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Effect of magnetite nanoparticles on the viscoelastic properties of magnetorheological elastomers

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Abstract

Advanced materials known as Magnetorheological Elastomers (MREs) can be used to dampen vibrations. These materials reduce vibration disturbances by responding to an externally applied magnetic field, which alternate their mechanical characteristics. The objective of this research is to explore the effect of incorporating magnetic nanomaterials (Fe_3O_4) on the properties of MRE. The modified material is expected to exhibit enhanced sensitivity to magnetic fields, thereby improving its vibration-damping performance. The MRE mixture utilized in this investigation consists of Carbonyl Iron Powder (CIP), silicone oil, and silicone rubber, with mass percentages of 30%, 5%, and 65%, respectively. The MRE was then given magnetite nanomaterials in amounts of 0.5%, 1%, 1.5%, and 2% of the total weight. To produce MRE, thoroughly mix the silicone rubber with silicone oil and then gradually add the carbonyl iron powder, ensuring uniform dispersion. Once the homogeneity was achieved, the magnetite nanomaterial were incorporated into the MRE mixture with precision. The resulting composite were then cured, optionally under a magnetic field to induce anisotropic alignment. Laboratory tests were conducted on the new material. These tests involved analyzing their elemental composition and evaluating their viscoelastic properties. The research findings indicate the successful development of MREs containing Fe_3O_4 nanomaterials for the purpose of vibration dampening within the frequency range of 1–100 Hz. At a center frequency of 1,167 Hz, MRE-2 (MRE with a 0.5% addition of Fe_3O_4) demonstrated the strongest damping performance, exhibiting the highest tan δ value. This makes MRE-2 the primary choice. MRE-1 is an excellent alternative due to its high stiffness and effective damping at low frequencies.

Keywords:
Smart material, nanomaterial, magnetorheological elastomer, magnetite.

1 Introduction

Smart materials are functional substances capable of sensing and responding to various environmental stimuli. These stimuli may include optical, electrical, magnetic, mechanical, thermal, and chemical factors [1]. The properties of smart materials can undergo significant alterations when exposed to specific conditions in a controlled environment [2], [3], [4].

A type of advanced smart material is Magnetorheological Elastomers (MREs) which consist of magnetic particles dispersed in an elastomer matrix. These particles respond to an externally applied magnetic field, allowing the material's mechanical properties to be tuned. An increase in current applied to the insulated coil strengthen the magnetic field, thereby enhancing the stiffness of the MRE [5], [6], [7], [8]. MRE has been successfully used as a research material for vibration-damping devices, as reported in studies conducted by Gigih et al. [7], [8].

Nanomaterials are defined as particles or materials with at least one dimension in the 1-100 nm range [9], [10]. Nanomaterials have a wide range of potential applications, including traditional materials, medical devices, electronic components, and coatings [11]. It is a magnetic material (Fe_3O_4) with a unique characteristic, recognized as the strongest naturally occurring magnetic mineral. Its magnetic properties are influenced by several factors, including oxidation level, particle size, and method of synthesis [12], [13], [14], [15], [16].

The objective of this research is to examine the effect of incorporating Fe_3O_4 nanoparticles, which possess robust magnetic characteristics, into MRE [17]. Meanwhile, MRE, which is often studied, is a vibration damper. Fe_3O_4 nano-materials are added. The new material is expected to exhibit enhanced sensitivity to magnetic fields, leading to significant damping of vibrations. The potential for MRE-based vibration dampers is opened up by this, as varying magnetic fields are provided, which significantly reduce unwanted vibrations by altering the stiffness of the MRE.

2 Method

2.1 Material

The manufacture of MREs involves the use of multiple materials, including Carbonyl Iron Powder (CIP), silicone oil, and silicone rubber [18], [19], [20], [21], [22]. The material mixture of the MR elastomer was modified in the present research by adding Fe_3O_4 nanomaterial. This modified material is referred to as the new MRE. Fig. 1 outlines the procedure for producing the new MRE, which generally encompasses three steps. First, the materials-silicone rubber, silicone oil, micrometer-sized iron CIPs, and Fe_3O_4 nanomaterials are combined. The weight percentage of each material can be found in Table 1.

