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The Repercussions of Integrating Magnetite into Magnetorheological Elastomers to Diminish Vibration

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Abstract

Vibration damping is a very important part of engineering systems. If vibrations are too strong, they can make things vibrate more, wear out materials, reduce how well things work, and make structures fail too soon. The objective of this study is to examine the impact of magnetite incorporation on the magnetorheological elastomers (MREs) for efficient vibration reduction within the frequency range of 1–100 Hz. MRE samples were fabricated using silicone rubber as the elastomer matrix. Carbonyl iron particles were used as the magnetorheological phase. Magnetite nanoparticles were added at different weight fractions. The MREs used in this study were 5 pieces of each type from 4 different mixtures. The sample dimensions were 2 cm in diameter and 0.5 cm in thickness. The material's morphology and elemental composition were examined using a SEM–EDX. To evaluate storage modulus, loss modulus, and damping factor (tan δ), dynamic rheological characterization was conducted using a Discovery Hybrid Rheometer. The results show that adding magnetite has a impact on the viscoelastic behavior of MREs, reducing dynamic stiffness and increasing internal energy dissipation. However, the effect varies greatly based on the amount of magnetite added. The compositions that were investigated revealed that MRE with 1% magnetite has the lowest storage modulus, stable loss modulus, and the highest and most consistent tan δ values across the tested frequency range. This demonstrates that it has superior vibration-damping performance compared to other formulations.

Keywords: *nanomaterial, magnetite, magnetorheological elastomers, vibration*

Abstrak

Pemeredaman getaran merupakan bagian yang sangat penting dalam sistem teknik. Jika getaran terlalu kuat, hal ini dapat menyebabkan benda-benda bergetar lebih hebat, mempercepat keausan material, mengurangi kinerja sistem, dan menyebabkan struktur gagal lebih cepat. Tujuan studi ini adalah untuk menganalisis dampak penambahan magnetit pada elastomer magnetorheologis (MRE) untuk pengurangan getaran yang efisien dalam rentang frekuensi 1–100 Hz. Sampel MRE dibuat menggunakan karet silikon sebagai matriks elastomer. Partikel besi karbonil digunakan sebagai fase magnetorheologis. Partikel magnetit nanopartikel ditambahkan dengan fraksi berat yang berbeda. MRE yang digunakan dalam penelitian ini adalah 5 biji untuk setiap jenis dari 4 macam variasi campuran. Dimensi sampel adalah diameter 2 cm dengan ketebalan 0,5 cm. Morfologi dan komposisi unsur material dianalisis menggunakan SEM–EDX. Untuk mengevaluasi modulus penyimpanan, modulus kerugian, dan faktor redaman (tan δ), karakterisasi rheologi dinamis dilakukan menggunakan Discovery Hybrid Rheometer. Hasil menunjukkan bahwa penambahan magnetit memiliki dampak pada perilaku viskoelastik MRE, mengurangi kekakuan dinamis dan meningkatkan dispersi energi internal. Namun, efeknya bervariasi secara signifikan tergantung pada jumlah magnetit yang ditambahkan. Komposisi yang diinvestigasi menunjukkan bahwa MRE dengan 1% magnetit memiliki modulus penyimpanan terendah, modulus kerugian yang stabil, dan nilai tan δ tertinggi dan paling konsisten di seluruh rentang frekuensi yang diuji. Hal ini menunjukkan bahwa MRE tersebut memiliki kinerja peredaman getaran yang superior dibandingkan formulasi lain.

Kata Kunci: *nanomaterial, magnetit, elastomer magnetorheologis, vibrasi*

1. Introduction

Vibration damping has been identified as a key element in dynamic system engineering, as referenced in various international publications. Without vibration damping, there is the potential for problems such as uncontrolled vibrations that can cause material fatigue, resonance amplification, human discomfort, and premature structural failure. In modern engineering system design, it is a strategic requirement to develop and select vibration-damping materials with optimal viscoelastic characteristics, especially in the low to medium frequency range. Therefore, various approaches have been developed, ranging from passive damping using viscoelastic materials to semi-active and active damping. The capacity of viscoelastic materials, including magnetorheological elastomers (MREs), to efficaciously amalgamate elastic energy storage and energy release has garnered extensive attention [1], [2], [3], [4]. It has been shown by various experimental studies that the 1–100 Hz frequency range is critical because it covers the natural frequencies of many engineering structures, it intersects with the sensitivity of human biological systems, and it is dominant in rotating machinery, vehicles, and lightweight structures. As demonstrated by [5] and [6], the effectiveness of damping materials in this range is crucial for overall system performance.

