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Study on the Preparation Process and Properties of Magnetorheological Fluid Treated by Compounding Surfactants

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Aiming to prepare high performance magnetorheological fluid, firstly, oleic acid and sodium dodecyl benzene sulfonate are chosen as surfactants. And then, the mechanical stirring process including stirring time, stirring temperature and stirring speed are optimized by measuring sedimentation ratio and zero-field viscosity. Finally, the properties of prepared magnetorheological fluid are elaborated. The results indicate that the compounding of oleic acid and sodium dodecyl benzene sulfonate can improve the properties of magnetorheological fluid distinctively, and the optimistic compounding content is 4g:4g or 5g:5g. The surfactants adding orders and the second stirring time have little effect on the properties of magnetorheological fluid, while obviously of the first stirring time, temperature and speed. Moreover, the sedimentation ratio of prepared magnetorheological fluid is less than 5.2% in two weeks, the zero-field viscosity is smaller than 0.6 Pa·s at 20 °C, and the maximum yield stress is higher than 50 kPa.

Keywords: preparation, optimization, surfactant, compound, process, magnetorheology

1. Introduction

Magnetorheological (MR) fluid is a typical kind of intelligent material that consists of micro-sized soft magnetic particles, additives, and nonmagnetic carrier fluid [1, 2]. MR fluid has a favorable rheological effect characterized by a reversible change in viscosity and yield stress caused by a magnetic field. That is, when an external magnetic field is applied, MR fluid shows non-Newtonian behavior, and its shear yield stress and viscosity can be adjusted by magnetic field. While the external magnetic field is removed, MR fluid can restore to the free flow state quickly, and shows the Newtonian like behavior. Given its unique characteristics, MR fluid is widely employed in various applications, such as in damping control, power transmission, polishing and composite components [3-6].

Actually, MR fluid is proposed by Rabinow in 1948 [7], however, due to the large density difference between the micro-sized soft magnetic particles and the carrier fluid, the particles are very prone to precipitate, which weakens the stability and engineering application of MR fluid. During recent twenty years, many researchers have suggested a variety of ways to improve the sedimentation stability of MR fluid, For example, adding different types of surfactants [8-11], adding carbon nano-tube or nano-sized particles magnetic fluid [12, 13], preparing special structure particles [14-16], the treatment of plasma [17]. Among them, coating particles with different additives is the most effective way for obtaining stable MR fluid [18], for example, Jiang *et al.* coats the particles with organic polymers [19], Cho *et al.* coats particles with PMMA [20], Ewijk *et al.* coats particles with Oleic acid [21]. These researchers usually coat particles with different single surfactant and the effectiveness is undesired usually. Therefore, in this paper, to obtain high performance MR fluid, firstly, the Oleic acid and Sodium dodecyl benzene sulfonate are chosen as surfactant. And then, the surfactants compounding process including surfactant content and the corresponding mechanical stirring process are investigated. Finally, the properties of prepared MR fluid are also evaluated by measuring the sedimentation ratio and the apparent viscosity.

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2. Materials and Properties Testing Methods for MR Fluid

2.1. Materials

The materials for preparing MR fluid are as follows: (1) Micro-sized carbonyl iron particles (CIP), supplied by TIANYI ultra-fine metal powder company (China), are used as solid phase of MR fluid. Average diameter of CIP is 2.5 μm, the particle is spherical and polydisperse, as shown in Fig. 1 observed by a scanning electron microscopy (SEM). (2) Silicone oil, which possesses excellent viscosity-temperature properties, is used as carrier fluid. The flash point of silicone oil can reach to 300 °C and can be used within −50 °C~250 °C. (3) Oleic acid and Sodium dodecyl benzene sulfonate (SDBS) are used as surfactant. The surfactant has amphiphilic structure and can provide hydrophilic and lipophilic groups, and hydrophilic end of the groups adsorbs on the particle surface, while the lipophilic end swings in carrier fluid, which can prevent particle sedimentation. The Oleic acid and SDBS has different Hydrophile-Lipophile Balance value (HLB).

2.2. Testing Method of MR Fluid

The sedimentation stability, zero-field viscosity or apparent viscosity, operating temperature, shear yield stress and response time are common properties of MR fluid. Among them, the sedimentation stability and zero-field viscosity are most important characteristics, and will be tested to evaluate MR fluid in this paper.

