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A Novel Preparation Process for Magnetorheological Fluid with High Working Temperature

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We report the preparation of a magnetorheological fluid with a high working temperature by using fluorocarbon surfactant and titanate coupling agent as additives at appropriate contents determined by a series of experiments. The sedimentation ratio, apparent viscosity, and yield stress are measured to evaluate the performance of the prepared magnetorheological fluid. Results indicate that AES dispersants, titanate coupling agents, and fluorocarbon surfactants all have improved dispersion properties, and that the compounding fluorocarbon surfactants and titanate coupling agent can further improve the settlement stability of magnetorheological fluid, with < 7 % one-week settlement rate. Diatomite has a good thixotropic effect, and the antisettling effect enhanced with increased content. The types of carrier fluid have no significant effect on the performance of MR fluids. The prepared MR fluid can also work at 180 °C, which is higher than most commercial fluids, and the shear yield stress can reach 50 kPa.

Keywords : preparation, process, magnetorheology, temperature, additives, particle, settlement, transmission

1. Introduction

Magnetorheological (MR) fluid is a new type of smart material formed with micro-sized soft magnetic particles dispersed evenly in the carrier fluid and has three main components, namely, particles, carrier fluids, and additives [1-4]. This particle suspension has unique MR effect, that is, when external magnetic field is not present, the MR fluid is in a free-flow state. The application of an external magnetic field causes a viscoplastic fluid behavior with certain shear force. Given its unique rheology characteristic, MR fluid is widely employed in various applications, such as damping and vibration control, power transmission, and polishing [5-10].

At present, most of the MR fluids are used in dampers and shock absorbers, and the main performance indicators concerned are the settlement stability and apparent viscosity. For the transmission occasion, the working temperature range is also an important performance factor due to more serious heating in the working state. However, the maximum working temperature of existing commercial MR fluids is usually smaller than 130 °C [11-13], which limits the slip power and application of the transmission device. Therefore, developing the preparation technology for high-performance MR fluid with higher temperature range and better settlement stability is necessary. Kormann *et al.* [14] developed a MR fluid with nanoparticles with excellent thermal stability. Weiss and Wu *et al.* [15, 16] studied the influence rule of temperature on the yield stress of MR fluid. Yildirim *et al.* [17] investigated the heat transfer performance of MR fluids.

The working temperature of common particles and carrier fluid can reach more than 200 °C; thus, the performance of the surface additive plays a decisive role in the MR fluid use temperature. In this paper, we improved the working temperature range of MR fluid by first selecting each component material and analyzing its basic characteristics. Then, the effects of various additive types and contents, thixotropic agent types and contents, and carrier fluids types on the settlement stability and apparent viscosity of MR fluids were studied. Finally, the MR fluid with high working temperature was prepared by using suitable surfactants, and the properties of the prepared MR fluid were also evaluated.

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2. Materials and Methods

2.1. Materials

2.1.1. Particle

Particle is an important component and plays a decisive role in the performance of MR fluids, such as in shear yield stress. As the saturation magnetization is higher (about 2.15 T), the preparation cost is lower, and the Curie point (above 400 °C) is higher, carbonyl iron powder (CIP) is used as the suspension phase. Fig. 1 shows the scanning electron microscope (SEM) photo of the CIP. The powders have a regular spherical structure; the particle size distribution is homogeneous; and the average particle diameter is 3 μm.

2.1.2. Carrier fluid

The common carrier fluid is mineral oil or synthetic oil. We chose several carrier fluids that have higher working temperature range, including mineral oil 32, mineral oil 8, silicone oil 100, fluorine oil 150, fluorine oil 310, and chain oil 300. The viscosity-temperature characteristic was also measured to obtain a high-performance carrier fluid, as shown in Fig. 2. It shows that silicone oil has excellent viscosity temperature characteristics, and its viscosity index reaches 598, which is significantly higher than other high-temperature oils. Besides, silicone oil, fluorine oil, and high temperature chain oil can meet high-temperature requirements above 200 °C.

