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Influence of particles size and concentration of carbonyl iron powder on magnetorheological properties of silicone rubber-based magnetorheological elastomer

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Abstract

In this study, the anisotropic magnetorheological elastomer (MRE) was prepared by mixing two-component room temperature vulcanized(RTV) silicone rubber, carbonyl iron powder particles and dimethyl silicone oil uniformly, then heated and solidified under 500 mT magnetic field intensity. Five types of magnetic particles with different concentrations of 20%, 30%, 40%, 50%, 60% and five different sizes of 1.7, 2.8, 3.9, 4.6, 7.2 μm, were used to investigate the effects of the concentrations and sizes of the magnetic particles on the microstructure, mechanical properties and the magnetorheological effect (MR-effect) of anisotropic MRES. The results obtained from this study showed that the MR-effect has a significant dependence on the concentrations and particle sizes of the magnetic particles. It increased with the increase of the particle concentrations, and the high particle concentration makes the MRE have a high magnetostrictive modulus and MR-effect. Nevertheless, with the increase of the particle sizes, the MR-effect showed a trend of strengthening firstly and then weakening, there is an optimal particle size of 4.6 μm, at this size, the MR-effect is the most significant.

1. Introduction

Magnetorheological (MR) materials are new smart materials in which their mechanical properties can be controlled by the magnetic field. Due to its unique MR-effect, fast response (ms magnitude), good reversibility (after removing the magnetic field, it can return to the original state). Besides, the mechanical properties of MR material can change continuously with the change of the external magnetic field. Thus, in recent years it gains too much attention in the applications of aerospace, automobile, architecture, and vibration control [1–3].

Magnetorheological elastomer (MRE) is one of the magnetorheological materials used widely in the current few years. The micro-scale magnetic particles are added to the polymer matrix to mix and solidify under the magnetic field environment; thus, the magnetic particles in the matrix form a chain or column-like ordered structure. MRE can address the issues of the problems of magnetic particles in MR fluid, such as easy leakage, easy settlement, environmental pollution and poor overall stability. Besides, it doesn’t need special containers to store [4–6]. There are several parameters to measure the performance of MRE, such as magnetostrictive modulus, tensile strength, hardness, lagging heat generation, etc. The key parameter is the magnetostrictive modulus part of MRE, which reflects the influence of the magnetic field on the material properties and is manifested in the material properties under the coupling field of force and magnetism.

Recently, the magnetostrictive modulus of MRE is generally in a small controllable range, which hinders its industrial application [7–9]. The MR-effect of the MRE is characterized by the change in its modulus under the
action of the magnetic field. The properties of MRE depend on the number and size of magnetic particles, the compatibility between polymer and magnetic particles, and the interface interaction [10–13]. The content, the arrangement, and the properties of the particles in the material play a key role in determining the MR-effect [14]. For instance, Sorokin et al. studied the MREs prepared by mixing two carbonyl iron powders with different particle sizes as reinforcements. Their results showed that the MR-effect increases with the increase of the amount of iron powders with larger particle sizes [15, 16]. Winger et al. [17] compared the MR-effects of four MREs prepared by four different sizes of carbonyl iron powder particles. Their results displayed a clear dependence of the MR-effect on the particle size fraction. Vinee et al. [18] used the solution mixing method to disperse the micron-sized carbonyl iron powder particles in RTV to prepare the MRE samples. Besides, they studied the correlation between the volume, size and distribution of particles and the mechanical properties of the samples. Furthermore, they carried out the isotropic mechanical test and the anisotropic effect test for the obtained MREs. Anna et al. [12] studied the polyurethane-based MRE composed of carbonyl iron powder particles with an average particle size of 1–70 μm. It was noticed that the MRE with carbonyl iron powder particle size of 6–9 μm had the highest MR-effect. By optimizing the particle size, shape and arrangement, the rigidity of the MRE element under the action of the external magnetic field was improved. Miao et al. [19] prepared MRE samples with different components of carbonyl iron particles under the action of the external magnetic field. Besides, they observed their microstructure with OM and SEM. After that, they measured the dynamic mechanical properties of MRE under different magnetic fields and frequencies with an improved dynamic mechanical analyzer. Their results exhibited that the carbon content of carbonyl iron particles has a significant influence on the dynamic mechanical properties and damping properties of the MRE. The low carbon content of carbonyl iron particles can improve the storage modulus and MR-effect. Lokander et al. [20] used large irregular particles to prepare the isotropic MRE materials. Their results showed that the absolute MR-effect of MRE materials with isotropic large irregular particles does not depend on the matrix material. Furthermore, they noticed the addition of plasticizer could improve the relative MR-effect. The influence of different volume ratios of magnetic particles on the MR-effect of MRE material is huge. Davis [21] analyzed the volume ratio of magnetic particles through the finite element method. He thought that a 27% volume ratio would get the best MR-effect. The results of Lokander [22] and Jin [23] displayed that the MR-effect of MRE materials is not a simple positive correlation with the particle size, but there is optimal particle size. When the particle size is smaller than the optimal particle size, the MR-effect may increase with the increase of particle size. On the other hand, if the particle size is larger than the optimal size, the MR-effect may decrease with the increase of particle size.