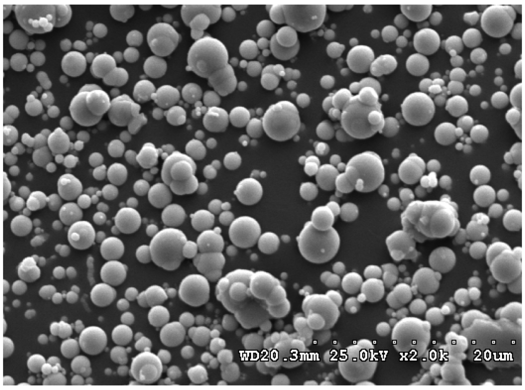


Fig. 1. SEM photo of CIP.

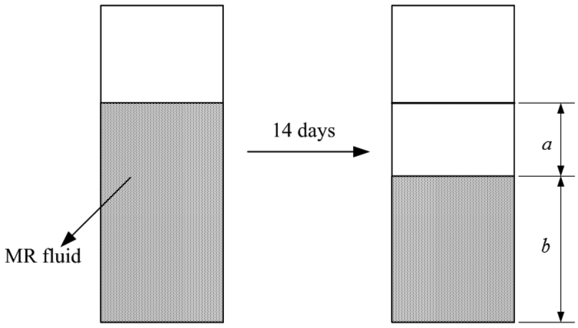


Fig. 2. sedimentation ratio testing.

A simple and effective method to obtain the sedimentation stability is to monitor the CIP evolution, as shown in Fig. 2. The prepared MR fluids will be placed in glass graduate for two weeks, and the CIP of MR fluid will deposit gradually. The sedimentation stability can be expressed by sedimentation ratio, which is defined as the nonmagnetic carrier fluid-rich phase height a relative to the total MR fluid height $a + b$.

Zero-field viscosity of MR fluid can be measured by the SNB-1 Viscosimeter (Shanghai Exact Science Instruments Co. Ltd). The zero-field viscosity is relative to measuring temperature and shear velocity, therefore, the measuring temperature is set to 20 °C, and the shear velocity of SNB-1 Viscosimeter is 1.0 s^{-1} constantly. Each measurement of MR fluid sample is repeated three times and the average value is taken as zero-field viscosity.

2.3. Preparation Method of MR Fluid

The carrier fluid displacement method is adopted to prepare MR fluid, and the process is as follows: (1) The CIP and the surfactants are put into the solution of absolute alcohol, and the mixture is stirred strongly for sufficient adsorption of surfactants on the surface of particles, this process is called first stirring which includes stirring time, stirring temperature and stirring rotate speed. (2) The mixture is dried in a vacuum drying oven, and then surfactants treated iron particles are grinded and mesh sieved to prevent the agglomeration. (3) The treated powders are added into the carrier fluid and the mixture is stirred strongly again, this process is called second stirring, and also includes the process of stirring time, stirring temperature and stirring rotate speed.

3. Results and Discussions

3.1. Compounding of surfactants

In this experiment, the influence of Oleic acid, SDBS, and the compounding of Oleic acid and SDBS on the sedimentation ratio and zero-field viscosity is researched according to the preparation process mentioned in section 2.3, and the result is shown in Fig. 3. The corresponding content of above surfactant is 2.0 g, 2.0 g, 1.0 g + 1.0 g respectively, and the CIP is 100.0 g, and the silicone oil is 30.0 g, which means the mass fraction of CIP, silicone oil and surfactants is 75.8%, 22.7% and 1.5% respectively.

