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A novel porous magnetorheological elastomer: preparation and evaluation

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Abstract
A new kind of magnetorheological elastomer (MRE), named porous magnetorheological elastomer (P-MRE), was prepared by filling with NH\textsubscript{4}HCO\textsubscript{3}. Two groups of samples with different content of NH\textsubscript{4}HCO\textsubscript{3} and carbonyl iron particles were prepared. The microstructures of the samples were observed by using a digital microscope, and image analysis was applied to analyze the microstructure of P-MRE. The dynamic performance of the shear mode was also investigated under different magnetic flux densities. The shear storage modulus, MR effect and loss factor were calculated by using a mechanical property measurement system. The experimental results indicate that the NH\textsubscript{4}HCO\textsubscript{3} has a greater impact on the properties of P-MRE, including the microstructures and dynamic mechanical performance. The increment of NH\textsubscript{4}HCO\textsubscript{3} content enhances the porosity of P-MRE, and decreases the shear storage modulus. Moreover, P-MRE has a more obvious MR effect than that of MRE without NH\textsubscript{4}HCO\textsubscript{3} filling, and the MR effect of P-MRE can be substantially increased by increasing the NH\textsubscript{4}HCO\textsubscript{3} and carbonyl iron particle content. The damping property is also affected by the NH\textsubscript{4}HCO\textsubscript{3} filling; the loss factor of the P-MRE can also be increased by increasing the NH\textsubscript{4}HCO\textsubscript{3} content. On the basis of these results, this study is expected to provide a good guide for optimization and design of a new kind of MRE.

(Some figures may appear in colour only in the online journal)

1. Introduction
In the past few decades, interest in the study of magnetorheological materials has shown huge growth. The group of magnetorheological materials includes MR fluids, foams and elastomers. Magnetorheological elastomers (MREs) are a new kind of smart material, whose mechanical and magnetic properties are controllable under applied magnetic field [1]. MREs basically consist of micrometer-sized magnetically permeable particles in a solid or gel-like non-magnetic matrix material. The functionality of these materials is based on the magnetic interaction of filler particles when subjected to an external magnetic field; the particles are firmly locked in place and the degree of freedom of movement is governed by the matrix elastomer [2]. Because of their unique characteristics, MREs have attracted increasing attention and have developed broad application prospects recently. A number of studies show that recent interest in applications has focused on three main areas. The first one is sound and vibration control, especially in vehicle applications, including dynamic vibration absorbers and isolators. The second one is controllable stiffness change and deformation. The third one is sensors and actuators such as the rolls in papermaking machines and releasable fastener systems [3].

MREs are the solid analogs of MR fluids, where the oil has been replaced by a rubber material. Conventionally, MREs are cured under a strong magnetic field, and the
iron particles will form chainlike structures embedded in the matrix; these are called anisotropic MREs. On the contrary, some papers have presented a method to fabricate isotropic MREs under natural conditions [4]. The property of the magnetic field-dependent modulus can be characterized by the MR effect, which is described as a relative change in modulus under an applied magnetic field [5]. There are still some problems, like low MR effect and dynamic damping, limiting their practical application. In order to get a good MR effect, Li et al. studied the effect of the pre-structure process on the MRE performance; the results showed that the pre-structure process is dominated by three influencing factors: magnetic field, curing time and temperature [6].

The results for special particles and high particle volume concentration used by Lokander and Stenberg showed that the MR effect in isotropic MR rubbers is larger than that previously reported [7]. Hu et al. fabricated MRE using PU and Si-rubber as the matrix, the MR effect was improved by optimizing the PU/Si-rubber ratio [8]. Böse and Roder found that MRE composites with large iron particles can increase the magneto-induced storage modulus [9]. Zhang et al. researched radiation vulcanization (RV) of MRE based on silicone rubber. The experimental results showed that the RV samples have large magnetic-induced modulus, large zero-field modulus, and good durability property of the MR effect [10]. Zajac et al. presented a technology of manufacturing isotropic MRE with a thermoplastic elastomer matrix, and the strongest MR effect was registered for the so-called ‘soft’ matrix, as the magnetic field strength was changed between $H_0 = 5$ kA m$^{-1}$ and $H_1 = 130$ kA m$^{-1}$; the stress amplitude changed by nearly 30% and the hysteresis loop area changed by about 80% [11]. Yu and Wang prepared a new composite MRE sample embedded with a copper coil; a shear stress–strain experiment for the composite MRE was carried out and the result showed that the composite MRE had a good MR effect [12]. A novel hybrid MRE that was embedded with magnetorheological fluids (MRFs) and magnetorheological gels (MRGs) was fabricated by Zhang et al.; all of the mechanical properties, especially the MR effect, exhibited significant improvement compared with those of traditional MRE [13]. Padalka et al. proved that the greater the permeability and magnetic saturation of the particles, the greater the difference in the magnitude of the particle–particle interaction as the strength of the applied field is changed. Therefore, the greatest MR effect was observed for Fe and it decreased accordingly with Ni having the smallest MR effect [14].