Thus, in this study, five different sizes and contents of carbonyl iron powder particles were used to prepare different MRE materials under the same preparation conditions. After that, SEM was used to characterize and analyze the obtained MRE materials to observe the orientation of magnetic particles. To explore the mechanical and the magnetorheological properties of the prepared MRE materials with different magnetic particle numbers and sizes, compression tests were performed under different conditions of the magnetic field.

2. Materials descriptions and experimental procedures

2.1. Materials descriptions

Choosing a soft matrix material is beneficial to improve the MR-effect of MRE materials and reduce the zero-field modulus of the matrix material as much as possible on the premise of satisfying the mechanical properties. Recently, silicone rubber is the most widely used matrix material in the preparation of MREs. Based on the above principles, AS40 Addition Cure Silicone rubber was used as the matrix.

The decisive factor that affects the MR-effect of MRE is the filled magnetic particles. When the external magnetic field was applied, the modulus of MRE changed due to the dipole effect between the magnetic particles in MRE, thus showing the MR-effect. Carbonyl-iron powder produced by Jiangsu Tianyi Ultrafine Metal Powder Co. LTD was used for the fabrication of the samples. This kind of magnetic particle has several advantages such as high permeability, high magnetic saturation strength and low remanence, high permeability and magnetic saturation strength, which can improve the magnetic modulus. While low remanence can reduce the response time of MRE to the magnetic field, which is conducive to enhancing the reversibility and stability of the material. In this paper, to explore the influence of five kinds of magnetic particles with frequently-used particle sizes on the MR-effect of MRE, five iron carbonyl powders with different particle sizes were used, it has a spherical shape and an average diameter of 1.7 μm ~ 7.2 μm. The chemical composition of these powders is listed in table 1 (provided by the supplier).

To improve the properties of materials, additives are usually used in the preparation of MRE. The plasticizer is the most commonly used additive at present. The addition of plasticizer can reduce the viscosity of matrix
The mechanical properties of MRE materials are mainly studied.

### 2.3. Mechanical testing

Samples were tested using a WDW-100D electronic universal testing machine in zero-field condition. Nine groups of MRE samples and a sample of pure rubber were tested. Each measurement was repeated five times to ensure reproducibility.

![Universal testing machine and magnetic field setup](image)

Table 1. The chemical composition of Carbonyl iron powders.

| Brand | Element content (%) | Density (g/cm³) |
|-------|---------------------|------------------|
|       | Fe      | C      | O      | Loose | Compaction | Particle size (μm) |
| F1    | 98.19   | 0.96   | 0.24   | 3.12  | 4.0        | 7.2 ± 0.1          |
| F2    | 98.35   | 0.76   | 0.15   | 2.46  | 4.03       | 4.6 ± 0.1          |
| F3    | 98.13   | 0.87   | 0.33   | 2.88  | 4.26       | 3.9 ± 0.1          |
| F4    | 98.17   | 0.84   | 0.32   | 2.54  | 4.15       | 2.8 ± 0.1          |
| F5    | 98.10   | 0.93   | 0.43   | 2.16  | 4.10       | 1.7 ± 0.1          |

![Table 1](image)

Table 2. The composition and curing conditions of MRE samples.