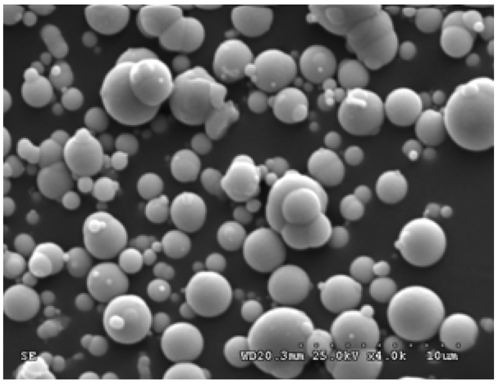


Fig. 1. SEM image of CIP.

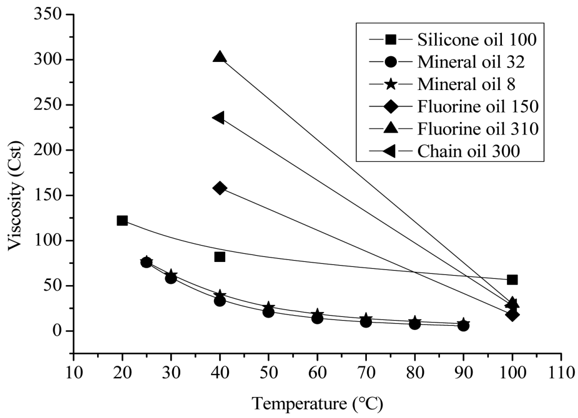


Fig. 2. Viscosity properties of different carrier fluids.

2.1.3. Additives

Selecting appropriate additives, including surfactants, coupling agents, and thixotropic agents is the key to the preparation of MR fluid, especially for the transmission occasion, which is usually used at a temperature higher than 150 °C. Surface additives are sensitive to temperature, and some additives are liable to decompose at high temperature. Some additives tend to be thickened and lose fluidity at high and low temperature cycles. Therefore, considering the temperature characteristics when choosing the additives are more necessary. After screening, several high-temperature additives are selected to carry out the experiments. The selected surfactants are oleic acid, fluorocarbon surfactant, AES dispersant, and sodium dodecyl benzene sulfonate (SDBS). The selected coupling agents are silane coupling agent and carbonate coupling agent, and the selected thixotropic agents are diatomite, organic bentonite, and kaolin.

2.2. MR fluid preparation

The key factor in the MR fluid preparation process is how to evenly coat the additives on the particle surface. The two main methods of preparation are direct addition method and base liquid replacement method. Among them, the basic liquid replacement method is the most widely used to prepare MR fluid. The process is as follows: (a) the CIP and the surfactants or coupling agents are placed into a solution of absolute alcohol, and the mixture is stirred strongly for sufficient adsorption of additives on the surface of particles; (b) the mixture is dried in a vacuum drying oven at 80 °C, and then, surfactant-treated iron particles are ground and mesh-sieved to prevent agglomeration; (c) The treated powders are added into the carrier fluid, and the mixture is stirred vigorously.

2.3. The evaluation of the MR fluid properties

The simplest and most convenient method to test the settlement stability of MR fluid is the static method, and the sedimentation performance can be directly reflected by recording the height of carrier-fluid-rich phase. As shown in Fig. 3, MR fluid is poured into the cylinder in a volume b every 24 h to record the upper carrier fluid height a, and the MR fluid sedimentation ratio can be expressed by a/b × 100 %.

The apparent viscosity of MR fluid is measured using

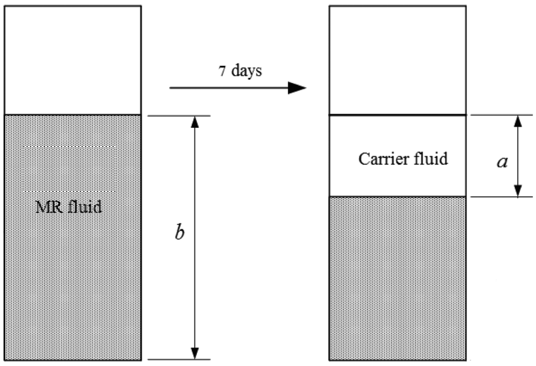


Fig. 3. Sedimentation ratio testing.

