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Elaboration and Identification of the Mechanical Properties of Magnetorheological Elastomer in Frequency-temperature Dependence

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Determining the mechanical properties of magnetorheological elastomers (MREs) is fundamental for creating smart materials and devices with desired properties and functionalities. While the MREs properties, in shear mode, have been extensively researched, the MREs properties with frequency-temperature dependence have been less exploited. In this article, we studied the performance of magnetorheological elastomers with frequency-temperature dependence. The elastic modulus, loss modulus, and loss factor of magnetorheological elastomers were studied under different temperature values, different values of magnetic field, and different values of frequency. The results showed the interest of these active materials in different industrial sectors.

Keywords: magnetorheological elastomers, mechanical properties, temperature, frequency.

1. INTRODUCTION

Polymer composite materials are materials with high mechanical performances, which can be shaped as desired by the designer and have unlimited potential. Polymer composite materials are developing today in practically all fields and are at the origin of tremendous challenges in various high-tech achievements, among them we distinguish Magnetorheological elastomers (MRE) which are, generally, prepared by dispersing magnetic particles in a non-magnetic elastomeric matrix [1 – 6]. Compared with MR fluids, the solid matrix of Magnetorheological elastomers can effectively overcome the problem in Magnetorheological fluid applications, such as particle sedimentation, sealing problems, and environmental contamination [7, 8]. Moreover, due to their large changes in modulus and fast response time, magnetorheological elastomers have attracted wide attention in semi-active vibration control [9 – 12], such as vibration isolators [13 – 16] and absorbers [17 – 19]. The viscoelastic properties of magnetorheological elastomers normally vary instantaneously and reversibly due to dipolar interaction in the presence of a magnetic field. In most cases, anisotropic magnetorheological elastomers appear to be more sensitive to the applied magnetic field with a slightly greater magnetorheological effect than isotropic magnetorheological elastomers [20, 21]. The elastic modulus of the material increases with increasing magnetic flux intensity up to magnetic saturation. MR elastomer matrices are typically a polymer such as silicone rubber [22], natural rubber [23 – 25], and polyurethane [26, 27], it is one of the most influential factors affecting the performance of polymer materials. Devices based on magnetorheological elastomers often operate over a wide range of temperatures. Therefore, it is important to study the effect of temperature on the mechanical properties of magnetorheological elastomers.

Until now, some research has been carried out on magnetorheological elastomer performances as a function of temperature. Zhang et al. [28] evaluated the mechanical properties of magnetorheological elastomers based on a mixed rubber matrix (cis-polybutadiene rubber and natural rubber). The results showed that temperature-dependent moduli exhibited different characteristics for magnetorheological elastomers with different rubber matrices. Lejon et al. [29] carried out a measurement to study the influence of temperature, dynamic deformation amplitude, magnetic field intensity, and frequency on the dynamic shear modulus of magneto-sensitive elastomers. The measurements indicated that the temperature was the most influential on the parameters especially when the temperature reached the transition phase of the material. Wan et al. [30] found that the transition temperature of magnetorheological elastomers appeared at about 50 °C, and the storage modulus initially decreased with increasing temperature, reaching its minimum value at 50 °C, and then began to increase with additional increase in temperature [31]. In this work an experimental analysis of the dynamic properties of microcomposite magnetorheological elastomer (MMRE) by a dynamic mechanical analyzer (DMA) was done. Dmitry Borin et al. [32] discussed the effect of repetitive quasi-static magnetization of a

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magnetorheological elastomer on its magnetic response. Typical components of this material, namely soft silicone rubber and carbonyl iron powder, are used to produce magnetically sensitive composite samples. Moreno-Mateos et al. [33] proposed a comprehensive study on the influence of magnetic boundary conditions and demonstrated the importance of considering them in the overall material structure modeling strategy. In this work, Zhang et al. [34] numerically analyzed the swelling of magnetorheological elastomers for sheet metal. The velocity and stress distribution of the sheet metal under different magnetic intensities were compared and analyzed. In this work, Selvaraj [35] studied an alternative vibration damper fabricated by magnetorheological elastomer. In this work, Gorshkov et al. [36] studied the physical driving mechanisms whose control makes it possible to act in real time on all the band gaps formed in 3D metamaterials based on magnetoelastomers. In this article, Khebli et al. [37] studied the phenomenon of instability which is the buckling of the beam elaborated of steel (E36-S355), and magnetorheological elastomer subject to compression-flexion solicitation. Settet et al. [38] studied the three-point bending of a magnetorheological elastomer beam.