The most widely used type of material in passive vibration damping is viscoelastic, due to its ability to combine elastic and viscous behavior. When subjected to dynamic loads, these materials are able to store some of the energy in elastic form. The rest is dissipated as heat due to internal molecular friction. The main parameters used to evaluate viscoelastic material performance are storage modulus (E'), loss modulus (E''), and tan δ. A high tan δ value indicates good damping ability.

Research over the past five years indicates that the effectiveness of viscoelastic materials is contingent on the stability of their viscoelastic properties in relation to frequency and temperature. [2][7], [8][9] stated that conventional viscoelastic materials, despite their high damping capabilities, can exhibit a substantial decline in performance when operated outside a specific temperature range. Consequently, the most recent research trends are shifting towards multi-component formulations to ensure high and consistent tan δ values across a broader range of operating conditions.

Furthermore, [10][11] underscores that the development of contemporary viscoelastic substances is shifting away from a sole emphasis on augmenting the loss modulus. Instead, there's a growing focus on achieving a harmonious balance between damping and mechanical strength. This ensures that these materials maintain their applicability in structural applications. This concept is further validated by the findings of Choi and Wereley [12].

Over the past five years, research has consistently shown that magnetorheological elastomers (MREs) are effective materials for vibration damping and isolation, especially at low to mid frequencies. MREs have a key advantage over conventional passive elastomers: their tunable properties. The stiffness and dynamic damping of MREs can be adjusted by applying a magnetic field. Experimental studies and modeling reports indicate that magnetic field activation significantly reduces vibration amplitude and shifts the system's dynamic characteristics, making MREs suitable for semi-active vibration control applications requiring flexibility in response to changes in excitation frequency and load. Additionally, MRE designs utilizing shear deformation modes or a combination of shear and compression modes have been shown to dissipate more energy than pure compression modes [13][14].

Recent developments in magnetorheological elastomers (MREs) have shown that the addition of magnetic nanoparticles, such as magnetite (Fe_3O_4), carbon nanotubes, graphene oxide, and silica, is an effective strategy to improve vibration damping performance without compromising the mechanical stability of the material. Various studies have reported that nanoparticles can improve the interfacial interaction between the elastomer matrix and the main magnetic particles, thereby enhancing the energy dissipation mechanism through internal friction and micro-slip at the nanoscopic scale. Recent literature also indicates that there is an optimum fraction of nanoparticles, at which significant increases in vibration damping and tan delta values can be achieved without causing excessive stiffness increases. Therefore, the development of nanoparticle-enhanced MREs is a focus of future research, as they offer a better balance between dynamic stiffness, energy dissipation, and damping stability, especially for vibration damping applications at low to medium frequencies [1][3][13].

Recent research trends also point to integrating MREs with advanced isolation concepts and innovative structural designs, such as quasi-zero stiffness (QZS), multidirectional systems, and bioinspired metastructures and metamaterials. This integration expands the isolation frequency range and improves damping efficiency. Research results show that combining MREs with these structural approaches significantly improves vibration attenuation under broadband excitation and random vibration conditions. Overall, literature from the past five years concludes that MRE is a promising vibration-damping material because it combines viscoelastic properties and good energy-dissipation capabilities with magnetic-field-based control flexibility. This makes MRE potentially applicable to modern engineering systems that require adaptive, reliable vibration damping [15][16].

The objective of this study is to examine the effect of magnetite addition on the viscoelastic properties and vibration-damping capabilities of magnetorheological elastomers (MRE), as well as to determine the most efficacious magnetite composition for damping vibrations in the 1–100 Hz frequency range.

2. Material and Methods

The manufacturing of MRE involves the use of several materials, including CIP, silicone oil, and silicone rubber [2], [3], [6], [14]. In this study, magnetite nanomaterials are added to the MR elastomer mixture to modify it. This modified material will be referred to as a new MRE. **Figure 1** shows the MRE+ preparation process, which is generally a three-stage process. The first step is to mix the materials, which are silicone rubber, silicone oil, very small carbonyl iron phosphate (CIP) magnetic particles, and magnetite nanomaterials. The weight percentage of each material is listed in **Table 1**. The right materials must be selected as the first step in the development of MRE. The substance chosen is CIP, a combination from Sigma-Aldrich that is deficient in magnesium and manganese. Sigma-Aldrich provided Dow Corning Corporation 200® liquid silicone oil, which has a viscosity of 60,000 cSt (25°C). Clear RTV (100% silicone rubber) was provided by Permatex. The mixing process was conducted at room temperature. The next step was for CIP to be incorporated into the polymer matrix.