On the basis of the literature review, it is quite clear that the MR effect can be increased remarkably in many ways. In this work, a new isotropic MR material (porous MRE) was fabricated by filling with NH$_4$HCO$_3$, and the MRE samples were tested under shear mode with increasing magnetic field strength. The shear storage modulus and loss factor could be calculated on the basis of the stress–strain curves. We hope that this study will provide good guidance for improving the properties of isotropic MRE.

### 2. Experimental details

#### 2.1. Sample preparation

The sample ingredients are carbonyl iron particles, silicone rubber, and ammonium bicarbonate (NH$_4$HCO$_3$). Carbonyl iron particles were provided by the BASF corporation with the size distribution $d_{10} = 3.5$ μm, $d_{50} = 6.5$ μm, $d_{90} = 14$ μm, and used as the magnetic particles dispersed in the matrix. There are three steps in the synthesis of the samples. Firstly, the NH$_4$HCO$_3$ was immersed with silicone rubber and then mixed with the carbonyl iron particles; all the ingredients were stirred in a beaker for about 10 min at room temperature. Secondly, the mixture was placed in a vacuum oven to remove the air bubbles and then packed into an aluminum mold. Finally, the mixture was cured at a temperature of 100°C for 2 h without external magnetic field. When the samples were cured, the NH$_4$HCO$_3$ could be decomposed into NH$_3$, CO$_2$ and H$_2$O; the porous MRE samples were prepared as a function of the NH$_4$HCO$_3$. The first group of samples was based on different NH$_4$HCO$_3$ content, four kinds of samples with 1, 2, 4, and 6 wt% NH$_4$HCO$_3$ content were fabricated to investigate the influence of NH$_4$HCO$_3$ content on the samples; these were named as P-MRE. In addition, samples without any NH$_4$HCO$_3$ for comparison purposes were also prepared; these samples were called C-MRE. These samples are listed in Table 1. Chen et al. have proved that the content of iron particles plays a significant role in the performance of MRE based on natural rubber [15]. In order to investigate the influence of iron particle content on the porous MRE’s performance, three samples with different iron particle contents were fabricated under the same NH$_4$HCO$_3$ content; the compositions of the second group of samples are listed in Table 2.

#### 2.2. Observation of microstructure

The microstructure of the MRE samples was observed by using a VHX-600 digital microscope, purchased from KEYENCE Corporation. Through the observation of the

### Table 1. Compositions of the first group of samples (wt%).

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Carbonyl iron particles</th>
<th>Silicone rubber</th>
<th>NH$_4$HCO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-MRE-70</td>
<td>70</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>P-MRE-70-1</td>
<td>70</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>P-MRE-70-2</td>
<td>70</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>P-MRE-70-4</td>
<td>70</td>
<td>26</td>
<td>4</td>
</tr>
<tr>
<td>P-MRE-70-6</td>
<td>70</td>
<td>24</td>
<td>6</td>
</tr>
</tbody>
</table>

### Table 2. Compositions of the second group of samples (wt%).

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Carbonyl iron particles</th>
<th>Silicone rubber</th>
<th>NH$_4$HCO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-MRE-60</td>
<td>60</td>
<td>38</td>
<td>2</td>
</tr>
<tr>
<td>P-MRE-70</td>
<td>70</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>P-MRE-80</td>
<td>80</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 1. Microstructures of porous MRE samples (800×).

Figure 2. Microstructures of porous MRE samples with different NH$_4$HCO$_3$ contents (20×).

Figure 3. Sketch of the mechanical property measurement system.
the excitation process. A laser displacement sensor (model LM10, SUNX Corporation) was fixed to monitor the vibration table displacement, which represented the deformation of the MRE samples. The signals of the force sensor and laser displacement sensor were transferred to a data acquisition instrument, and then sent to a computer for processing and analysis. Both the modulus and loss factor can be calculated from the data of strain and stress.