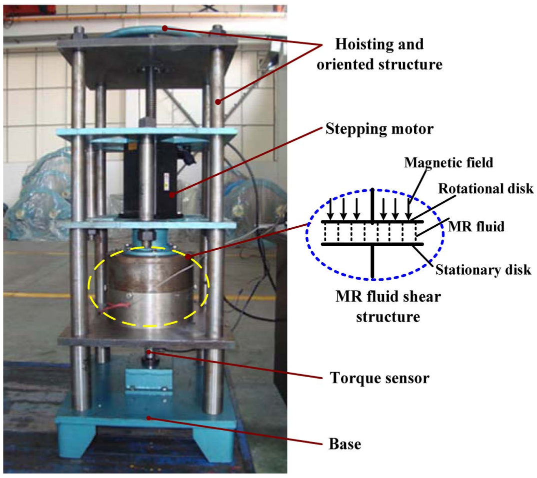


Fig. 4. (Color online) Yield stress measurement device of MR fluids.

the SV-10 vibration viscometer. The measurement accuracy error is smaller than 1 %, and the measurement range is 0.3 mPa.s to 10000 mPa.s.

A disk-type measurement system is established to carry out the shear yield stress test on the MR fluid, as shown in Fig. 4. This system is mainly composed of the hoisting and oriented structure, stepping motor, MR fluid shear structure, torque sensor, and base. MR fluid is filled between rotational disk and stationary disk, and the rotational disk is driven by the stepping motor. The transmittable torque T of the MR fluid shear structure can be obtained using the torque sensor, and the corresponding yield stress can be expressed as follows[18]:

$$\tau_0 = \frac{3T}{2\pi R^3}$$

Where R is the radius of transmission disk, and τ_0 is the magnetic-dependent shear yield stress.

3. Results and Discussions

3.1. Types and contents of components

3.1.1. Thixotropic agent type

The main function of the thixotropic agent is to form a three-dimensional thixotropic network in the carrier fluid. To shorten the experimental time, only MR fluids with particle mass fraction of 20 wt.% are prepared, and the thixotropic efficiency of several thixotropic agents is analyzed through chemical amplification method. The sedimentation ratio curves are obtained, as shown in Fig. 5. The mass fraction of the thixotropic agent is 2 wt.%, and the carrier liquid is silicone oil.

As can be seen from Fig. 5, the MR fluid containing diatomite has the lowest settlement rate among the three kinds of thixotropic agents, indicating that the diatomite has better thixotropic effect due to its highest silica content and more silicon hydroxyl groups on the surface of silicon dioxide. The silicon hydroxyl group can cascade small silica particles to form a network structure by hydrogen bonding, which has strong thixotropy and improves the stability of the MR fluid. Although kaolin and organic bentonite also contain silica, they also contain a certain amount of alumina and magnesium oxide, which have thixotropies lower than that of silica.

3.1.2. Types and contents of additives

Several high-temperature surface additives, including oleic acid, three different kinds of fluorocarbon surfactants (FC51, FC64 and FC3100), AES dispersant, SDBS, silane coupling agent, and titanate coupling agent are screened. A variety of MR fluids are prepared by the carrier liquid replacement method, and the sedimentation ratio and apparent viscosity are also tested, as shown in Fig. 6. The

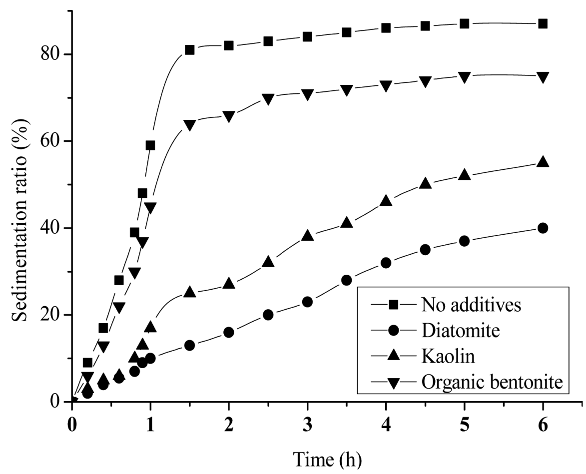


Fig. 5. Thixotropic effects of different thixotropic agents.