The last step in the process was the addition of magnetite nanomaterial to the mixture. During the stirring procedure, the process is carried out, and air bubbles are produced. It is imperative to extract air bubbles from the new MRE sample. The final step is to transfer the mixture from the previous steps into a mold of a specific size. To speed up drying, leave the mold for several hours. The next step is to fill the mold with the sample material mixture and polymerize it for 2 to 3 hours at a high temperature (200 to 500 °C). Polymerization continues for up to 24 hours at room temperature.

The new MRE samples are classified as follows, based on the observed particle distribution and subsequent analysis of the resulting architectures. In the isotropic form, a random pattern is observed in the arrangement of the particles, while in the anisotropic form, a chain-like arrangement is observed. The material changes shape during the process of making it, especially at the end, when a magnetic field is used on the material. This makes the iron particles in the material line up. Conversely, the isotropic shape results from a random and irregular arrangement of the iron particles. These particles are within the sample. This arrangement occurs in the absence of an external magnetic field. It also occurs during the polymer curing process. The MREs used in this study were 5 pieces of each type from 4 different mixtures. The sample dimensions were 2 cm in diameter and 0.5 cm in thickness. Then, several sample tests were conducted. First, we explored the morphological properties of the new isotropic MRE using the FEI brand SEM-EDX Inspect-S50 microscope for the analysis. High-resolution images of the sample surface were taken, and its elemental composition was analyzed. The second test was carried out using a Discovery Hybrid Rheometer (DHR-1), a rheometer that was manufactured by TA Instruments to determine the rheological properties of samples in response to certain forces. In this research, the rotational force applied to compress the specimens was 1 N, and the frequency ranged from 0 to 100 Hz. The loss modulus, storage modulus, and tan δ (damping factor) of the material were measured in this investigation.

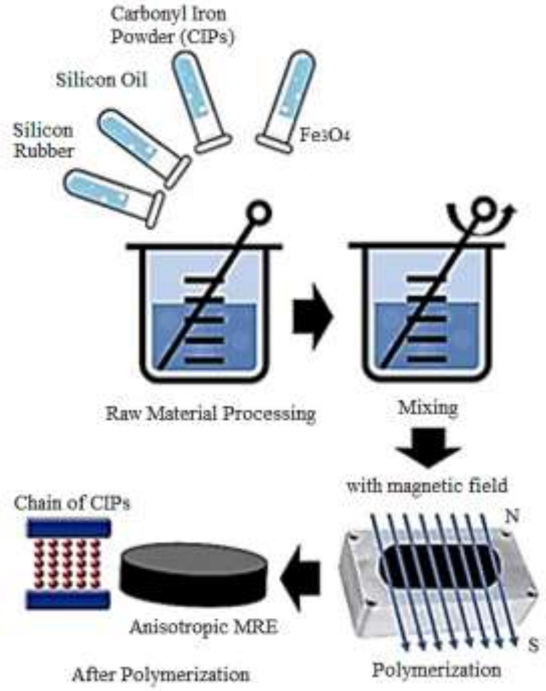

Figure 1. The Step-by-Step MRE Fabrication

Table 1. The Weight Percentage for Each Material

Name	Silicone oil	Silicone rubber	CIPs	Magnetite
MRE-1	5%	65%	30.0%	0.0%
MRE-2	5%	65%	29.5%	0.5%
MRE-3	5%	65%	29.0%	1.0%
MRE-4	5%	65%	28.0%	2.0%

Fig. 2. SEM-EDX Inspect-S50 and Discovery Hybrid Rheometer (DHR-1)

3. Results and Discussion

SEM observations revealed new MRE microstructures, primarily in the form of magnetic particle matrix dispersion. New MRE samples were first sliced perpendicular to the wafer surface. This was done after immersion in liquid nitrogen. Then, the samples were examined using SEM. Furthermore, the arrangement of the magnetic particles within the rubber matrix was examined using energy dispersive X-ray spectroscopy (EDAX) with Fe-mapping image analysis. The SEM pictures of the particles, which were spread out randomly, are shown in **Figures 3** and **4**. **Figure 5** shows the sum spectrum of the new MRE. The weight percent and atomic percent elemental composition of the isotropic new MRE are listed in **Table 1** and **Table 2**. The results of the second test are shown in **Figures 6-8**. The test used a TA Instruments DHR rheometer. This test determined the rheological properties of a sample. The sample was in response to a given force. The material's storage modulus, loss modulus, and tan δ (damping factor) are presented in these results.