| Samples | Matrix | Mass ratio (%) | Fe particle size (μm) | Fe particle mass ratio (%) | Dimethyl silicone oil mass ratio (%) | Magnetic field during curing (mT) | Temperature during curing (°C) |
|---------|--------|----------------|-----------------------|---------------------------|-------------------------------------|----------------------------------|-------------------------------|
| L-20    | AS40   | 60             | 4.6 ± 0.1             | 20                        | 20                                  | 500                              | 70                            |
| L-30    | AS40   | 50             | 4.6 ± 0.1             | 20                        | 20                                  | 500                              | 70                            |
| L-40    | AS40   | 40             | 4.6 ± 0.1             | 40                        | 20                                  | 500                              | 70                            |
| L-50    | AS40   | 30             | 4.6 ± 0.1             | 50                        | 20                                  | 500                              | 70                            |
| L-60    | AS40   | 20             | 4.6 ± 0.1             | 60                        | 20                                  | 500                              | 70                            |
| L-60    | AS40   | 20             | 1.7 ± 0.1             | 60                        | 20                                  | 500                              | 70                            |
| L-60    | AS40   | 20             | 2.8 ± 0.1             | 60                        | 20                                  | 500                              | 70                            |
| L-60    | AS40   | 20             | 3.9 ± 0.1             | 60                        | 20                                  | 500                              | 70                            |
| L-60    | AS40   | 20             | 7.2 ± 0.1             | 60                        | 20                                  | 500                              | 70                            |

![Table 2](image)

Material without changing its chemical substance. In this investigation, Dow Corning pmx-200 silicone oil is selected as a plasticizer.

#### 2.2. MRE samples preparation

Magnetic particle is the most commonly used filler in MRE. Qiao et al [24] showed in their investigation that the size and concentration of magnetic particles have a significant impact on the mechanical properties of MRE.

Under the same magnetic field intensity, five types of magnetic particles with different particle sizes were selected as enhancers to prepare MREs. The average particle sizes of the five types of magnetic particles were 1.7, 2.8, 3.9, 4.6 and 7.2 μm, respectively. Besides, five kinds of MREs with different particle concentrations were prepared under the same magnetic field intensity. The mass percentages of the magnetic particles were 20%, 30%, 40%, 50% and 60%, respectively, to evaluate the influence of size and concentration of the particles on the MR-effect.

The composition of the prepared MRE samples is listed in Table 2. Firstly, a mixture of silicone rubber, magnetic particles and silicone oil were mixed evenly. After that, put it into a vacuum container, and after vacuuming, pour it into a cylindrical mould of Ø29*13 mm for curing. In this study, the method of heating and curing in the magnetic field environment was adopted, and the magnetic field direction is parallel to the axial direction of the cylindrical sample. Under the condition of 500 mT magnetic field intensity and 70 °C, the samples were placed in the magnetic field and solidified for 0.5 h to form chain orientation of the magnetic particles inside.

Thereafter, the samples were solidified for 0.5 h at 70 °C after the magnetic field was removed to get the MRE samples.

#### 2.3. Mechanical testing

The mechanical properties of MRE materials are mainly reflected in the magnetic field controllability of mechanical properties. In addition to the dynamic behavior, the static and quasi-static behavior of MRE used for evaluating its MR-effect. Through the quasi-static compression test of the sample, the change of Young's modulus of silicone rubber-based MRE under the action of zero field and external variable magnetic field was studied. Nine groups of MRE samples and a sample of pure rubber were tested by WDW-100D electronic universal testing machine in zero field and variable magnetic field intensity, respectively, as depicted in figure 1, to ensure reproducibility, five specimens were measured per sample under the same conditions, the five specimens are from the same batch, and five measurements were made continuously, a new sample was used for each measurement, through five groups of measurement results, the average value and standard deviation of five specimens were obtained. Figure 1 presents the combination of universal testing machine and magnetic field generator, according to GB/T 7757-2009, the room temperature compression test was conducted at a speed of 10 mm min⁻¹ up to 0.4 strain. The MRE sample was located in the common center of the compression testing.
machine and electromagnet, the chain structure of magnetic particles was parallel to the compression direction, and the direction of the applied magnetic field was perpendicular to the compression direction, as shown in figure 2. In order to ensure the uniaxial stress during the test, a thin layer of silicone oil lubricant was coated on the top and bottom of the cylindrical MRE sample. This makes the sample expand uniformly in the radial direction under the axial compression condition. The Young’s modulus is determined in the linear elastic regime before plastic deformation occurs by calculating the slope of linear elastic part. The MR-effect of MRE was characterized by the change of its modulus under the action of the magnetic field. $E_0$ represents Young’s modulus under the zero-field condition; however, $E_B$ is Young’s modulus under magnetic field condition. Thus, the MR-effect can be expressed as $R_E$, as shown in equation (1).

