the LPLT filtration testing, PHBH mud with the addition of 3.0 wt% PHBH powder reduced the filtrate volume by up to 22% and the filter cake thickness by 52% compared to the base mud. In the HPHT filtration testing, PHBH mud with the addition of 3.0 wt% PHBH powder reduced the filtrate volume by up to 31% and the filter cake thickness by 41% compared to the base mud. The experimental findings suggest that the improved lost circulation prevention performance of PHBH powder results from single particles and agglomerated particles with diameters of around 2 μm that plug the pores of the filter cake and lost circulation zone.

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