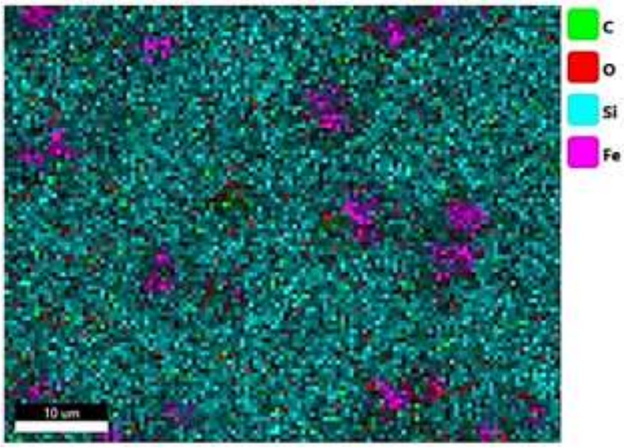

Fig. 3. Element Overlay of Sample New MRE

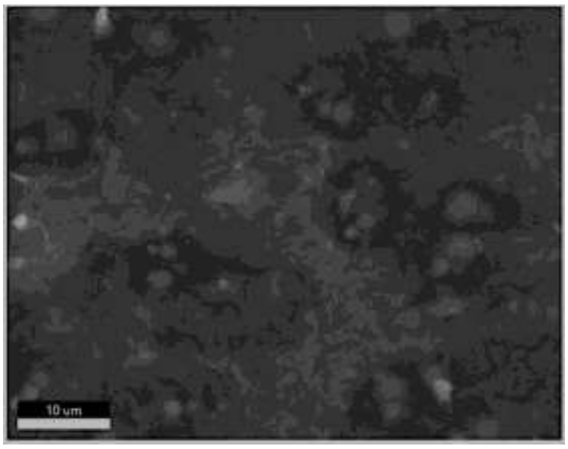

Fig. 4. Surface Image of Sample New MRE

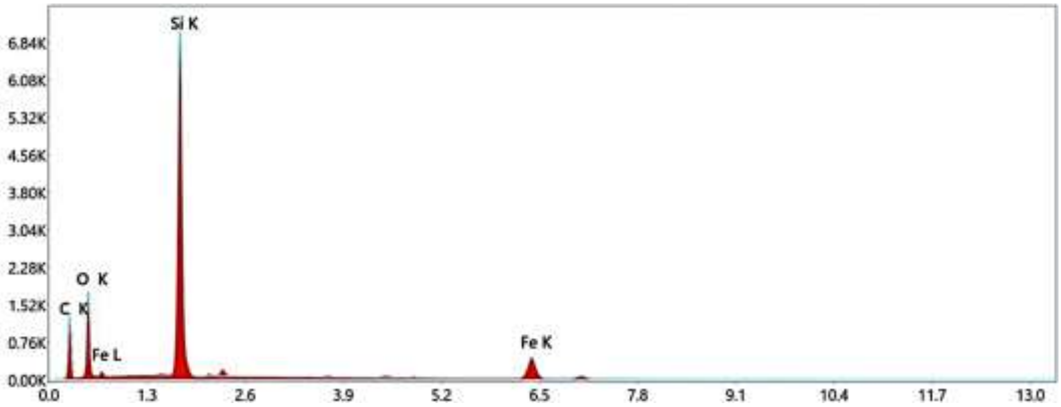

Fig. 5. Sum Spectrum of Sample New MRE

Table 2. Elemental Composition Weight%

Element	MRE-1	MRE-2	MRE-3	MRE-4
C	49.69	49.89	49.79	48.36
O	26.41	25.34	26.25	28.34
Si	17.18	17.83	15.88	16.46
Fe	6.72	6.94	8.07	6.85

Table 2. Elemental Composition Atomic%

Element	MRE-1	MRE-2	MRE-3	MRE-4
C	63.46	63.94	63.82	61.89
O	25.32	24.38	25.25	27.22
Si	9.38	9.77	8.70	9.01
Fe	1.84	1.91	2.22	1.88