$$R_E = \frac{E_B - E_0}{E_0}$$ (1)
3. Results and discussion

3.1. Morphology observation
The MR-effect and mechanical properties of MRE are closely related to the distribution of magnetic particles in the silicone rubber matrix. In order to observe the dispersion of magnetic particles with different concentrations and particle size in silicone rubber matrix, nine groups of MREs with different concentrations and particles size were characterized by an FEI Quanta 200 SEM, the acceleration voltage is 20.0 kv and spot is 4.0, the SE probe is used in the detection system. Firstly, the samples are cut along the direction of the chain structure of particles in MREs, to ensure the existence of particle chain in the cutted sample, then the samples were pretreated: soaked in anhydrous ethanol, cleaned, and placed in the ultrasonic water tank to remove grease, dust, dirt and moisture. Finally, the samples were stuck on the special sample table by a conductive adhesive.

The morphologies of five carbonyl iron powder particles with different particle sizes are depicted in Figure 3. It is noticed clearly from these morphologies that the particle size of carbonyl iron powder increases gradually. Besides, by increasing the magnetic particle size, the number of particles decreased, and with the same concentration of magnetic particles, the number of magnetic particles in the same volume of MRE also decreased.

When the particle size is 4.6 μm, five groups of MRE samples with a magnetic particle concentration of 20%, 30%, 40%, 50% and 60% were analyzed by SEM, and the results are depicted in figure 4. The white particles are carbonyl iron powder particles, the black area represents the silicone rubber matrix, and the white flow area is dimethyl silicone oil, the red arrows indicate the arrangement of particles chain structure. It is seen from figure 4 that the concentration of magnetic particles is increasing, and with the increase of the concentration of magnetic particles, the particles are more likely to form chain orientation under the effect of the external magnetic field. When the particle concentration is only 20%, the chain orientation is less than those in the high particle concentration, and it’s not obvious because the particle concentration is too low. When the concentration increases to 60%, as shown in figure 4(e), a clear chain orientation can be observed. Due to the weakness of the strengthening effect of low magnetic particles in the silicone rubber matrix, the mechanical properties and magnetorheological properties of MRE with a low concentration of magnetic particles are small. The SEM morphologies of MRE with different particle sizes are depicted in figure 5. Under different magnifications, it is observed that the magnetic particles present a chain structure along the magnetic field direction in the silicone rubber matrix.

3.2. Influence of the magnetic particle concentration on the magnetorheological properties of MRE
Because the MR-effect of MREs is obvious when the particle size is 4–5 μm. Therefore, choosing the particle size of 4.6 μm is beneficial to compare the MR-effect of different concentrations of MREs. Based on the compression
test of MREs with five different magnetic particle concentrations under various magnetic fields, the influence of particle concentration on the magnetorheological properties of MREs was investigated. The experimental results depicted in figure 6 show the compression stress-strain curve of MRE with different magnetic particle concentrations under different magnetic field intensity. It is noticed from figure 6 that under different magnetic field intensity, the tangent modulus of MRE increases with the increase of strain, and the stress-strain relationship is obviously nonlinear. Under the same magnetic field, when the strain is the same, the stress output of MRE with different magnetic particle concentration is different. There was an increase in the compressive stress as the magnetic particle concentration increased. At almost all strains in the stress-strain curve, the compressive stress of MRE increased with the increase of magnetic particle concentration. This indicates that the higher concentration of magnetic particles in MRE leads to increase in the Young’s modulus. On the other hand, the higher concentration of magnetic particles reduced the distance between particles, which leads to the strengthening of the magnetic force; thus, the higher the concentration is, the greater the stress of MRE is. The increase of the Young’s modulus can also be attributed to the increase of the rigidity of the sample with the increase of the volume fraction of the magnetic particles. Besides, the improvement of the contact between the interactive components and the formation of an efficient filling network.

Figure 4. When particle size is 4.6 μm, SEM of MREs with different concentration of magnetic particles: (a) 20% (b) 30% (c) 40% (d) 50% (e) 60%.

