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STUDY OF UTILIZABLE MAGNETORHEOLOGICAL ELASTOMERS

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This paper presents two kinds of magnetorheological elastomers (MREs). One is composed of appropriate silicon rubber, carbonyl iron particles and some other materials. It is cured under a strong magnetic field at a room temperature. Its shear modulus change from 0.34MPa at zero magnetic field to 3.34MPa at 1T magnetic field, the relative MR effect reaches 878%. Such high MR effect has not been reported until now. The other is composed by appropriate natural rubber, carbonyl iron particles and some other materials. After the compositions are mixed in a two-roll mill, they are cured under a strong magnetic field according to a temperature profile. The increment of its modulus reaches 3.6MPa, and the relative modulus increment is 133%. Their mechanical properties are also evaluated. All observed results show that the fabricated MREs are utilizable. They have successfully been utilized to adaptive tuned vibration absorbers, which will serve for vibration absorption of vehicles.

Keywords: Magnetorheological elastomers; modulus.

1. Introduction

Magnetorheological (MR) materials are a kind of intelligent materials whose performance can be controlled by an applied magnetic field. Since MR effect was discovered by Rabinow in 1948[1], up to now, MR materials have already become a large family with MR fluids, MR foams and MR elastomers (MREs) etc.[2]. MREs are mainly composed of micrometer size magnetizable particles and elastomer matrix. After the particles and matrix material are mixed, the mixture is usually cured in the presence of a magnetic field. Some special structures, such as chains or columns of particles, remain in the matrix. When MREs are exposed to an external magnetic field, their storage moduli will change with the intensity of applied field.

Similar to MR fluids, MREs have also attracted considerable interest in both academic and industrial fields[3-13]. MREs based on soft silicone elastomers, hard natural rubber, poly (vinyl alcohol), gelatin and RTV polyurethane sealant have been prepared. The field-dependent mechanical properties of the MREs have been investigated experimentally[14-18]. A number of models have been developed to describe MRE's performances[4,5,19,20]. MREs can be used in many applications that require variable stiffness components, such as adaptive tuned vibration absorbers (TVAs), stiffness tunable mounts and suspensions, and variable impedance surfaces[2,4,5]. The Ford Motor

Company has patented an automotive bushing employing a magnetorheological elastomer[7,8]. Although there is currently little report on applications of MREs, it is still a kind of promising material that can be used in many applications with its controllable stiffness and other unique characteristics[2].

However currently developed MREs have not large enough MR effects, which have limited their wide industrial applications. And after adding the iron particles, their mechanical shouldn't become much weaker than the matrix. This paper aims to prepare MREs having good MR effect and good mechanical properties; a reliable evaluation system is also presented.

2. Experimental

2.1. *Preparation of MRE materials*

Two kinds of MREs are prepared.

One is based on natural rubber. A conventional rubber-mixing technique, Two-Roll Mill, is used. Through the rolls uninterruptedly rotating, the molecular chains in natural rubber are breakdown, and the natural rubber losses its elastic and becomes viscous body gradually. Then crosslinkers, processing aids, carbonyl iron particles and plasticizers are added into the natural rubber. The used carbonyl iron particles are grade CN from BASF with the average sizes of 3.5μm, the natural rubber and other additives are provided by Hefei Wangyou Rubber Company. The resulting material is compressed into a mold. Then the mold is set in a self-developed magnet-heat coupled device (as shown in Fig. 1) which is capable of applying the sample a magnetic field of 0 to 1.5Tesla and a temperature field in the range from 50°C to 200°C. During the pre-cured stage, the heating system and the magnetic field are both turned on. The particles are magnetized and then form chains aligned along the magnetic field direction. 30 minutes later, the procedures of forming pre-configuration is finished. After shutting down the magnetic field, the temperature is raised to 153°C. At this condition, the sample is cured on sulfuration for 15min.

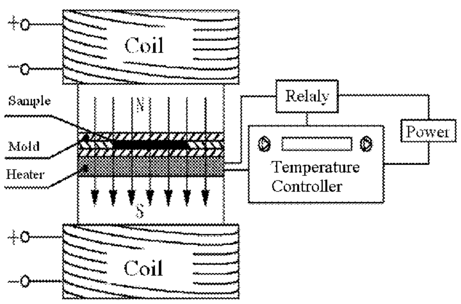

Fig. 1. The sketch map of self-developed magnet-heat coupled device.

The other is based on RTV silicone rubber (Xida Adhesives Factory, China, Model 704). RTV silicon rubber and silicone oil are chosen as matrix. After the carbonyl iron particles are immersed in the silicone oil, they are mixed with RTV silicone rubbers. Then the mixture is put into a vacuum case to remove the air bubbles inside it. After cured about 24 hours at the room temperature under a magnetic field applied by above magnet-heat coupled device, MREs are prepared.