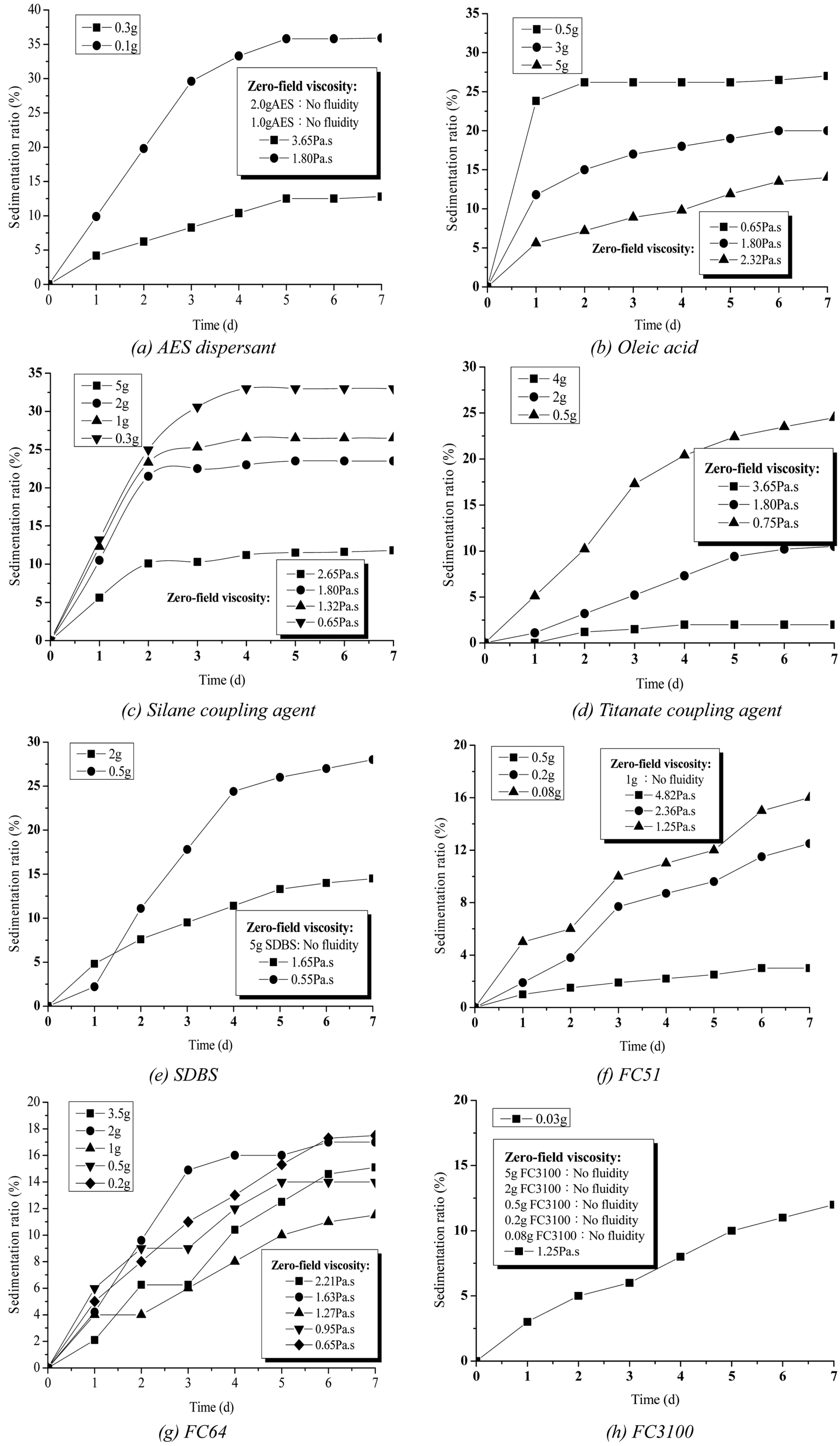


Fig. 6. Experiments on different types and contents of surface additives.

contents of each component are as follows: 76 wt.% CIP, diatomite as thixotropic agent, 2 wt.% content, silicon oil as carrier fluid, and 22 wt.% content. The actual content changes slightly with the content of the surface additives, and each MR fluid sample prepared in the experiment is 100 g.