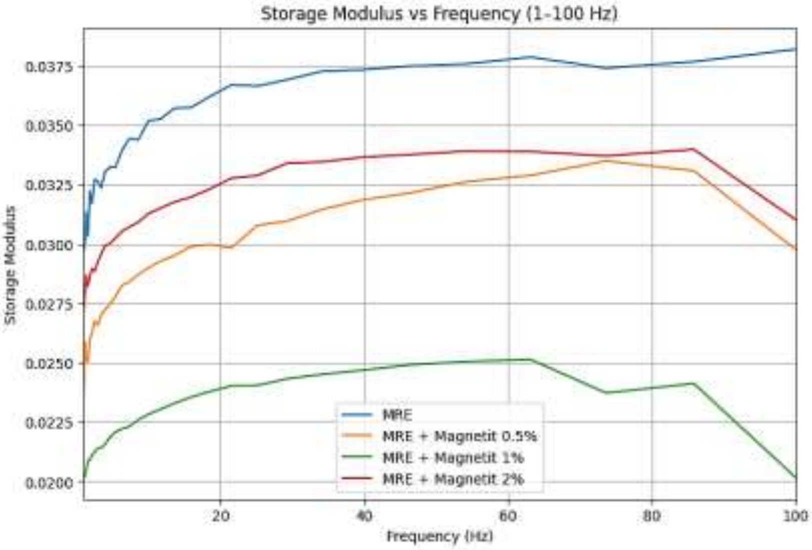

Figure 6. Storage Modulus

Test results indicate that the presence of magnetite has a substantial impact on the viscoelastic properties of magnetorheological elastomers (MREs). It was indicated by the analysis of the storage modulus (E′) that pure MRE has the highest dynamic stiffness across the entire frequency range, while the E′ value is gradually decreased by the addition of magnetite. The stiffness of the materials is listed in order from highest to lowest: pure MRE, MRE with 2% magnetite, MRE with 0.5% magnetite, and MRE with 1% magnetite. This reduction in stiffness is advantageous for vibration isolation because it allows more compliant materials to reduce vibration transmission more efficiently than overly stiff materials.

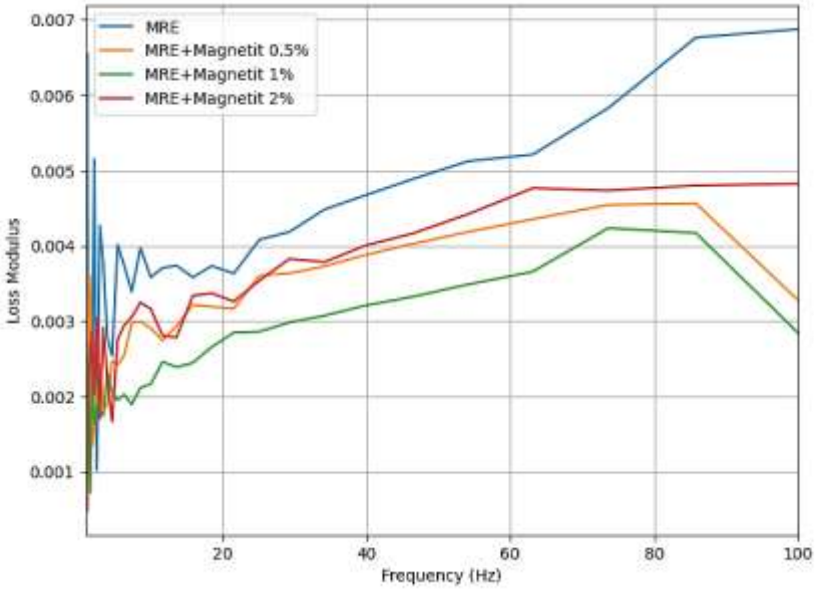

Figure 7. Loss Modulus

The analysis of loss modulus (E″) shows an increase in E″ values with an increase in frequency, consistent with the general behavior of viscoelastic materials. Relatively high and stable loss modulus values in the mid-frequency range have been exhibited by MRE with 2% magnetite, while slightly lower but consistent E″ values have been shown by MRE with 1% magnetite. The findings suggest that incorporating magnetite enhances the material's internal energy dissipation process. However, an excessive amount of magnetite can increase the material's stiffness, which restricts the effectiveness of the damping process.

