Study on the properties of porous magnetorheological elastomers under shock effect

B X Ju\textsuperscript{1,2}, M Yu\textsuperscript{1,2,1}, J Fu\textsuperscript{1,2}, X Zheng\textsuperscript{1,2} and Q Yang\textsuperscript{3}

\textsuperscript{1} Research Center of Sensing and Instrumentation Technologies, Chongqing University, Chongqing 400044, China
\textsuperscript{2}College of Optoelectronic Engineering, Chongqing University, Chongqing 400044, China
\textsuperscript{3}State Key Laboratory of Polymer Materials Engineering, Sichuan University, Chengdu 610065, China

E-mail: yumiao@cqu.edu.cn

Abstract. As a safe protector, buffer has been widely applied to engineering applications. The properties of cushion materials play a key role in the performance of the buffer under shock loading. Magnetorheological elastomers (MRE) are a kind of novel smart materials and show to have a controllable, field-dependent modulus, which have attracted increasing attentions and broad application prospects. This paper aims to fabricate a new kind of MRE, named as porous MRE, and study on the properties of porous MRE under shock effect in the presence of an external magnetic field. Three kinds of MRE samples based on polyurethane matrix were prepared without external magnetic field, and ammonium bicarbonate was used as foaming agent with content of 0 wt.\%, 0.26 wt.\%, 0.67 wt.\%, respectively. The microstructures of the sample were observed by using a digital microscope, and image processing and analysis was applied to calculate the parameters of porous MRE. A sleeve structure and mass block were used to test the shock performance of porous MRE under shear mode, and an electromagnetic vibration and shock table was used to provide shock signal with half-sine shock signal. The results show that the content of foaming agent has an obvious influence on the microstructures of porous MRE. The porosity of the porous MRE samples increases with increasing of foaming agent content. Moreover, experimental results show that shock energy dissipation capacity is better than that of traditional MRE. This study is expected to provide guidance in the application of MRE in practical devices, such as in buffer devices.

1. Introduction

Magnetorheological (MR) materials are known as smart materials that have rheological properties that can be changed under a magnetic field, which can be classified into several groups, including magnetorheological fluids (MRF) [1-2], magnetorheological elastomers (MRE) [3-5], magnetorheological gel (MRG) [6], magnetorheological foam [7], magnetorheological plastomer (MRP) [8], and so on. The most common is MRF and MRE. MRF is magnetically polarizable particles suspended in viscous fluids. MRE is a kind of material, which have polarizable particles arranged in chains in polymer media such as silicon rubbers, natural rubbers and polyurethane matrix [5, 9]. There

\textsuperscript{1} Corresponding author.
are some problems in MRF, such as particle sediment, stability and leakage in application devices, these problems hinder its further development. To solve these problems, MRE with polymer matrices are developed. Obvious advantages of MRE are that the particles are not able to settle with time and that there is no need for containers to keep the MR material in fixed place.

MR materials have many analogical mechanical behaviors. But, MRE have a unique mechanical performance from other material, MRE have a controllable, field-dependent modulus while MRF have a field-dependent yield stress [10]. The applications of MRE have focused on several areas, such as MRE adaptive tuned vibration absorbers [11], MRE isolators [12], and MRF-MRE dampers [13]. In order to broaden the scope of application of MRE, several aspects of MRE performance have been studied. Chen et al. [9] investigated the effects of fabrication conditions (matrix type, external magnetic flux density, and temperature), and materials (plasticizers and iron particles) on MRE performances. When the iron particle weight fraction is 80% and the external magnetic flux density is 1 T, the field-induced increment of shear modulus reaches 3.6 MPa, and the relative MR effect is 133%. Li et al. [5] studied the effect of the pre-structure process on MRE performance, the results demonstrated that the pre-structure process strongly affected the magnetic field dependence of shear storage modulus of MRE. The interfacial friction damping properties of MRE is investigated experimentally by Fan et al. [14]. The experimental results imply that the interfacial friction damping mainly comes from the frictional sliding at the interfaces between the free rubber and the particles. Moreover, the influence of the matrix type, dynamic strain amplitude, driving frequency, and content of iron particles on damping property was investigated by Li et al. [15]. Zhang et al. [16] investigated fatigue properties of MRE samples, the results revealed that MR effect, storage modulus, and loss modulus of MRE depended strongly on the strain amplitudes and the number of cycles. The mechanical properties of MRE were tested in compression passively and with increasing magnetic flux density by Kallio et al. [17]. It was noted that the dynamic stiffness of aligned MRE increased with increasing testing frequency range, the loss factor of aligned MRE was also tunable with the magnetic flux density but the absolute values also depend on the testing frequency. Therefore, more work should be done to enlarge practical applications of MRE.