As observed in Fig. 3, different surfactants have obviously impact on the sedimentation ratio and zero-field viscosity

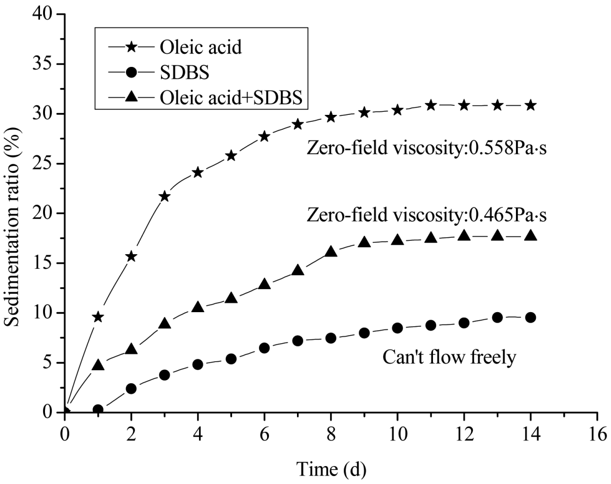


Fig. 3. Influence of surfactants compounding on sedimentation ratio and zero-field viscosity of MR fluid.

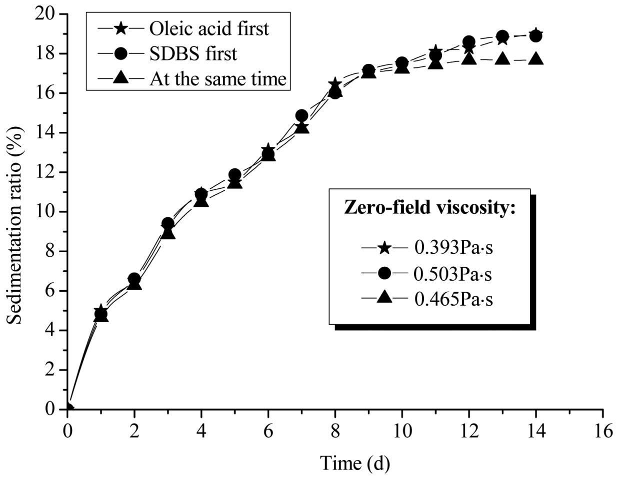


Fig. 4. Influence of surfactant adding orders on sedimentation ratio of MR fluid.

of MR fluid, the MR fluid with 2.0 g Oleic acid has better zero-field viscosity, but worse sedimentation ratio, while inverse of the SDBS, the MR fluid with 2.0 g SDBS even lose its fluidity due to thick covering of surfactant. It is also observed that the combination properties of MR fluid can be further improved by the compounding of OA and SDBS because of the partial covering of OA and SDBS. Therefore, in following experiments, the optimization mechanical stirring process and content of compounding surfactants will be further researched.

3.2. Adding orders of the surfactants

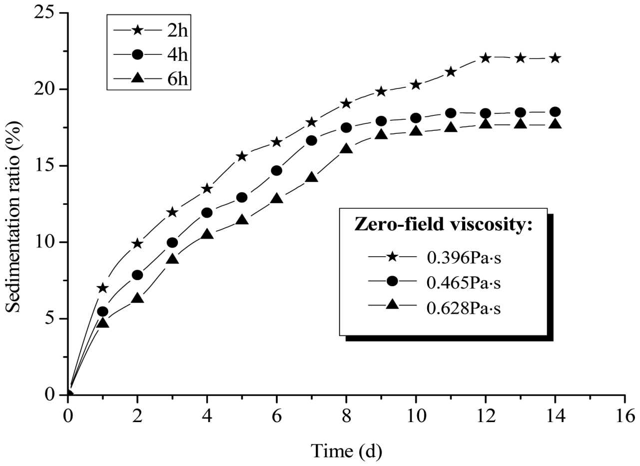
For the surfactants compounding preparation process, it is necessary to research the effect of surfactants adding orders on the properties of MR fluid. Based on oleic acid and SDBS, this paper conducted three cases of experiments as the following: the first one: oleic acid is added into the absolute alcohol firstly, and after one hour of stirring, SDBS is added; The second one: SDBS is added into the absolute alcohol firstly, after one hour of stirring, the oleic acid is added; The third one: oleic acid and SDBS are added into the absolute alcohol at the same time. Besides, the total first stirring time is 2 hours, the second stirring time is rationed to 1 hour, the stirring speed is set for 400 r/min and the stirring temperature is 20 °C. The sedimentation ratios and zero-field viscosity of MR fluids prepared by the method described above are shown in Fig. 4.