As can be seen from Fig. 6:

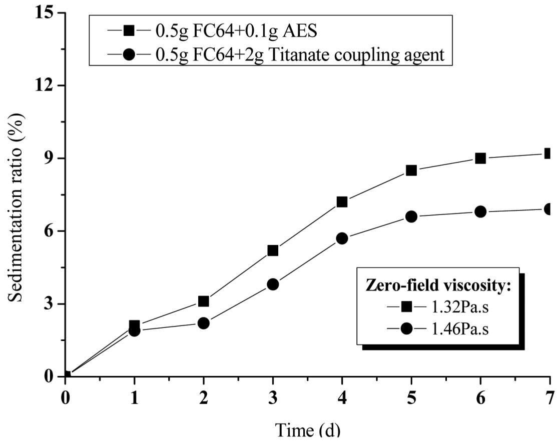
(a) On the whole, the type and content of the surface additives have significant influence on the settling stability and apparent viscosity of the MR fluid. With increased content, the stability of the settlement increases, but the apparent viscosity increases and even loses the fluidity. The effects of different types of surface additives are different. For example, when the content of oleic acid is up to 5.0 g, the MR fluid will have better anti-settling performance, whereas the content of fluorocarbon 3100 needs only 0.03 g.

(b) In a week, the depositions of MR fluids with non-fluorocarbon surface additives are basically stable, with MR fluids with one week sedimentation ratio of less than 15 % and better fluidity of 0.3 g of AES dispersant (sedimentation ratio 12.8 %, apparent viscosity 1.8 Pa.s), 5.0 g of oleic acid (sedimentation ratio 14 %, apparent viscosity 2.32 Pa.s), 5.0 g of silane coupling agent (sedimentation ratio 11.8 %, apparent viscosity 2.65 Pa.s), 2.0 g of titanate coupling agent (sedimentation ratio 10.5 %, apparent viscosity 1.8 Pa.s), and 2.0 g of SDBS (sedimentation ratio 14.5 %, apparent viscosity 1.65 Pa.s). Among the above non-fluorocarbon surfactants with 0.3 g of AES dispersant, 2.0 g of titanate coupling agent shows the best comprehensive performance.

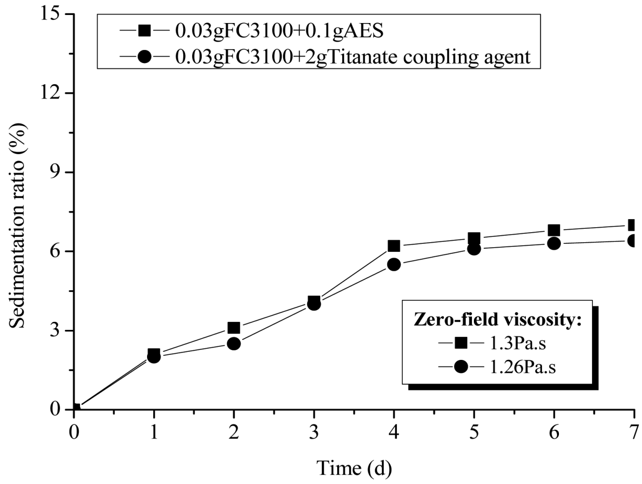
(c) With fluorocarbon surfactants, the MR fluids with one-week sedimentation ratio of less than 15 % and better fluidity are 0.08 g of FC51 (sedimentation ratio 14 %, apparent viscosity 1.25 Pa.s), 0.03 g of FC3100 (sedimentation ratio 10%, apparent viscosity 1.25 Pa.s), and 1.0 g of FC64 (sedimentation ratio 12 %, apparent viscosity 1.27 Pa.s). FC3100 and FC64 have higher comprehensive performance, and only a very small amount of fluorocarbon surfactant can provide better antisettling effect. The dosages of the three fluorocarbon surfactants selected have differences due to their different storage conditions and effective activity content. For example, the active ingredient content of FC3100 is about seven times that of FC64.

3.1.3. Effect of surface additive compounding

With the above surfactants, the one-week settlement rates of MR fluids with better fluidity are all higher than 10 %. To further improve the settling stability, FC64 and FC3100 fluorocarbon surfactants are separately compounded with AES dispersant and titanate coupling agent, and their sedimentation ratio and apparent viscosity are also tested, as shown in Fig. 7.