In this work, the MRE samples were tested under shear mode at room temperature, the applied frequency and strain amplitude were fixed at 30 Hz and 0.97% respectively; this strain amplitude can ensure that the testing data fall in the linear viscoelastic range [16]. The magnetic flux density varied from 0 to 600 mT. In addition, the MRE samples had a uniform size of 15 mm × 15 mm × 4 mm.

3. Results and discussion

3.1. Stress–strain relationships

The real-time force and displacement signals were recorded and used to reconstruct the stress–strain relationships. Stress–strain curves for the first group of samples are shown in figure 5, from which it can be found that all stresses and strains form nice elliptical shapes, the areas of which increase steadily with increment of the external magnetic fields. It should also be mentioned that the shear stress values depend on the intensity of the applied magnetic field with a fixed maximum strain. The areas of the stress–strain curves showed a marked increase in the energy dissipated with increasing magnetic flux density; the phenomenon that a mechanical hysteresis loop arises under harmonic loads indicates irreversible energy dissipation. Figure 5 also shows relationships between stress–strain and NH$_4$HCO$_3$ content under different magnetic flux densities. As shown in the curves, the stress amplitude of different samples decreases with increasing NH$_4$HCO$_3$ content. As can be seen, the stress amplitude of the first group of samples changed from 121.6 to 38.1 kPa, decreased by 68.7%, with a variation of the NH$_4$HCO$_3$ content from 0 to 6 wt%. When the NH$_4$HCO$_3$ content increased, the area and long axis slope of the stress–strain curves had more obvious change trends with increasing external magnetic field. In combination with the
phenomenon above, it is clear that P-MRE is more sensitive to external magnetic field and the NH$_4$HCO$_3$ content in P-MRE has a greater impact for stress–strain relationships.

3.2 Analysis of the influence of NH$_4$HCO$_3$ content on the MR effect

The shear storage moduli of P-MRE samples with different NH$_4$HCO$_3$ content were investigated under various magnetic flux densities from 0 to 600 mT, as shown in figure 6.

It can be seen from figure 6 that the storage modulus has a great dependence on the NH$_4$HCO$_3$ content. The storage modulus of the samples decreases steadily with increasing NH$_4$HCO$_3$ content. For example, when the NH$_4$HCO$_3$ content is zero, the maximum storage modulus of C-MRE-70 is 2.42 MPa, while the maximum storage modulus of P-MRE-70-6 is 0.74 MPa. In other words, the storage moduli of the MRE samples show a downward trend with NH$_4$HCO$_3$ filling content. However, when the NH$_4$HCO$_3$ content is higher than 2 wt%, the downward trend is not so obvious, which means that the influence of NH$_4$HCO$_3$ content on the moduli of the samples became smaller under higher mass ratio of NH$_4$HCO$_3$.

All the samples were cured at a high temperature, NH$_4$HCO$_3$ can be decomposed into several kinds of gas, and the porous structure was created due to the gas formation. As the iron particle contents are close, the storage modulus of the MRE samples is significantly influenced by their matrix. It can be seen from figure 2 that lots of pores are freely dispersed in the P-MRE samples. Thus, the matrix of P-MRE is regarded as a kind of mixed matrix consisting of silicone rubber and pores, and quantitative image analysis techniques were used to analyze the influence of the porosity on the P-MRE properties. Figure 7 shows the results of slice microstructure threshold segmentation.

The biggest issue is one referred to as ‘segmentation’, which is that of distinguishing the object from the background; once the object has been successfully segmented, it can be analyzed. Threshold segmentation can convert the microstructure image to be a ‘binary’ image, i.e. white or black. When the ‘threshold’ range is set and the pixels in the image whose values lie in this range are converted to white, the pixels with values outside this range are converted to black. The white represents the pore regions, and the black is the area composed of silicone rubber and iron particles. The areas of the white and black regions can be calculated from the numbers of pixels. Therefore, the porosity of P-MRE can be expressed as

$$P = \frac{N_{\text{white}}}{N_{\text{white}} + N_{\text{black}}} \times 100\% \quad (1)$$

where $P$ is the porosity of the P-MRE sample, and $N_{\text{white}}$ and $N_{\text{black}}$ represent the number of pixels in the pore and black regions respectively. The porosities of the P-MRE samples as a function of NH$_4$HCO$_3$ content are presented in figure 8.

Figure 8 shows the relationship between porosity and NH$_4$HCO$_3$ content; the porosity of the P-MRE samples increases with increasing NH$_4$HCO$_3$ content. However, if the NH$_4$HCO$_3$ content exceeds 4 wt%, the porosity tends to a slow growth. In this case, when the NH$_4$HCO$_3$ content...
Figure 8. Porosities of P-MRE samples with different NH$_4$HCO$_3$ contents.