As illustrated in Fig. 4, The sedimentation ratio curves of MR fluid obtained by different adding orders of surfactants are basically in coincidence. It indicates that the adding orders have little effect on the sedimentation stabilities of MR fluid, and the two surfactants have similar adsorption ability. Therefore, in the following experiments, in order to simplify the experimental procedures, surfactants are added into the absolute alcohol at the same time. According to the zero-field viscosity value, the adding orders have some effect on zero-field viscosity of MR fluid, but not very striking. The zero-field viscosity of MR fluid prepared by the oleic acid first is small and the reason is that the dispersion function of oleic acid is better than that of SDBS.

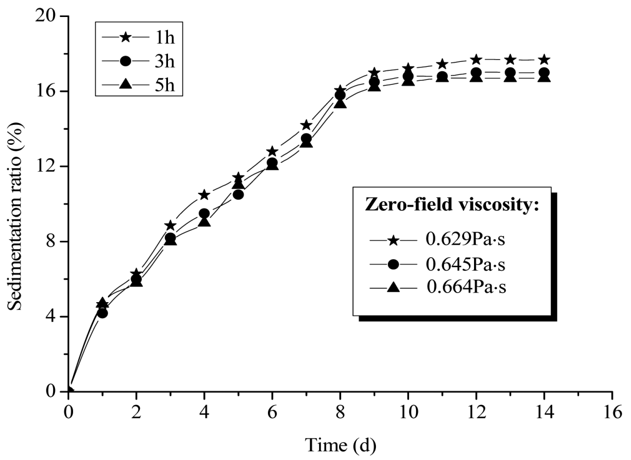
3.3. Influence of the first stirring time and second stirring time

In the experiments, the first stirring time is set for 2, 4 and 6 hours respectively to observe the influence of first stirring time on the performance of MR fluid, and the second stirring time is rationed to 1 hour, the stirring speed is set for 400 r/min and the stirring temperature is 20 °C. The experimental results are shown in Fig. 5(a); And then, the second stirring time are set for 1, 3 and 5 hours respectively to research the effect of different second stirring time, the first stirring time is rationed to 6 hours, the stirring speed is set for 400 r/min and the stirring temperature is 20 °C. And the results are shown in Fig. 5(b).

As shown in Fig. 5(a), the first stirring time has obvious impact on the sedimentation stability of MR fluid and the longer the stirring time is, the better the sedimentation stability of MR fluid is, but the zero-field viscosity is slightly increased. There are two possible reasons for the phenomenon. One possible reason is that the particles are coated with the surfactants more thickly as the stirring time increasing, which leads to the increase of the apparent viscosity. Another possible reason is that the shear-



(a) Different first stirring time



(b) Different second stirring time

Fig. 5. Effect of stirring time on sedimentation ratio of MR fluid.

thickening behavior which often appears in the preparation of MR fluid.

The preparation of first stirring time of 6 hours improves the sedimentation stability of MR fluid, but not very obviously when the two kinds of MR fluid are compared, which are obtained respectively through the 4 hours stirring and 6 hours stirring. So increasing the stirring time has a less effect on the improvement of the sedimentation stability of MR fluid. According to the results described above, in order to shorten the experimental time, the first stirring time in the following experiments is rationed to 6 hours.

According to the Fig. 5(b), the second stirring time has only slightly effect on the sedimentation stability and apparent viscosity of MR fluid. The reason is as follows: the function of the second stirring process is to disperse the particles coated with the surfactants in the carrier fluid sufficiently, but before the stirring and dispersing, the particles coated with the surfactants have already been dried, ground and mesh-sieved, the dispersion property of the particles is better. Therefore it is not necessary to mix for long to disperse the particles fully, and the 1 hour second stirring time will be chosen for the following experiments. Besides, it should be pointed out that, the non-uniform adsorption of surfactant on particle surface may occur due to the non-uniform stirring of first stirring process, therefore, the seconding stirring can also improve the sedimentation ratio slightly.

3.4. Influence of stirring temperature

The stirring temperature influences the dissolving ability of the surfactants in the absolute alcohol and further influences the coating effect of the surfactants on the particle surface. So in the following experiments, the effect of stirring temperature on the sedimentation stability of MR fluid will be tested. The stirring temperature is set for 20 °C, 30 °C and 40 °C respectively through the thermostatic water bath, and the first stirring time is 6 hours, the second stirring time is 1 hour, the stirring speed is 400 r/min. The influence rule of stirring temperature on the sedimentation stability and zero-field viscosity of MR fluid is obtained, as shown in Fig. 6.