However, previous studies are focused on the performance of magnetorheological elastomers as a function of temperature and mainly concern the effect of temperature on the properties of the polymer matrix, and little attention is paid to the effect of temperature on magnetomechanical properties. The change in modulus under an external magnetic field is the most distinctive rheological property of magnetorheological elastomers [9]. In addition, the magnetomechanical properties of magnetorheological elastomers are closely related to the arrangement of internal particles [20, 39], and its changes can directly reflect the differences in the microscopic arrangement of internal particles. Q. Wen, et al. [40] studied the influence of temperature on magneto-mechanical performances, which is useful for their practical application and mechanism analysis. Previous studies focus on the performance of magnetorheological elastomers as a function of temperature for values lower than 60 °C, at different values of magnetic field intensity.

In this work, we studied the performance of magnetorheological elastomers with frequency-temperature dependence. The elastic modulus, loss modulus, and loss factor of the magnetorheological elastomer were studied under different temperature values, different values of the magnetic field, and different values of the frequency.

2. MATERIAL AND EXPERIMENTAL CHARACTERIZATION

2.1. Elaboration of the magnetorheological elastomer

The elastomer magnetorheological is prepared according to the following steps:

1. The silicone oil and the RTV141 polymer marketed by Rhodia will perceive its good fluidity, which is used for the highest infilling rates; its cross linking is ensured by heating to 100 °C via a heating resistor connected to a 0-240 V auto transformer, (Fig. 1 a) these were manually mixed in a container for 10 minutes to obtain a well-homogenized elastomer gel.
2. A quantity of this gel obtained by silicone and RTV141 is mixed for 30 min with a quantity of carbonyl iron (CI) particles with an average diameter of 2.5 µm until a homogeneous paste is obtained. By this process, elastomers filled with 30 % and 40 % ferromagnetic particles are produced.

In our work, the storage modulus, loss modulus, and loss factor of the MRE are determined based on the magnetic field intensity; temperature, and frequency of elastomers loaded in 30 % and 40 %. The constituents in the mass fraction of the elastomers produced are given in Table 1 and Table 2. The steps for preparing the magnetorheological elastomer are given in Fig. 1.

Table 1. Magnetorheological elastomer constituents with 30% of iron particles mass

$m_{\text{silicone oil}}$, g	$m_{\text{RTV(A)}}$, g	$m_{\text{RTV(B)}}$, g	m_{Fe}, g
1.064	1.0385	0.104	7.559

Table 2. Magnetorheological elastomer constituents with 40% of iron particles mass

$m_{\text{silicone oil}}$, g	$m_{\text{RTV(A)}}$, g	$m_{\text{RTV(B)}}$, g	m_{Fe}, g
0.912	0.890	0.089	10.080

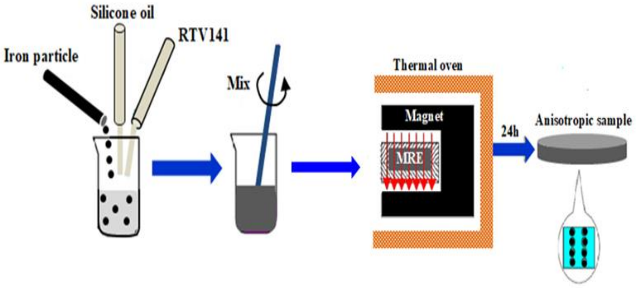


Fig. 1. Preparation steps of anisotropic magnetorheological elastomer

2.2. Experimental characterization

The dynamic mechanical characterization tests (Fig. 2) were carried out on elastomer samples of 30 mm length, 20 mm width, and 2 mm thickness. The applied test magnetic fields were parallel to the thickness direction of the sample, i.e., parallel to the chain direction of the particles. To determine the viscoelastic properties of anisotropic MREs subjected to variable temperatures and magnetic fields. The measurements were taken at 25 N force.