It is noted that all percentages used in the context refer to weight percentages. The density of iron particle is 7.9g/cm^3. For natural rubber based MREs, the density of rubber and plasticizer are both about 0.97 g/cm^3. So when the content of iron particle is 60%, 70%, 80% and 90% by weight, it is 15%, 22%, 33% and 52% by volume, respectively. For silicone rubber based MREs, the density of matrix are both about 1.02 g/cm^3. So when the content of iron particle is 50%, 60%, 70% and 80% by weight, it is 11%,16%, 23% and 34% by volume, respectively.

2.2. *Dynamic testing system of MRE performance*

Dynamic Mechanical Analyzer (DMA) is widely used to characterize materials' specific properties such as modulus and damping factor. DMA involves the application of a periodic stress to a sample and the measurement of the resultant strain. From these parameters a complex dynamic stiffness may be calculated, having two parameters, namely the in-phase component, or real stiffness and the out-of-phase component, or imaginary stiffness. The ratio of these two quantities defines the damping factor. A typical experiment consists of single or multiple frequencies applied to the test sample, which is subjected to a temperature ramp. Temperature profiles can be more complex, allowing for ramp and soak segments. The sample stiffness will depend upon its Modulus of Elasticity and its geometry or shape. The modulus measured will depend upon the choice of geometry, Young's (E*) for tension, compression and bending, Shear (G*) for torsion. For MRE, the most important properties are their viscoelastic properties under applied magnetic field. However, DMA cannot measure sample's properties under a magnetic field. So we have modified the DMA. A magnetic field ranging from 0mT to 1100mT is applied to Tritec 2000B of Triton Technology Ltd. (England). The system is shown as Fig. 2. It can measure the shear modulus and damping factor at different frequency and different magnetic field. Using this system, the field dependence of shear modulus can be measured. The effects of strain amplitude and driving frequency as well as the temperature on viscoelastic properties of MREs can also be characterized. In the experiment, a Tesla gauge (Shanghai Hengtong Magnetoelectricity Co. Ltd, China) is used to measure the magnetic induction density outside the MRE.

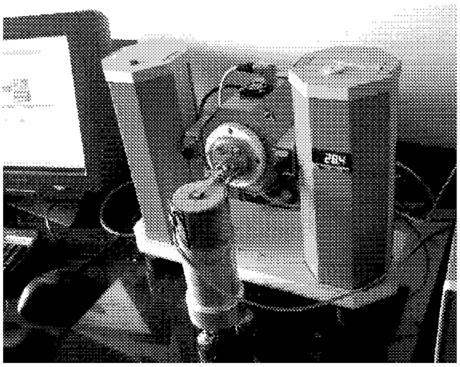

Fig. 2. A magnet-mechanics coupled DMA.

2.3. *Mechanical measurement system*

The static properties can be observed by an Electronic Pull Test Machine, which is also fit by a self-developed magnetic field ranging from 0 to 400mT. In order to supply reference for properties of materials and applications, Shaw's LX-A Rubber Hardness

Gauge, Akron Abrasion Test Machine, Thermal Ageing Test Oven, Rubber Fatigue Test Machine, and Impact Elasticity Test Machine are also set up to monitor their corresponding mechanical properties, respectively.

3. Results and Discussion

3.1. *Natural rubber based MRE*

The influences of fabrication condition and work condition on the natural rubber based MRE performances are experimentally investigated. Their mechanical properties are also monitored. In the following results (Fig. 3-Fig. 6), the according testing strain is set at 0.3%.

Figure 3 shows the field-dependence of shear modulus and damping factor of a group of MREs which contain same compositions (60% of iron particles, 30% of natural rubber and additives, and 10% of plasticizers) and pre-cured at same temperature of 80℃, but at different magnetic field of 0mT, 300mT, 600mT and 900mT, respectively. As can be observed from Fig. 3(a), shear modulus of each sample shows an increasing trend with magnetic field prior to the iron particle saturation, but strong magnetic field applied during curing leads to the high magneto-induced modulus. From Fig. 3(b), it can be observed that strong magnetic field applied during curing also leads to high loss factor.