According to Fig. 6, the stirring temperature has an obvious effect on the sedimentation stability and zero-field viscosity of MR fluid. Increasing the stirring temperature can improve the sedimentation stability of the particles, but lead to the increase of the apparent viscosity. The reason is that the increase of the stirring temperature is helpful to the dissolution of the surfactants in the absolute alcohol, which improves the coating effect of the surfactants on the particle surface.

Increasing the stirring temperature can accelerate the

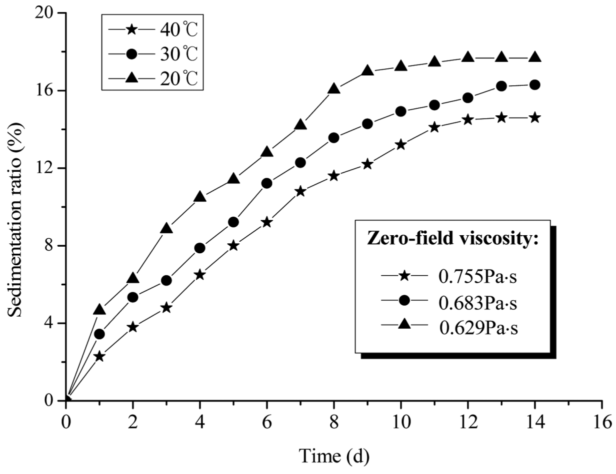


Fig. 6. Influence of stirring temperature on sedimentation stability of MR fluid.

volatilization of the absolute alcohol in the stirring process and enhance the coating speed of the surfactants on the particle surface. So in order to shorten the stirring time and improve the efficiency of the stirring, the stirring temperature could be increased properly. If the stirring temperature is higher than 40 °C, the absolute alcohol will volatilize very quickly, which will result in bad uniformity of the coating of the surfactants and further influence the sedimentation stability and apparent viscosity of MR fluid.

3.5. Influence of stirring speed

The increase of the stirring speed contributes to the rapid dispersion of the particles, the function of which is similar to those of the stirring time and temperature. The influence rule of different stirring speeds is tested in the following experiments. The speeds of the rotary blender are set for 100 r/min, 200 r/min, 400 r/min, 800 r/min and 1000 r/min respectively, the first stirring time is 6 hours, the second stirring time is 1 hour and the stirring temperature is 20 °C. The influence law of stirring speed on the sedimentation stability and apparent viscosity of MR fluid is revealed in Fig. 7.

As illustrated in Fig. 7, the stirring speed has an obvious effect on the sedimentation stability and apparent viscosity of MR fluid. And the MR fluid prepared at lower stirring speed (usually less than 400 r/min) has poor sedimentation stability. So in the preparation process, the stirring speed is usually above 400 r/min. When the stirring speed is more than 800 r/min, the MR fluid prepared exhibits higher sedimentation stability but worse fluidity. If the stirring speed is ultrafast, MR fluid will even lose its fluidity. The reason of this phenomenon is similar to that of the stirring time, which means shear-thickening behavior may have occurred in the preparation process.

3.6. Influence of compounding surfactants content

The previous research on surfactants compounding content indicates that 1:1 is the optimistic proportion between Oleic acid and SDBS [17]. In this paper, we will further investigate the influence of content on the sedimentation ratio, zero-field viscosity and shear yield stress of MR fluid, and the result is shown in Fig. 8. In this experiments, the content of Oleic acid and SDBS is 1g:1g, 2g:2g, 3g:3g, 4g:4g, 5g:5g respectively, which means that the mass fraction of surfactants is 1.53%, 2.98%, 4.41%, 5.80%, 7.14%, 8.45%, and the mass fraction of CIP is 75.76%, 74.63%, 73.53%, 72.46%, 71.43%, 70.42%.