Figure 5. SEM of MREs with different sizes of magnetic particles: (a) 1.7 μm (b) 2.8 μm (c) 3.9 μm (d) 4.6 μm (e) 7.2 μm.
The stress-strain curves of the samples under different magnetic field intensities when the magnetic particle concentration is 60% and the particle size is 4.6 μm is depicted in figure 7. It is observed from the stress-strain curves of the samples with the magnetic particle concentration of 60% and the particle size of 4.6 μm under zero and variable magnetic field intensities. When the strain is small, the compressive stress of the sample increases slowly with the strain. On the other hand, with the increase of strain, the compressive stress of the MRE sample increased exponentially. Under the same strain, the stress output of the sample after adding the magnetic field is obviously larger than that of the sample without adding the magnetic field. Besides, the higher the intensity of the external magnetic field is, the greater the stress of the sample is. Furthermore, the higher the intensity of the external magnetic field is, the greater the Young’s modulus is. It can be attributed to the magnetization of the magnetic particles by the external magnetic field, and the stronger the magnetization caused by the higher magnetic field intensity, that is, the internal force of the material is not only the restoring force of the rubber matrix. However, the magnetic force between the particles under the external magnetic field and the magnetic force is directly proportional to the external magnetic field intensity, which indicates that the MRE sample has an obvious magnetostrictive effect and the mechanical properties of the sample can be greatly affected by the external magnetic field.

The Young’s modulus of MREs with different concentrations of the magnetic particles under different magnetic field intensities is depicted in figure 8. It is noticed from this figure that when the concentration of magnetic particles is constant, the Young’s modulus of the sample increased with the increasing of the magnetic field intensity. This consistent with the conclusion in figure 7, and reflecting the magnetostrictive effect of the MREs. No matter in zero magnetic fields or in the presence of a magnetic field, the Young’s modulus of the MRE samples increased with the increasing of the magnetic particle concentration. The Young’s modulus of the MRE sample with 60% magnetic particle concentration is the highest in zero magnetic fields or in the presence of a magnetic field. It reached 4.7 MPa under the external magnetic field of 375 mT, which is due to the increase of concentration of the particle reinforcement phase, which improves the mechanical properties of MRE. Table 3 describes mean Young’s modulus and standard deviation of MREs with five particle concentrations under zero field and 375 mT magnetic field and the ratio of the magnetostrictive modulus to the zero-field modulus of the
Figure 7. Compression stress-strain curves of samples under different magnetic field intensities when the magnetic particle concentration is 60%, and the particle size is 4.6 μm.

Figure 8. The relationship between the Young’s modulus and the magnetic field of MRE with different concentration of magnetic particles.

Table 3. The ratio of magnetostrictive modulus to zero field modulus of different concentration particles in 375 mT magnetic field.

| Concentration(%) | Modulus(MPa) | 20  | 30  | 40  | 50  | 60  |
|------------------|--------------|-----|-----|-----|-----|-----|
| Mean Young’s modulus $E_B$ | 3.05  | 3.4  | 3.69 | 3.95 | 4.7 |
| Standard deviation | 0.09  | 0.08 | 0.09 | 0.12 | 0.12 |
| Mean Young’s modulus $E_0$ | 2.48  | 2.54 | 2.57 | 2.8  | 3.2 |
| Standard deviation | 0.1   | 0.09 | 0.1  | 0.13 | 0.11 |
| Ratio            | 1.23  | 1.34 | 1.44 | 1.41 | 1.47 |
sample with each concentration of magnetic particles under the condition of 375 mT magnetic field. It is seen from the table that the ratio of the magnetostrictive modulus to the zero-field modulus of the elastomer increased gradually with the increase of the concentration of particles. This shows that the enhancement effect of the high concentration of magnetic particles on the Young’s modulus is more significant.

According to equation (1), the MR-effect of MRE samples with different magnetic particle concentrations under different magnetic field intensity was obtained, as depicted in figure 9. The results showed that the MR-effect of MRE is basically in a positive proportion to the concentration of the magnetic particles under the three magnetic fields. Thus, the MR-effect increased with the increase of the concentration of particles, and the MR-effect of MRE with 50% of the concentration of magnetic particles decreased slightly when the magnetic fields are 125 mT and 375 mT.

It is also observed from figure 9 that the influence of magnetic field intensity on the MR-effect is significant. As shown in table 4, it shows the comparison of MR-effect of MRE with 60% and 20% particle concentrations under different magnetic fields and the standard deviation of MR-effect, and taking into account the propagation of uncertainty, the standard deviation of MR-effect is larger than that of the Young’s modulus. When B = 125 mT, the ratio between the MR-effect of the MRE with 60% particle concentrations and 20% particle concentrations is 1.62. Besides, when the magnetic field intensity increased to 250 mT, the ratio between the two is increased to 1.93. Furthermore, when B = 375 mT, the ratio increased to 2.04, which indicates that high magnetic field intensity is conducive to improving the enhancement of MR-effect by the concentration of the magnetic particles.