It is known that the MR effect is also influenced strongly by the zero-field modulus. P-MRE samples have a great MR effect, achieving 169.7% at a NH$_4$HCO$_3$ content of 6 wt%. Thus, the P-MRE shows a higher performance than the previously reported isotropic MRE cured under natural conditions. Therefore P-MRE is a significant advance and will have promising applications in tunable stiffness devices.

3.3. Influence of carbonyl iron particle content on the P-MRE samples

Three kinds of P-MRE samples had a NH$_4$HCO$_3$ content of 2 wt%, the difference between them was the iron particles content used, 60, 70, or 80 wt%. The influence of content of iron particles on the modulus of the P-MRE samples is shown in figure 10; the results show that the shear storage modulus increases dramatically with the particle content increases.

The storage modulus was as high as 1.53 MPa when the content was 80 wt% under a magnetic flux density of 600 mT, while for iron particle contents of 60 wt% and 70 wt%, the storage moduli of the P-MRE samples are 0.61 MPa and 0.87 MPa, respectively. The increase in the storage modulus of P-MRE samples with increasing particle content can also be explained by using equation (2).

Figure 11 shows the MR effect of P-MRE with different carbonyl iron particle contents, it agrees well with previous literature [15]. The results from figure 10 show that the magneto-induced modulus increases dramatically when the particle content increases. The modulus is induced by the interactional force between the iron particles. So, the more particles there are, the higher the magneto-induced modulus is. Thus, it is applicable to fabricate practical P-MRE by increasing iron particle content and NH$_4$HCO$_3$ filling.

\[ G'_c = \frac{G'_G G'_m}{G'_{Vf} V_f + G'_{Vm} V_m} \]  

(2)

where $G'_c$ is the storage modulus of the composite material, $G'_f$ and $G'_m$ are the storage moduli of the filler and matrix, $V_f$ and $V_m$ are the volume fractions of the filler and matrix. When MRE samples were fabricated with the same content of iron particles as filler, the storage modulus of the MRE samples was mainly decided by their matrix modulus. Lots of pores are freely dispersed in P-MRE samples. Thus, P-MRE is regarded as a kind of mixed matrix, while the matrix of C-MRE is purely silicone rubber, and the storage modulus of silicone rubber is larger than that of a mixed matrix. Furthermore, with the increase in porosity, the storage modulus mixed matrix becomes smaller. So the storage modulus of P-MRE samples shows a decreasing trend with increasing porosity, and the zero-field modulus also attenuates sharply with increasing porosity; these results will influence the MR effect greatly. The MR effect is a key parameter for evaluating MRE performance. When MRE samples are subjected to a magnetic field, the magnetic particles tend to align in the direction of the magnetic field in that carbonyl iron particles can be magnetized easily. The field-induced magnetic forces between the magnetic particles provide an ability of anti-deformation, resulting in a change of shear modulus [18]. The MR effect is expressed as [19]

\[ G_{MR-effect} = 100\% \times (G_{max} - G_0)/G_0 \]  

(3)

where $G_0$ is the initial shear storage modulus and $G_{max}$ is the maximum shear storage modulus under variable magnetic field strength from 0 to 600 mT. The MR effect is clearly shown in figure 9, where all the data were calculated from the experimental results shown in figure 6.

As shown in figure 9, the MR effect of all P-MRE samples increased steadily with increasing magnetic flux density. These results display a reversed tendency in comparison with figure 6. The P-MRE samples with higher mass ratios of NH$_4$HCO$_3$ exhibit a greater MR effect, and when the NH$_4$HCO$_3$ content is higher than 1 wt%, the MR effect of the P-MRE samples has obvious changes. P-MRE samples prepared with different NH$_4$HCO$_3$ contents have different zero-field moduli as in the above analysis. From equation (3), it is found that the MR effect is also influenced strongly by the zero-field modulus. P-MRE samples have a great MR effect, achieving 169.7% at a NH$_4$HCO$_3$ content of 6 wt%. Thus, the P-MRE shows a higher performance than the previously reported isotropic MRE cured under natural conditions. Therefore P-MRE is a significant advance and will have promising applications in tunable stiffness devices.
3.4. Damping property