According to Fig. 8, it is observed that the sedimentation ratio of MR fluid decreases with the increase of

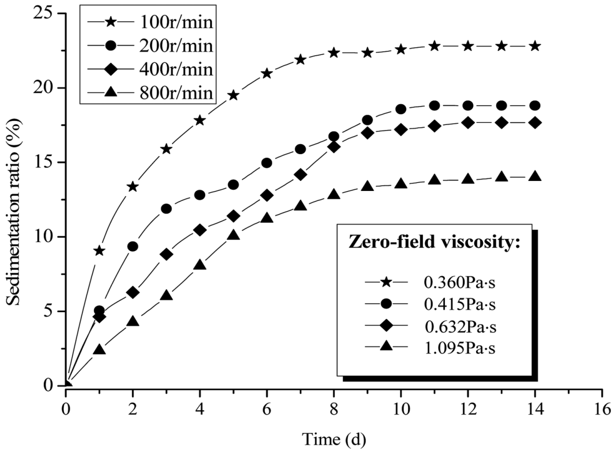
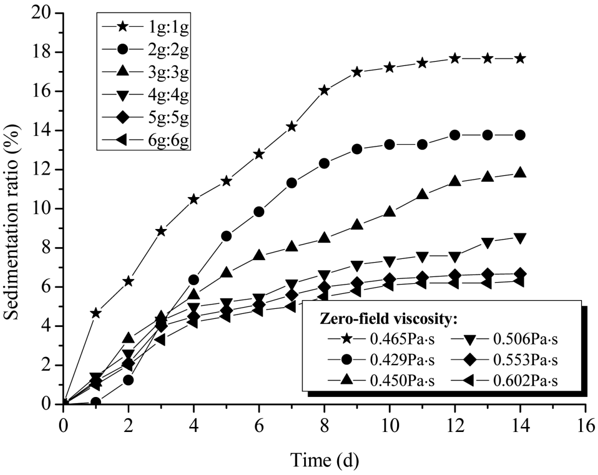
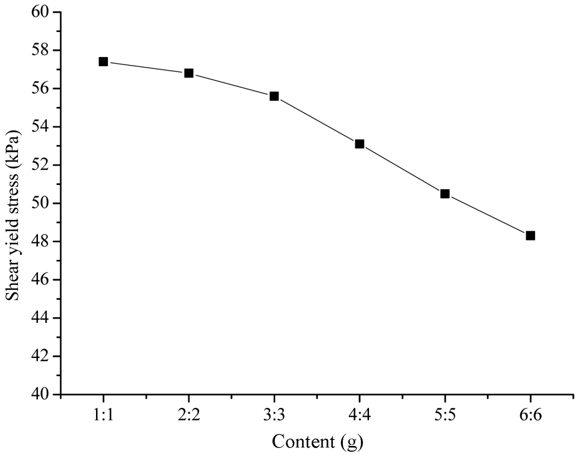


Fig. 7. Influence of stirring speed on sedimentation stability of MR fluid.



(a) Sedimentation ratio and zero-field viscosity



(b) Shear yield stress

Fig. 8. Influence of compounding surfactants content on properties of MR fluid.

surfactants content due to the thick covering of surfactants, and when the content of compounding surfactants change from 1g:1g to 6g:6g, the sedimentation ratio in two weeks can decrease from 17.2% to 6.3%. The adding of surfactants increases of zero-field viscosity because of the interactive connection between particles, and decrease the shear yield stress due to reduction of CIP, of which the mass fraction decrease from 75.76% to 70.42%.

4. Conclusions

Through the experiments of the adding orders of surfactant, stirring time, stirring temperature and stirring speed, an interaction relationship between them can be established. The increase of the stirring temperature and speed could shorten the stirring time; contrarily increasing the stirring time could decrease the stirring temperature and the stirring speed. Therefore, according to the interaction relationship between them, the optimized preparation process could be designed as the following: the stirring temperature is 40 °C and the stirring speed is 400 r/min, the first stirring time is 6 hours and the second stirring time is 1 hour. Totally, in order to ensure the comprehensive performance of prepared MR fluid, the 4g:4g or 5g:5g surfactants will be adopted. The corresponding shear yield stress is higher than 50 kPa as the magnetic field is 0.5T, which is similar with the commercial MR fluid from Lord Company, and the sedimentation ratio can decrease to 6.3% in two weeks, and has also well fluidity.

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