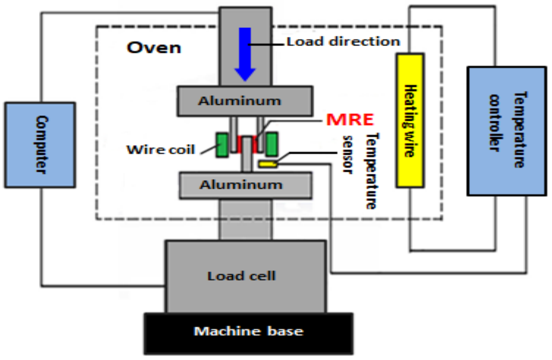


Fig. 2. Dynamic mechanical analysis of MRE under temperature

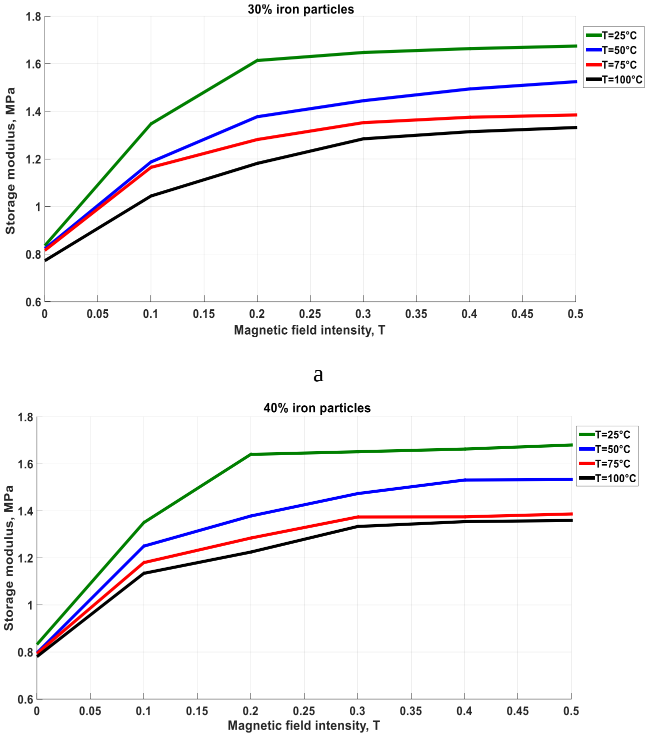
3. RESULTS AND DISCUSSION

3.1. Influence of temperature

Temperature is one of the main factors that change the performance of magnetorheological elastomers (MREs). Thus, the study of the MREs mechanical behaviour, related to their physicochemical properties, varies significantly depending on the temperature, in particular in the glass and fluid transition zones.

The results of the DMA tests carried out for samples of anisotropic magnetorheological elastomers exposed to variable temperatures and magnetic fields are represented by Fig. 3 – Fig. 5), the latter represent the dependence on the magnetic field of the elasticity modulus in shear G' , the loss modulus G" and the loss factor η (η=G"/G') under different temperature values. Fig. 4 represents the temperature dependence of the elastic modulus G', Fig. 4 represents the temperature dependence of the loss modulus G" and Fig. 5 represents the temperature dependence of the loss factor η.

Fig. 3 and Fig. 4 showed that the moduli G’ and G’’ of the magnetorheological elastomer decreased with increasing temperature.



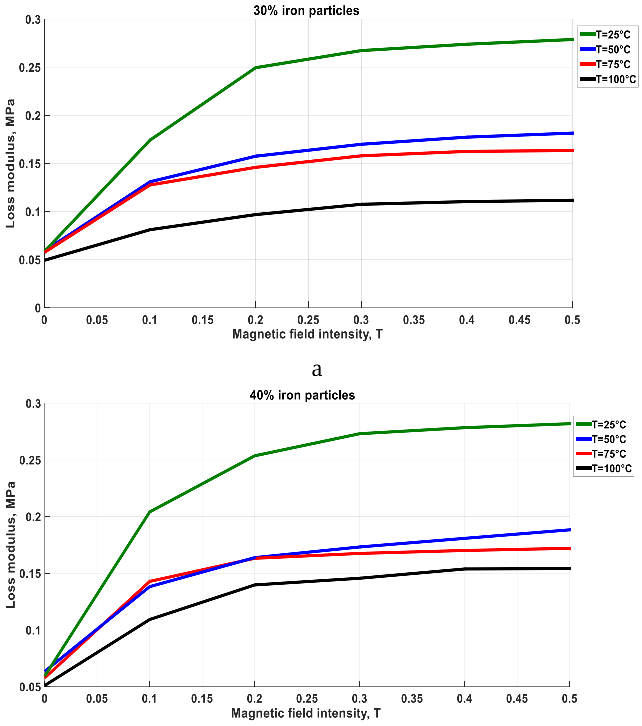
a

b

Fig. 3. Influence of temperature on the storage modulus: a – 30 % iron particles; b – 40 % iron particles