(a) FC64 compounding



(b) FC3100 compounding

Fig. 7. Experiments on surface additives compounding.

As can be seen from Fig. 7, the anti-sedimentation effect of the MR fluid with the fluorocarbon surfactants compounding is significant, and the effect of fluorocarbon surfactant compounded with titanate coupling agent is better than that of AES dispersant. FC64 and FC3100 are separately compounded with titanate coupling agent, and the one-week settlement rate of MR fluid is 6.9 % and 6.2 %, respectively, and both of the two kinds of MR fluids have better fluidity.

3.1.4. Thixotropic agent content

The thixotropic agent content changed to 1.0 g, 2.0 g, and 3.0 g, respectively. The surface additives are FC64 surfactant and titanate coupling agent; three kinds of MR fluids are prepared; and the sedimentation ratio and apparent viscosity are shown in Fig. 8.

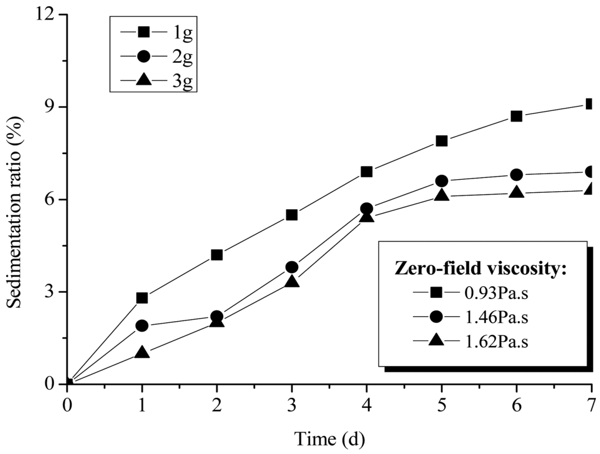


Fig. 8. Content of thixotropic agent.

As can be seen from Fig. 8, the thixotropic agent content has a significant influence on the particle settlement rate. Higher content results to denser thixotropic mesh forms and better antisettling performance. At the same time, the apparent viscosity increases. In actual use, under the fluidity premise of the MR fluid, the content of the thixotropic agent can be increased to improve the antisettling effect.

3.1.5. Carrier fluid type

In this paper, silicone oil, high-temperature chain oil, and fluorine oil are selected as the carrier fluids, and the settlement stability of three kinds of carrier fluids is also studied, as shown in Fig. 9. In this experiment, the surface additives are still FC64 surfactant and titanate coupling agent.

As can be seen from Fig. 9, the three kinds of carrier fluids have no significant effect on the settlement stability of MR fluids, and the fluidity of MR fluid with fluorinated oil is relatively poor due to its higher density. Therefore, considering the economy and viscosity characteristics, we still select silicone oil as the carrier fluid.

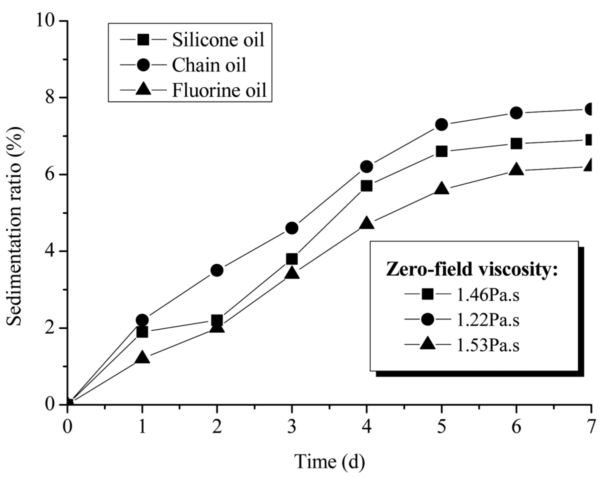


Fig. 9. Types of carrier fluids.