This study investigate the shock performance of porous MRE, several kinds of MRE samples based on polyurethane matrix were prepared, the microstructures, dynamic mechanical properties and shock performance were analyzed. We hope this study can provide a good guidance for improving performance of isotropic MRE.

2. Experimental

2.1. MRE samples’ fabrication

The material of fabricated MRE samples consist of carbonyl iron particles (type CN, with the size distribution: $d_{10} = 3.5 \, \mu m$, $d_{50} = 6.5 \, \mu m$ and $d_{90} = 14 \, \mu m$, provided by BASF corporation) and rubber matrix, stannous octoate (Sinopharm Chemical Reagent Co. Ltd., China) was used as catalyst. The matrix based on polyurethane material was mainly synthesized from castor oil (CO) and diphenylmethane diisocyanate (MDI: 4,4- ≈ 50%, 2,4- ≈ 50%, Yantai wanhua polyurethanes Co. Ltd., China). There are three steps in the synthesis of the MRE samples. Firstly, the mixture was mixed by CO and MDI, and weight ratio of CO and MDI is 100:26. Secondly, ammonium bicarbonate was added to mixture with stirring. At last, the mixture was mixed with carbonyl iron particles, and the mixture was cured at a temperature of 60°C for 2 hours without external magnetic field. When the samples were cured, ammonium bicarbonate can be decomposed into $NH_3$, $CO_2$ and $H_2O$, the porous MRE samples were prepared as a function of ammonium bicarbonate. In addition, the samples without any ammonium bicarbonate for comparison purposes were also prepared. In this research, three kinds of MRE samples were prepared, the composition of MRE samples were listed in table 1.
| Sample name | Carbonyl iron | Matrix | Ammonium bicarbonate |
|-------------|---------------|--------|----------------------|
| Sample 1    | 70            | 30     | 0                    |
| Sample 2    | 70            | 29.74  | 0.26                 |
| Sample 3    | 70            | 29.33  | 0.67                 |

2.2. Microstructure of MRE
The microstructures of the samples were observed by using scanning electron microscope (SEM, FEI Corporation) and VHX-600 digital microscope (Keyence Corporation). In this paper, three kinds of MRE samples with different foaming agent content were prepared without magnetic field at a certain temperature. The microstructures were investigated and shown in figure 1 and figure 2.

![Microstructure of MRE sample (500×).](image)

![Microstructures of MRE samples (50×, A: sample1, B: sample2, C: sample3).](image)

Figure 1 shows that the carbonyl iron particles are randomly distributed in the rubber matrix; the particles are embedded in and well bound with the rubber matrix. In addition, it can be seen from figure 2 that ammonium bicarbonate has an important influence on the structure of the MRE samples. When ammonium bicarbonate is added to the samples, lots of pores freely distribute in the matrix after curing under a certain temperature, the porosity is very different with different ammonium bicarbonate content.

2.3. Testing of dynamic mechanical properties
Dynamic mechanical properties of MRE samples were tested by using an advanced rheometer (MCR301, Anton Paar), where a magnetorheological device was added on rheometer. The electromagnetic field can generate magnetic fields ranging from 0 to 1.2 T. The picture of testing system is shown in figure 3. This system can applies a fixed oscillatory strain and frequency to samples, shear storage modulus, loss modulus and the damping factor can be calculated. The size of each sample is 20 mm in diameter and 1.2 mm in thickness.
To study the influence of magnetic field on the dynamic mechanical properties of MRE samples, MRE samples were tested under shear mode with constant strain amplitudes of 0.1%, 1% and 2%, respectively. Testing frequency was fixed at 10 Hz, and testing magnetic flux densities of from 0 to 1.2 T were selected. Figure 4 shows the relationship between the shear modulus of MRE and the magnetic flux density under different testing strain amplitude. From this figure, it can be seen that the initial and maximum shear storage modulus of MRE have decreasing trend with increasing of strain amplitude. In additional, magneto-induced shear storage modulus and MR effect are key parameter for evaluating MRE performance. In this study, magneto-induced modulus is defined as the absolute difference between the maximum value of shear storage modulus and the initial modulus. MR effect is the ratio of magneto-induced modulus and initial modulus. The magneto-induced modulus can achieve to 1.16MPa when strain amplitude is 0.1% and MR effect is as high as roughly 209.8%.