When the temperature was 25 °C, the moduli G’ and G’’ were 1.6743 MPa and 0.2788 MPa, respectively. For a temperature value of 100 °C, the moduli G' and G" respectively reached the values of 1.3321 MPa and 0.1117 MPa, i.e. with a reduction of 20 % and 60 % respectively.

We also note that the variation of the moduli G' and G" as a function of the magnetic field intensity becomes linear in the range from 0.25 T to 0.5 T with low gradients compared to the nonlinear range from 0T to 0.25 T.



a

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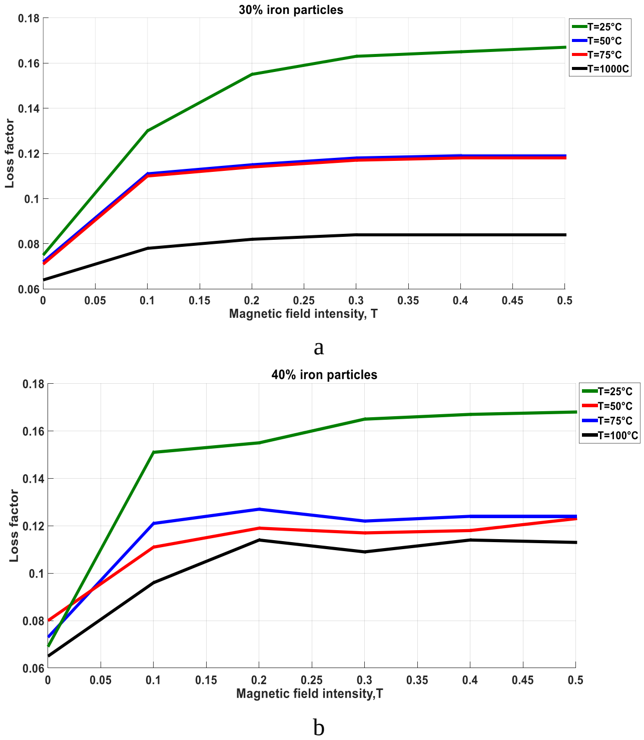
Fig. 4. Influence of temperature on loss modulus: a – 30 % iron particles; b – 40 % iron particles

Fig. 5 shows the variation of the loss factor as a function of the magnetic field intensity with different temperature values.



a

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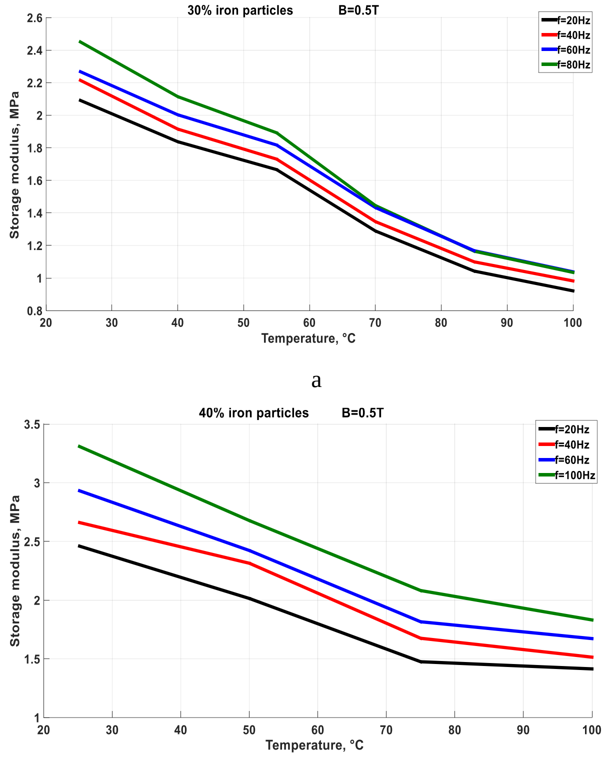
Fig. 5. Influence of temperature on the loss factor: a – 30 % iron particles; b – 40 % iron particles