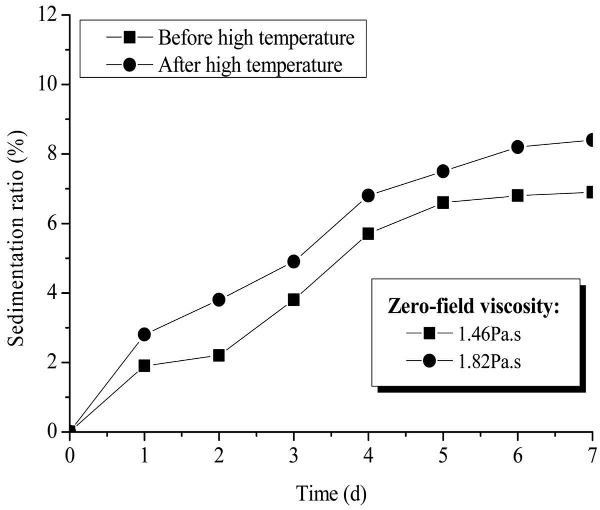


Fig. 10. Sedimentation stability of MR fluid before and after high temperature.

3.2. Other performance tests of prepared MR fluids

3.2.1. Settlement stability after high temperature

The MR fluid prepared with silicone oil as carrier fluid and FC64 surfactant and titanate coupling agent as the surface additives was placed in a vacuum drying oven, heated to 180 °C, held for 10 min, taken out, cooled to room temperature, and then stirred again. The settlement stability after high temperature can be observed, as shown in Fig. 10.

As can be seen from Fig. 10, high temperature caused the coating effect between the surface additives and the particles to deteriorate, resulting in a slight increase in the settlement rate of the MR fluid, but the one-week settle-

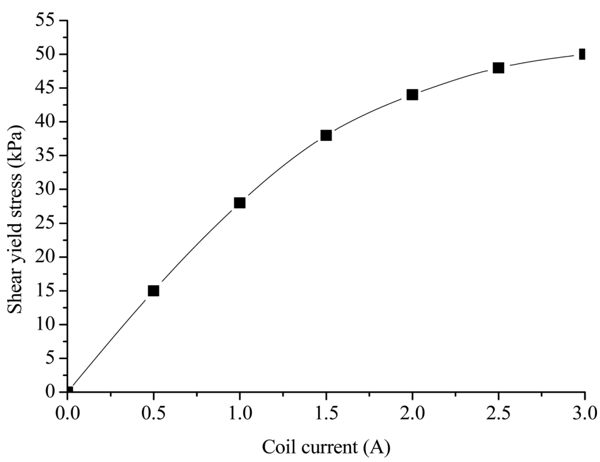


Fig. 11. Shear yield stress of MR fluid.

ment rate is still less than 9 %, which meets the needs of transmission applications. Furthermore, the partial thickening of the titanate coupling agent after high temperature caused the apparent viscosity of MR fluid to increase slightly but still maintain good fluidity. This result indicates that the prepared MR fluid can work at the temperature of 180 °C.

3.2.2. Shear yield stress

The shear yield stress of the prepared MR fluid is measured by the shear yield stress measurement device shown in Fig. 4, and the result is shown in Fig. 11.

As can be seen from Fig. 11, the shear stress of the prepared MR fluid increases with the enhancement of coil current, the highest shear yield stress can reach 50 kPa, which is slightly lower than that of the existing commercial MR fluid (about 55 kPa). This result is because the mass fraction of the MR fluid particles in this paper is 76 %wt, while most of commercial MR fluid is 80 %wt.

4. Conclusion

In this paper, each component material of MR fluid is selected; the basic characteristics are analyzed; the preparation process of MR fluid is clarified; and the effects of various additive types and contents, thixotropic agent types and contents, and carrier fluids types on the settlement stability and apparent viscosity of MR fluids are studied. A variety of transmission MR fluids are prepared, and the settlement ratio, apparent viscosity, and shear yield stress are tested. The results show that AES dispersants, titanate coupling agents, and fluorocarbon surfactants all have higher dispersion properties. Fluorocarbon surfactants and titanate coupling agent compounding can further improve the settlement stability of MR fluid and the one-week settlement rate is less than 7 %. Diatomite has a good thixotropic effect. Higher content results to better antisettling effect and at the same time leads to increased apparent viscosity. The types of carrier fluid have no significant effect on the performance of MR fluids. The prepared MR fluid can work at a temperature of 180 °C, which is higher than those of most commercial fluids, and the shear yield stress can reach 50 kPa.

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