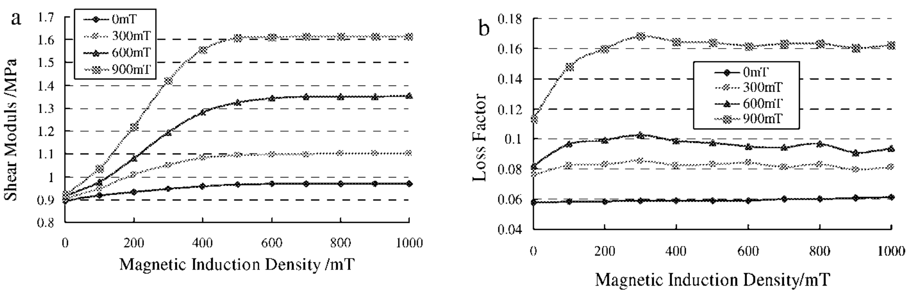

Fig. 3. Magneto-induced modulus (a) and loss factor (b) *versus* applied magnetic strength for MREs cured under different magnetic field.

Figure 4 shows the field-dependence of shear modulus of a group of MREs with the same compositions (60% of iron particles, 20% of natural rubber, and 20% of plasticizers) and pre-cured at same magnetic field (1T), but pre-cured at different temperature of 60℃, 80℃,100℃,120℃, respectively. As can be observed from Fig. 4, the MRE pre-cured at 80℃ has the best MR effects in this group. 80℃ is the ideal temperature for the particles to move and form ordered pre-configuration.

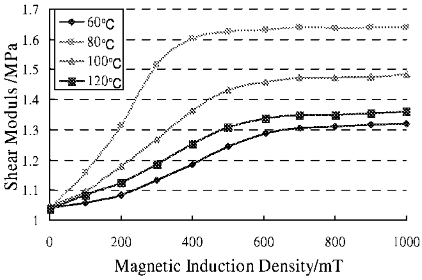

Fig. 4. Shear modulus of MREs pre-cured at different temperature.

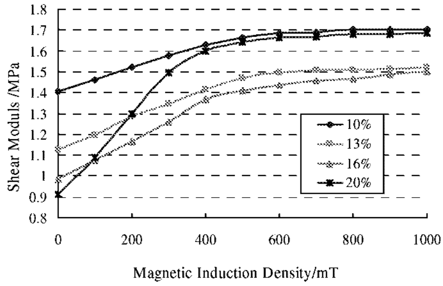

Fig. 5. Shear modulus of MREs with different plasticizer.

Figure 5 shows the field-dependence of shear modulus of a group of MREs which is pre-cured at same temperature of 80°C and at same magnetic field (1T). They contain same content of iron particles (60%), but contain different content of plasticizers: 10%, 13%, 16% and 20%. From this figure, the zero-field moduli (G_0) of the samples with 10% and 20% of plasticizer are 1.4MPa and 0.9MPa, respectively. Also, their corresponding magneto-induced moduli are 0.2MPa and 0.7MPa. So the relative MR effects $\Delta G/G_0$ are 14% and 78%, respectively. Therefore, the amount of plasticizers in the matrix plays an important role in improving MR effects, especially the relative MR effects.

Figure 6 shows the field-dependence of shear modulus of a group of MREs which is pre-cured at same temperature of 80°C and at same magnetic field (1T). But they contain different content of iron particles: 60%, 70%, 80% and 90%. The results show that the magneto-induced modulus increases dramatically with the particle content increasing. More the particles are, higher the magneto-induced modulus is. However, the increment of iron particles also enhances the zero-field modulus, which may decrease the relative MR effect. For example, the relative MR effect is reduced from 133% to 107% when particles content changed from 80% to 90%. Thus, it is not applicable to fabrication practical MRE by solely increasing particle contents.

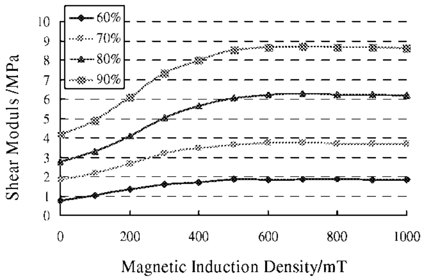

Fig. 6. Shear modulus of MREs with different iron particles.

The influence of work condition on MRE's properties is also investigated. From above results, sample with 80% iron particles, 10% natural rubber and 10% plasticizers is pre-cured at 80°C and at the magnetic field of 1 T. Figure 7 shows the field dependence of modulus at various strain amplitudes, where the driving frequency is fixed as 5 Hz. The experimental results demonstrate the MREs behave as classical viscoelastic materials. In other words, the modulus of MREs shows a decreasing trend with strain amplitude.

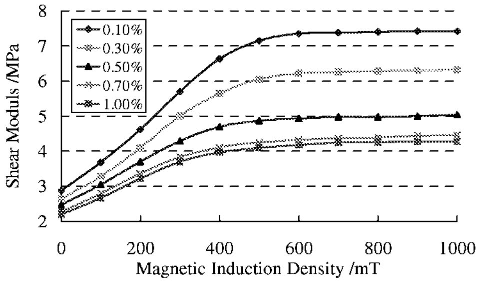

Fig. 7. Shear modulus measured at different strain amplitudes.