It is observed that the loss factor decreased significantly with increasing temperature. For the magnetic field intensity value of 0.5 T, the loss factor has a value of 0.275 for a temperature of 25 °C and a value of 0.125 for a temperature of 100 °C, i.e. a decrease of 50 % approximately. We also notice that the loss factor varies in a non-linear manner for low magnetic field intensities (B < 0.2 T), then beyond this value the curves converge towards a constant value, this means that the magnetic field reached a saturation value and the elastomer paste has entered the phase of complete crosslinking.

Experiments show that anisotropic MREs produced with iron particles, RTV41 and silicone oil have the best characteristics when the mass of ferromagnetic particles is around 30%. We note that improvements in the storage modulus, loss modulus and loss factor are practically the same degree as for the MRE filled with 40% of the iron particle mass. The experimental data of the Dynamic Mechanical Analysis (DMA) characterization are given in Table 3 and Table 4.

3.2. Influence of temperature-frequency

Fig. 6 and Fig. 7 show the temperature-frequency dependence of the shear elastic modulus G', the loss modulus G" and the loss factor under the influence of 0.5 T magnetic field intensity.

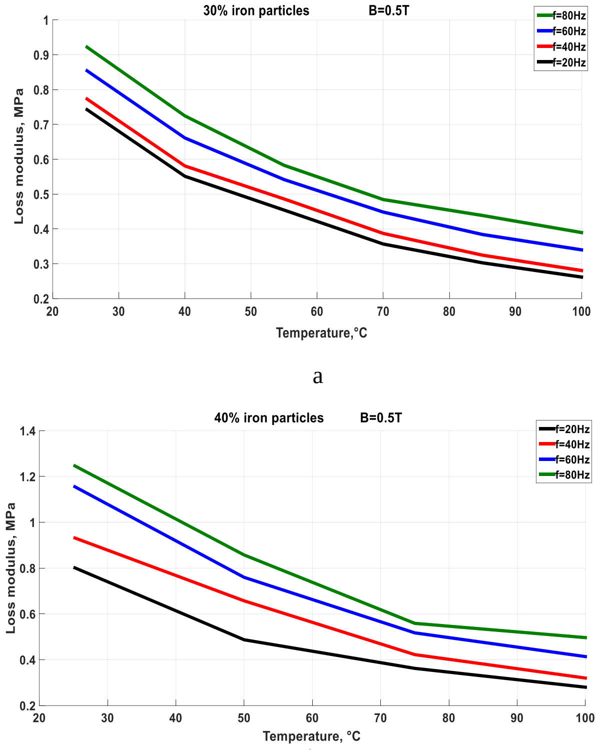


a

b

Fig. 6. Influence of temperature-frequency on the storage modulus: a – 30 % iron particles; b – 40 % iron particles

It can be seen that the storage and loss moduli (Fig. 6 and Fig. 7) increase with increasing frequency. For a temperature of 25 °C, and with frequencies of 20 Hz and 80 Hz, the storage modulus increases practically by 20 % and the loss modulus increases practically by 15 %.



a

b

Fig. 7. Influence of temperature – frequency on the loss modulus: a – 30 % iron particles; b – 40 % iron particles

On the other hand, for a temperature value of 100 °C, we notice a slight increase in the storage modulus, and a 10 % increase in the loss modulus.

We note, from Fig. 6 and Fig. 7, that increasing the percentage rate of iron particle mass slightly increases the mechanical MRE properties. We have a storage modulus of 2.5 MPa for MRE filled with 30 % of iron particles mass, and a storage modulus of 3.3 MPa for MRE filled with 40 % of iron particles mass, for a frequency of 80 Hz. We have a loss modulus of 0.93 MPa for MRE filled with 30 % of iron particles mass, and a loss modulus of 1.25 MPa for MRE filled with 40 % of iron particles mass, for a frequency of 80 Hz. This downward tendency of the G' and G" curves is even more pronounced when the MRE samples are simultaneously subjected to the magnetic field and high temperature.