3.3. Influence of magnetic particle size on the magnetorheological properties of MRE

It can be seen from the above when the particle concentration is 60%, the MR-effect of MREs is more significant. Therefore, selecting the concentration of 60% is beneficial to compare the MR-effect of MREs with different particle size. Based on the compression tests of MREs with five different particle sizes under various magnetic fields, the influence of particle sizes on the magnetorheological properties of MREs is explored. As shown in figure 10, the stress-strain curves of MREs with five different magnetic particle sizes under different magnetic field intensities and the pure rubber are shown. It is seen from figure 10 that under both zero magnetic fields and

| Mean MR-effect(%) | 125 mT | 250 mT | 375 mT |
|-------------------|--------|--------|--------|
| 60%               | 28.1   | 40.6   | 46.9   |
| Standard deviation| 1.13   | 2.52   | 1.46   |
| 20%               | 17.3   | 21     | 23     |
| Standard deviation| 1.81   | 2.22   | 2.02   |
| Ratio             | 1.62   | 1.93   | 2.04   |
with a magnetic field, the samples of MREs with five different particle sizes show a positive correlation between stress and strain. Besides, the stress increased exponentially with the increase of strain, and the tangent modulus also increases with strain. When the strain is small, the stress-strain curves of MRE with different particle sizes have little difference, but when the strain increases to 0.2, the stress shows an obvious difference. This indicates that the stiffness of MRE increased significantly under a large strain. This is attributed to the decrease of the distance of magnetic particles in MRE samples under pressure, and the increase of the interaction between particles and matrix. Under the same magnetic field, the stress-strain curves of MRE with different magnetic particle sizes show the same rule, and under the same strain, the stress decreased with the increase of particle size. This is attributed to the orientation of smaller particles and the improvement of particle distribution in the rubber matrix.

The Young’s modulus of MREs with different magnetic particle sizes under different magnetic field intensities are depicted in figure 11. It can be seen from the figure that the increase of the particle size leads to the decrease of the Young’s modulus of MRE. This is because of the particles with a constant mass fraction. Besides, the increase of the particle size leads to a decrease in the number of particles in the same volume of MRE. Therefore, the contact area between the magnetic particles and the matrix was reduced, and the interaction between the particle surface and the matrix was weakened. This results in a decrease in the overall stiffness of MRE. Besides, the reduction of the number of particles leads to the increase of particle spacing, which weakens the reinforcement effect of particles, which may also be a reason for the decrease in material stiffness. When the particle size is 1.7 μm and 2.8 μm, the zero-field modulus of the MRE sample is slightly larger than that under 125 mT magnetic field, which may be caused by the fact that the MRE with small magnetic particles is not sensitive to a low magnetic field. When the particle size increased, the magnetostrictive modulus under each magnetic field intensity is larger than the zero-field modulus, and the magnetostrictive modulus increased with the increase of magnetic field intensity.

According to equation (1), the MR-effect of MREs with different particle diameters is calculated, as shown in figure 12. The results show that under the same magnetic field, the MR-effect increased firstly and then decreased with the increase of the particle size. When the particle size is 4.6 μm, the MRE showed the largest MR-
effect. When the particle size increases to 7.2 μm, the MR-effect begins to decrease. This indicates that the MR-effect does not increase monotonously with the increase of the particle size, but there is an optimal particle size. The optimal particle size in this study is 4.6 μm. When the particle size is smaller than the optimal particle size, the MR-effect increased with the increasing of particle size, larger than the optimal particle size, and the MR-effect decreased with the increase of particle size.

4. Conclusion

In this study, five kinds of magnetic particles with different particle sizes were selected as the reinforcements to prepare the MREs under the same magnetic field, the average particle sizes of the five kinds of magnetic particles were 1.7, 2.8, 3.9, 4.6 and 7.2 μm respectively. And five kinds of MREs with different particle concentrations were prepared under the same magnetic field, the mass percentages of the magnetic particles were 20%, 30%, 40%, 50% and 60%, respectively. In order to evaluate the influence of particle size and concentration on the microstructure and magnetorheological properties of MREs, SEM and compression tests were carried out on the samples. Based on the results acquired from the current study, the main conclusions can be deduced as follows:
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