Figure 4. Shear storage modulus of MRE sample (ammonium bicarbonate content is 0 wt.%).

Figure 5. Loss factor of MRE sample (ammonium bicarbonate content is 0 wt.%).
MRE is a new kind of magnetic functional materials, which has been successfully applied to the variable stiffness vibration isolation and vibration absorption device [18-19]. In order to improve vibration absorber and isolation control effect, appropriate damping values of MRE is needed; the relationship of loss factor and magnetic flux density is shown in figure 5. As shown in figure 5, loss factor of MRE sample decrease steadily with increasing of external magnetic field, which represents the ability of dissipating energy of MRE.

2.4 Porosity of MRE

All the samples were cured at a certain temperature, ammonium bicarbonate can be decomposed into several kinds of gas (NH\textsubscript{3}, CO\textsubscript{2} and H\textsubscript{2}O) when temperature is more than 36ºC, and the porous structure was created due to the gas formation. In order to calculate the porosity of MRE, quantitative image analysis techniques were used to analyze microstructures of the MRE samples. Image segmentation technology was utilized to distinguish the object from the background; it is to distinguish between the rubber matrixes and pores. Threshold methods are widely used in image segmentation because of their simplicity and efficiency. Therefore, this study used threshold segmentation to convert the microstructure image as a ‘binary’ image. The threshold methods can be expressed as follow:

\[
 f_j(x, y) = \begin{cases} 
 h_0, & f(x, y) < t \\
 h_1, & f(x, y) \geq t 
\end{cases}
\]

(1)

Where \( f(x, y) \) represent gray scale of pixel point \((x, y)\), \( t \) is threshold value, \( h_0 \) and \( h_1 \) is binary gray level. 0 and 1 was used to instead of \( h_0 \) and \( h_1 \). 0 and 1 is represented by black and white, respectively. Once the object has been successfully segmented, threshold segmentation can convert the microstructure image to be a ‘binary’ image, i.e. white or black, as shown in figure 6.

\[\text{Figure 6. Microstructures of samples with different ammonium bicarbonate contents: A–C respectively corresponds to 0 wt.\%, 0.26 wt.% and 0.67 wt.%; D–F corresponds to the results of image threshold segmentation of A–C.}\]

The black represents the pore regions, and the white is the area without pores. So the porosity can be calculated from the numbers of pixels of white and black. The porosity of the MRE samples as a function of ammonium bicarbonate content is shown in table 2.
Table 2. Porosity of MRE samples.

| Sample name | Porosity (v/v %) |
|-------------|------------------|
| Sample 1    | 0                |
| Sample 2    | 32.5             |
| Sample 3    | 52.7             |

It can be seen from table 2 that the porosity of the MRE samples increases with increasing ammonium bicarbonate content. Previous studies have shown that the porosity has a great influence on the performance of the MRE [20].

2.5 Structure of shock experimental device

A MRE-based shock experimental device was constructed as a closed magnetic circuit consisting of iron core, MRE, outer sleeve and excitation coil, as shown in figure 7.

![Figure 7. Schematic diagram of shock experimental device.](image)

The metallic portions of the magnetic circuit were constructed of electrical pure iron in order to carry magnetic flux. The magnetic field is adjusted by controlling the current values of the excitation coil, which was parallel with the thickness direction of the MREs. Excitation coil is a kind of copper enamel wire with roughly 500 turns around the iron core. Two MRE samples, worked in shear mode, the mechanical properties of MREs can be adjusted by input electric current to the coil, resulting in variable stiffness and damping characteristics. In this study, the shock experimental device was based on a single degree of freedom system.

3 Results and discussion

In order to test the performance of porous MRE under shock effect, its performance is studied under various shock conditions using electromagnetic vibration table, the photo of equipment for shock experiment is shown in figure 8.

![Figure 8. Photo of equipment for shock experiment.](image)
The experiments were carried out using constant acceleration excitation input of 2 g, an electric current ranging from 0 to 2A was applied to the equipment, which can change stiffness and damping of MRE samples during each set of testing, and each testing has been executed at room temperature.