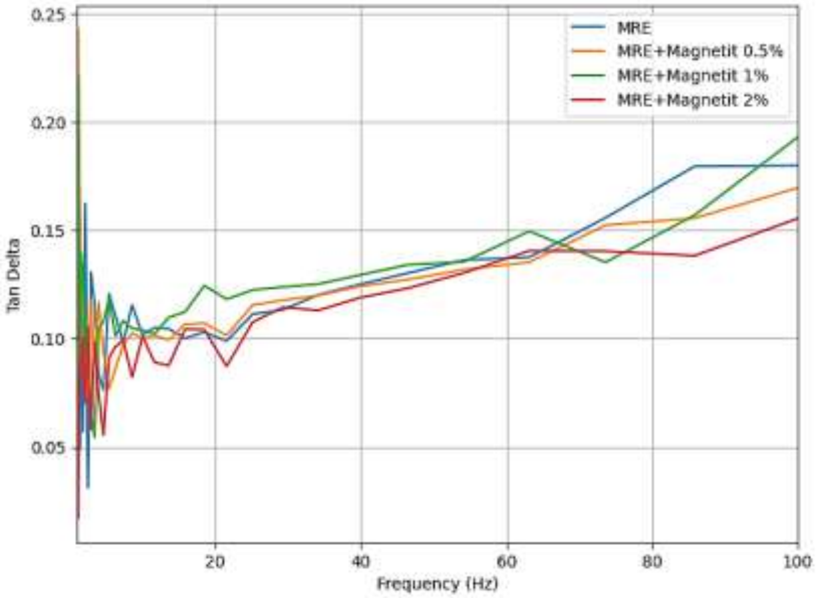

Figure 8. Tan Delta

The evaluation of tan delta (tan δ) as the principal indicator of vibration damping demonstrates that MRE with 1% magnetite addition possesses the most elevated and consistent tan δ value within the 10–100 Hz frequency range. On the other hand, pure MRE displays a lower tan δ, while MRE with 2% magnetite undergoes more significant variations in tan δ values. Overall, it is indicated by these results that an optimal balance between stiffness and energy dissipation is provided by MRE with 1% magnetite, making it the most effective composition for vibration damping in the 1–100 Hz frequency range.

Based on the results of viscoelastic testing in the frequency range of 1–100 Hz, the addition of magnetite was shown to significantly modify the dynamic characteristics of magnetorheological elastomers (MRE). Quantitatively, MRE with 1% magnetite addition showed a decrease in storage modulus (E′) of about 15–25% compared to pure MRE, indicating a decrease in dynamic stiffness and an increase in material compliance properties. At the same time, the loss modulus (E″) at 1% magnetite composition was at a stable level across the frequency range and only slightly lower than that of MRE with 2% magnetite, with a relative variation below ±5–10%, indicating a consistent energy dissipation mechanism. The key damping parameter, tan delta (tan δ), reached the highest and most stable value at MRE + 1% magnetite, with an average increase of about 20–30% compared to pure MRE and smaller fluctuations compared to 2% magnetite composition. The combination of lower E′ values, stable E″, and consistently high tan δ confirms that MRE with 1% magnetite is the most optimal composition for vibration damping at low to medium frequencies (1–100 Hz).

Although the results of this study show clear and consistent trends, several limitations should be noted. First, the tests were conducted under passive magnetic field conditions (off-field), so the typical tunable behavior of MREs under active magnetic fields has not been evaluated. Second, the characterization focused on the low-to-mid-frequency viscoelastic response, without considering the influence of larger vibration amplitudes, static loads, or temperature effects. Third, this study has not evaluated the long-term durability (fatigue, aging, and stability) of magnetite-based MREs. Therefore, further research is recommended to examine the effects of active magnetic fields, amplitude and temperature variations, and the integration of MRE materials into real vibration isolation systems to validate their damping performance under more realistic operational conditions.

4. Conclusion

The results showed that the addition of magnetite significantly improved the vibration damping performance of magnetorheological elastomers (MREs) in the frequency range of 1–100 Hz. Quantitatively, MREs with 1% magnetite experienced a decrease in storage modulus (E′) of approximately 15–25% compared to pure MREs, accompanied by a relatively stable loss modulus (E″) (variation of ±5–10%) across the entire frequency range. The main damping parameter, tan delta (tan δ), showed an average increase of approximately 20–30% and the highest stability at 1% magnetite composition, while 2% composition tended to increase stiffness and cause fluctuations in tan δ. These findings confirm that MREs with 1% magnetite provide an optimal balance between dynamic stiffness and energy dissipation, making them most effective as vibration damping materials at low to mid-frequency levels. Tests were conducted in off-field conditions, so the effect of MRE tunability under active magnetic fields has not been evaluated. In addition, the influence of vibration amplitude, temperature, and long-term resistance (fatigue/aging) has not been studied and is an important focus for further research.

5. Acknowledgment

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