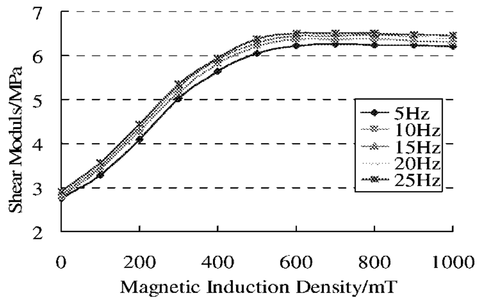

Fig. 8. Shear modulus measured at different exciting frequencies.

Under the same dynamic stain amplitude of 0.3%, the frequency dependence of MRE's shear modulus is measured and shown in Fig.8. It is demonstrated that the exciting frequency has little influence on the magneto-induced modulus.

The mechanical properties of above MRE are monitored. Its tensile strength before thermal aging is 1.38MPa, after thermal aging at 70℃ for 2 days is 1.04MPa, angle tear strength is 5.5N/mm, resilience factor is 15%, and hardness is 65A , density is 2.9g/cm^3, abrasion decrement at press force of 28N after 50000 rounds is 1.1%. They are same order as usual natural rubber.

3.2. *Silicone rubber based MRE*

The influences of composition content and magnetic field strength during curing on the silicone rubber based MRE's performances are also experimentally investigated. The testing strain is set at 2%. The composition contents of samples are shown in Table 1.

Table 1. Composition percentages of MREs based on silicone rubber.

Sample No.	Carbonyl iron particle	Silicone rubber	Silicone oil
1	50%	25%	25%
2	60%	20%	20%
3	70%	15%	15%
4	80%	10%	10%

The field dependence of modulus of samples with different contents is shown in Fig. 9. All samples are cured under a magnetic field of 1.5T. With the iron particles increase, the magneto-induced modulus increase quickly. When the MREs are composed by 80% carbonyl iron particles, 10% silicon rubber and 10% silicone oil, the shear modulus change from 0.34MPa at zero magnetic field to 3.34MPa at 1T magnetic field, the relative MR effect reaches 878%. The field dependence of modulus of samples cured under different magnetic field is shown in Fig. 10. All samples have same composition as sample 4 in Table 1.

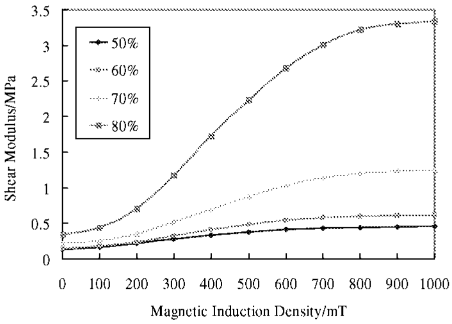

Fig. 9. Shear modulus of samples with different contents.

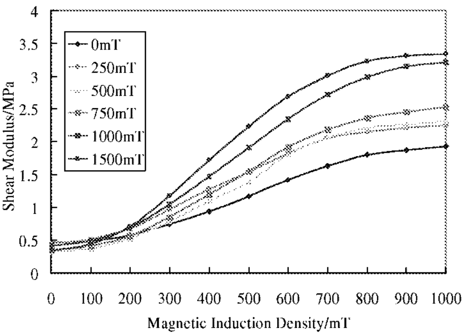

Fig. 10. Shear modulus of samples cured under different magnetic field.

Similar to MREs based on natured rubber, magnet field intensity in curing the mixture affects the MR effect greatly. Strong magnetic field applied during curing leads to high magneto-induced modulus. Their mechanical properties are also monitored. For sample 4 in Table 1, its tensile strength is 0.28MPa, angle tear strength is 1760N/mm, resilience factor is 9%, hardness is 28A, and density is 3.3g/cm^3. They are same order as usual silicone rubber.

4. Conclusion

- A system of fabricating MREs is setup to mix the composition completely and cure the mixture at a coupled controllable magnetic field and temperature field.
- A reliable evaluation system is setup to measure the dynamic properties and mechanical properties of MREs.
- Prepared MREs based on natural rubber has good mechanical properties, its MR effect can also reach 3.6MPa, and the relative MR effect is 133%. MREs based on silicone rubber have better MR effect, its best MR effect can reach 3.34MPa, and the relative MR effect is 878%. These results have exceeded the best report in the literatures regarding MREs which is based on the same kind of matrix and measured at same condition. They also have mechanical properties at same order as the matrix.
- To fabricate utilizable MREs, the most important thing is to form good ordered-structure during curing. The following factors should be considered:
  a) suitable compositions and suitable contents;
  b) strong magnetic field during curing;
  c) suitable curing temperature profile for some kinds of MREs.

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