![Experimental system for testing the shock performance of porous MRE.](image)

Figure 9. Experimental systems for testing the shock performance of porous MRE. In order to investigate the performance of porous MRE under shock effect, the experimental device was mounted on an electromagnetic vibration system (model: MPA406/M232A, ETS Solutions (Beijing) Ltd), this system include power amplifier, controller and electromagnetic vibration table. Half-sine shock signal with different acceleration amplitude and pulse width was generated by this electromagnetic vibration system. A mass block, used as payload, was fixed on the top of the experimental device. Two accelerometers (model: 24108, China Aerospace Science and Technology Corporation) were used to measure the acceleration responses of the base and the payload. The acceleration signals were sent to a data acquisition instrument (model: MDR-05, Beijing Aerostandard New Technology Company), and then sent to a computer for processing. The performance of porous MRE under shock effect can be analyzed through the signals of acceleration excitation and response.

The modulus and damping property of MRE have shown in figure 4 and figure 5, these performances are function of applied electric currents and input strain amplitudes. In order to evaluate the performance of porous MRE under shock effect, the mechanical model of shock can be written as

\[ m \ddot{x}(t) + c \dot{x}(t) + kx(t) = P(t) \]  

(2)

Where \( P(t) \) is shock excitation function, \( m \) is payload mass, \( c \) is viscous damping coefficient, and \( k \) is stiffness of MRE.

The duration of shock effect is very short. Therefore, shock excitation can be expressed as

\[ P_s = \int_0^T P(t) \, dt \]  

(3)

The maximum response acceleration of the system can be solved through expression 2 and 3

\[ \ddot{x}_{\text{max}} = \frac{P_s \omega_n e^{-\frac{c}{2m} t_{\text{max}}}}{\sqrt{1 - \xi^2}} \sin(\omega_n \sqrt{1 - \xi^2} t_{\text{max}} + \varphi) \]  

(4)

\[ \xi = \frac{c}{2m \omega_n} \]  

(5)

\[ \omega_d = \sqrt{1 - \xi^2} \omega_n \]  

(6)

\[ \varphi = \arctan \frac{2 \xi \sqrt{1 - \xi^2}}{1 - 2 \xi^2} \]  

(7)

Performance of porous MRE under shock effect can be expressed by following equation
\[ T = 20 \lg \frac{\dot{x}_{\text{max}}}{a} \]  

(8)

Where \( \dot{x}_{\text{max}} \) is maximum response acceleration, \( a \) represent excitation acceleration.

The relationship between excitation acceleration signals and excitation acceleration signals is shown in figure 10 and figure 11.

Figure 10. Excitation acceleration signal of shock testing.

From figure 10, the excitation acceleration signal response to a half-sine shock signal, where the acceleration amplitude is 2 \( g \). Due to this excitation shock signal, the response acceleration signals of shock testing are shown in figure 11.

Figure 11. Response acceleration signals of shock testing: A–C respectively corresponds to sample1, sample2, sample3 with current of 0A; D-F corresponds to the results of sample1, sample2, sample3 with current of 2 A.

Compared to the response acceleration signals of shock testing, the results show that response acceleration amplitude decreases with increasing of the porosity of MRE samples and current. For example, acceleration amplitude of three samples are 1.693 \( g \), 1.681 \( g \), 1.6 \( g \) with current of 0 A, while acceleration amplitude with current of 2 A are 1.483 \( g \), 1.445 \( g \), 1.345 \( g \). In figure 12, the results of buffer effect of three samples under different current are shown.

It can be seen from figure 12 that buffer effect of three samples is dependent on the porosity and current. The porosity of MRE samples has an obviously influence on buffer effect at current of from 0 to 2 A. Sample3 has higher buffer effect than that of sample1 and sample2, Therefore, porous MRE has better buffer effect performance.
4 Conclusions

Three kinds of porous MRE samples based on polyurethane material were fabricated without external magnetic field. Their microstructures and dynamic performance were studied, and image analysis has been applied to analyze the microstructure of porous MRE. It was found that the ammonium bicarbonate content influence the porosity of porous MRE samples greatly and different porous MRE have different buffer effect. The response acceleration amplitude decreases with increasing of the porosity of MRE samples and current, sample3 with higher porosity has higher buffer effect than that of sample1 and sample2. Due to its unique properties, this porous MRE will have broad applications in isolation and buffer device.

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