In this work, the influence of the NH$_4$HCO$_3$ content on the damping property of the P-MRE samples was also studied. The damping property of an MRE sample can be described by the using loss factor, which can be used for characterization of the efficiency of damping caused by the material [20]. MRE is normally operated in the pre-yield regime in the linear viscoelastic region with small deformation, and is intended to be the structural material in applications, where the load is often of a dynamic type. In dynamic loading, the material deforms and returns back to its original form during one cycle. The shear force is varied periodically, with a sinusoidal alteration at the angular frequency $\omega$. In addition, the MRE samples are a kind of viscoelastic material; when they are subjected to sinusoidal stress, the strain will alternate but out of phase with the stress. In this paper, the strain of MRE samples is below 1%; the time-dependent stress can be expressed in sinusoidal form [21]:

$$\sigma = \sigma_0 \sin(\omega t + \delta)$$

(4)

where $\sigma_0$ is the maximum amplitude of the stress, $\delta$ is the phase angle, whose range is $0^\circ < \delta < 90^\circ$. Otherwise, the strain $\gamma$ can be expressed as follows [21]:

$$\gamma = \gamma_0 \sin \omega t$$

(5)

where $\gamma_0$ is the maximum amplitude of the strain. The signals of the force sensor and the laser displacement sensor were recorded, and could be used to reconstruct the relationship between stress--strain and time, as shown in figure 12.

The damping property of an MRE sample can be described by using $\tan \delta$ (also called the loss factor). The relationship between P-MRE samples with different NH$_4$HCO$_3$ contents and the loss factor under different magnetic flux densities is shown in figure 13.

It can be seen from figure 13 that the loss factor of P-MRE samples increases with increasing NH$_4$HCO$_3$ content. This interesting phenomenon can be explained from the composite material’s behavior. The P-MRE samples are a kind of composite material, and the components include carbonyl iron particles, the rubber matrix and pores. A sketch of the distribution of the P-MRE components is shown in figure 14.

In figure 14, the black points are the carbonyl iron particles and the white spheres are the pores; the iron particles and pores are freely embedded in the rubber matrix. So the damping property of the P-MRE samples can be expressed as

$$P\text{-MRE}_{\text{lossfactor}} \propto E_{P1} + E_{P2} + E_{P3} + E_{P4} + E_{P5}$$

(6)

where $E_{P1}$, $E_{P2}$ and $E_{P3}$ are the energy dissipation values for the rubber matrix, the carbonyl iron particles and the pores, $E_{P4}$ is the energy dissipation of the interfacial friction between the rubber matrix and the carbonyl iron particles, $E_{P5}$ is the energy dissipation between the rubber and pores. Chen et al and Fan et al have indicated that the damping properties of MRE greatly depend on the interfacial slipping between the inner particles and the matrix [22, 23]. So the energy dissipation of the iron particles and the rubber matrix as well as the pores can be ignored compared with the others, and equation (6) can be simplified to

$$P\text{-MRE}_{\text{lossfactor}} \propto E_{P4} + E_{P5}.$$  

(7)

When an external magnetic field is applied, the magnetic force is applied to the iron particles and an interaction force between the particles is generated. Iron particles and silicone rubber are different kinds of material, so they do not have a perfect combination with each other [22]. In addition, NH$_4$HCO$_3$ can be decomposed into NH$_3$, CO$_2$ and H$_2$O under...
heating, and the decomposition of NH₄HCO₃ has a great impact on the combination between the iron particles and the rubber matrix. Figure 15 shows the microstructures of the P-MRE samples based on different NH₄HCO₃ contents in the first group.

It is seen from figure 15 that the iron particles are not all embedded in the matrix and they are poorly combined with each other. When the components are combined with each other weakly, there is some defect existing between the components, and the defect between the rubber matrix and the iron particles shows an increasing tendency with increasing NH₄HCO₃ content. In other words, the interfacial slipping displacement between two kinds of material can also be increased by increasing the NH₄HCO₃ content, as shown in figure 15. A sketch of the influence of NH₄HCO₃ content on the combination between the iron particles and the matrix is shown in figure 16.

Therefore $EP_4$ can be expressed by the following equation:

$$EP_4 \propto F_1 S_1$$  \hspace{1cm} (8)

where $F_1$ is the interfacial friction force between the iron particles and the matrix, and $S_1$ represents the displacement of interfacial slipping between the iron particles and the rubber matrix. The interfacial friction force ($F_1$) is decided by the external magnetic field, while $S_1$ has a large growth with the change of NH₄HCO₃ content. As can be seen, when the NH₄HCO₃ content increases, the interfacial slipping displacement is enlarged, so $EP_4$ will increase under fixed magnetic flux density in equation (8). On the other hand, it is indicated that the interfacial friction plays an important role in increasing the damping properties of P-MRE. When P-MRE samples are fabricated by filling with different NH₄HCO₃ contents, that will have a significant impact on the number of pores in P-MRE. To verify our explanation of the relationship between the number of pores and NH₄HCO₃ content, when the image has been segmented, the object label operator is used to mark the pore regions in the segmentation images. The number is set to include objects that appear in the binary image that are clearly objects of interest. The ‘outlines’ are selected to display an image of the detected objects; the marked image is shown in figure 17.