Table 3. Variation of elastic modulus, damping modulus and loss factor as a function of magnetic field intensity for different temperature values with 30% of iron particles

B, T	T = 25 °C			T = 50 °C			T = 75 °C			T = 100 °C		
	G', MPa	G'', MPa	η	G', MPa	G'', MPa	η	G', MPa	G'', MPa	η	G', MPa	G'', MPa	η
0.00	0.8357	0.0585	0.075	0.8225	0.0590	0.072	0.8157	0.0575	0.071	0.7725	0.0493	0.064
0.10	1.3473	0.1742	0.130	1.1873	0.1309	0.111	1.1646	0.1276	0.110	1.0443	0.0811	0.078
0.20	1.6137	0.2495	0.155	1.3774	0.1575	0.115	1.2815	0.1459	0.114	1.1813	0.0968	0.082
0.30	1.6474	0.2673	0.163	1.4447	0.1699	0.118	1.3526	0.1579	0.117	1.2846	0.1075	0.084
0.40	1.6636	0.2739	0.165	1.4941	0.1773	0.119	1.3752	0.1625	0.118	1.3145	0.1103	0.084
0.50	1.6743	0.2788	0.167	1.5247	0.1815	0.119	1.3848	0.1634	0.118	1.3321	0.1117	0.084

Table 4. Variation of elastic modulus, damping modulus and loss factor as a function of magnetic field intensity for different temperature values with 40% of iron particles

B, T	T = 25 °C			T = 50 °C			T = 75 °C			T = 100 °C		
	G', MPa	G'', MPa	η	G', MPa	G'', MPa	η	G', MPa	G'', MPa	η	G', MPa	G'', MPa	η
0.00	0.8321	0.0592	0.069	0.7962	0.0634	0.080	0.7934	0.0577	0.073	0.7803	0.0510	0.065
0.10	1.3502	0.2041	0.151	1.2501	0.1382	0.111	1.1801	0.1428	0.121	1.1345	0.1092	0.096
0.20	1.6401	0.2536	0.155	1.3782	0.1638	0.119	1.2845	0.1632	0.127	1.2249	0.1397	0.114
0.30	1.6514	0.2731	0.165	1.4735	0.1732	0.117	1.3741	0.1675	0.122	1.3337	0.1456	0.109
0.40	1.6628	0.2784	0.167	1.5312	0.1808	0.118	1.3747	0.1701	0.124	1.3543	0.1538	0.114
0.50	1.6801	0.2819	0.168	1.5333	0.1883	0.123	1.3869	0.1720	0.124	1.3594	0.1541	0.113

It is therefore obvious that temperature has a more marked influence on the MRE dynamic moduli in shear in the presence of the magnetic field. The continuous decrease in the storage modulus can be explained by the temperature-dependent of the MRE matrix rheological properties. The MRE matrix is generally made of a high molecular weight polymer, such as natural rubber or silicone rubber, used in this experiment. As the temperature increases, the increasing thermal movement of the molecular chains in the polymer gradually overcomes the interaction between the molecules. This results in relative movement between the molecular chains, which results in a continuous decrease in the overall modulus of the elastomer.

4. CONCLUSIONS

Recent magnetorheological elastomer composite materials are currently sought-after materials for several industries. Their advantages include a combination of light weight with efficient use of material leading to improved and adjustable mechanical properties by a magnetic field, particularly storage modulus, loss modulus and loss factor. In addition, other properties, such as rigidity, are very important for certain applications. The latter is due to the increase in the interaction force between the ferromagnetic particles.

In this study, the influence of temperature as well as the frequency-temperature dependence on the mechanical properties of the magnetorheological elastomer were studied, it was observed that an increase in temperature decreases the mechanical properties, such as storage modulus, loss modulus and loss factor. On the other hand, increasing the frequency increases these latter properties.

The increase in MREs magnetic field density strengthens the inter-particle's magnetic attraction, which results in an increase in the storage modulus. As the applied magnetic field increases, particles are magnetized until saturation is reached, and at this point; inter-particle attractions no longer vary with further increase in magnetic field density. This means that the magnetorheological effect reaches its maximum. Moreover, energy dissipation in MREs mainly occurs at the interface between the matrix and the magnetic particles. Higher magnetic field density leads to increased internal friction between the magnetic particles and the MRE matrix. This increases the material's ability to dissipate energy, which results in an increase in loss modulus.

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