The number of pores was counted as a result of B–E image marking; the statistical results are displayed in figure 18. It can be seen from figure 18 that the number of pores is influenced by NH₄HCO₃ content greatly; the number of pores presents an increasing tendency with increasing NH₄HCO₃ content. Therefore, $EP_5$ can be written as

$$EP_5 \propto nF_2 S_2$$  \hspace{1cm} (9)
Figure 17. Image object marking of P-MRE: B–E correspond to figure 7.

Figure 18. The relationship between the total number of pores and the NH\textsubscript{4}HCO\textsubscript{3} content.

where \(n\) is the number of pores, \(F_2\) is the interfacial friction force between the pores and the rubber matrix, \(S_2\) represents the average displacement of the interfacial slipping between the pores and the rubber matrix. \(F_2\) is dependent on the externally applied periodic strain, and figure 18 shows that the number of pores \((n)\) increases with increasing NH\textsubscript{4}HCO\textsubscript{3} content. Therefore, there is a direct proportional relationship between \(EP_5\) and NH\textsubscript{4}HCO\textsubscript{3} content. In combination with the analysis above, when \(S_2\) is larger, \(EP_5\) will much higher. The distribution of cross-sectional areas of pores was also calculated through the image analysis, as shown in figure 19.

After image processing for quantitative analysis, the aim of the image analysis was to quantify the size distribution of the pores. The NH\textsubscript{4}HCO\textsubscript{3} was used as the foaming agent during the preparation of the P-MRE. When a higher NH\textsubscript{4}HCO\textsubscript{3} content was applied, the P-MRE had more pores and the cross-sectional areas of the pores were larger, as can be seen from figures 18 and 19. \(S_2\) and the cross-sectional areas of the pores have high degree direct ratio relations, and the cross-sectional areas are increased by the NH\textsubscript{4}HCO\textsubscript{3} filling. The above results indicate that the higher the NH\textsubscript{4}HCO\textsubscript{3} content is, the larger \(S_2\) is. So, when the sample is prepared by filling with NH\textsubscript{4}HCO\textsubscript{3}, the damping of the MRE will increase. Therefore, \(EP_4\) and \(EP_5\) are mainly influenced by the NH\textsubscript{4}HCO\textsubscript{3} filling. It is clear that these results can explain the relationship between the loss factor of P-MRE and the NH\textsubscript{4}HCO\textsubscript{3} content. This interesting phenomenon may enable the P-MRE material be widely used in practical applications.

4. Conclusion

In this study, a new kind of isotropic MRE sample with different porosities was prepared by filling with NH\textsubscript{4}HCO\textsubscript{3}; this MR material is called porous MRE (P-MRE). Its microstructures and dynamic performance were studied, and image analysis was applied to analyze the microstructures of P-MRE. It was found that the construction in such MRE is no longer chains or columns of particles, and carbonyl iron particles and pores are homogeneously distributed in the matrix. The NH\textsubscript{4}HCO\textsubscript{3} content influences the porosity of P-MRE samples greatly and C-MRE and P-MRE have very different dynamic mechanical properties. P-MRE has a greater impact for stress–strain relationships and is more sensitive to external magnetic field. When this new kind of P-MRE is exposed to a magnetic field, the shear storage moduli of the P-MRE samples are lower than those of the C-MRE samples. However, experiments show that P-MRE has a more obvious MR effect, which increases with increasing NH\textsubscript{4}HCO\textsubscript{3} content. In addition, the compatibility between the iron particles and the matrix becomes weak though filling with NH\textsubscript{4}HCO\textsubscript{3}, and more and more interfacial friction occurs between pores and matrix. Furthermore, the loss factor of the P-MRE can be increased by increasing the NH\textsubscript{4}HCO\textsubscript{3} content. This P-MRE shows some special properties, such as a higher MR effect and a high damping property under an external magnetic field. Due to its unique properties, this P-MRE will have broad applications in stiffness tunable and damping devices.

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