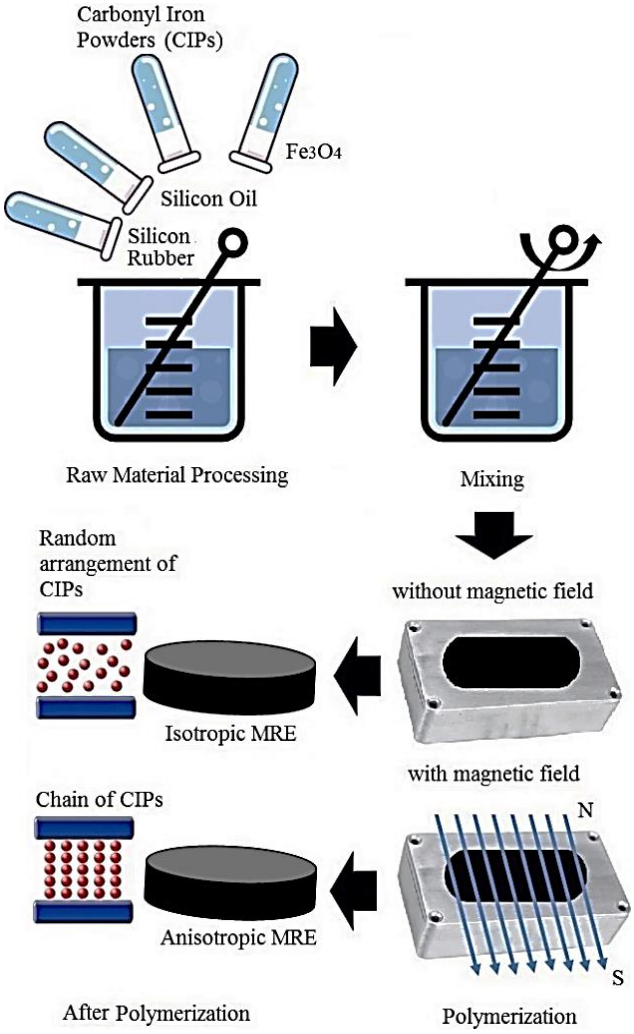

Fig. 1. The step-by-step new MRE fabrication.

Table 1. The weight % for each material

Name	Silicone oil	Silicone rubber	CIPs	Fe_3O_4
MRE-1	5%	65%	30%	0%
MRE-2	5%	65%	29.5%	0.5%
MRE-3	5%	65%	29%	1.0%
MRE-4	5%	65%	28%	2.0%

2.2 Preparation process

The initial phase in creating this modified type of MRE was the selection of suitable raw. CIPs, with low magnesium and manganese content were obtained from Sigma-Aldrich. Dow Corning Corporation 200® liquid silica oil with a viscosity of 60,000 cSt (25°C) was also purchased from Sigma-Aldrich, while transparent RTV (100% silicone rubber) was supplied by Permatex. The Fe_3O_4 used in this study was synthesized by the researchers. All mixing processes were carried out at room temperature. The preparation of MREs involved CIP, magnetite nanomaterial, silicone oil, and silicone rubber. The process begins with thoroughly mixing of the two silicone rubber components, followed by the gradual addition of silicone oil to reduce viscosity and enhance flexibility. Once the silicone matrix was prepared, the carbonyl iron powder was slowly incorporated and mechanically blended to ensure uniform particles dispersion. After blending the initial MRE mixture and potentially vacuum degassing it to remove air bubbles, the magnetite nanomaterial is carefully introduced and dispersed. Meticulous mixing is required for this second addition to prevent agglomeration of the nanoparticles and ensure their even distribution within the existing CIP-silicone mixture. The reduced viscosity of the silicone oil aids in dispersion. Finally, the mixture is poured into a mold and cured. For an isotropic MRE, it is cured without a magnetic field. For an anisotropic MRE, it is cured within a strong magnetic field to align the particles (CIP and potentially some magnetite nanoparticles) [19], [20], [23], [24], [25].

MRE specimens are commonly classified according to particle dispersion. In isotropic type, the nano-sized iron particles arrange randomly, whereas in the anisotropic type, the nano-sized iron particles arrange in a chain-like configuration. The anisotropic structure is a result of the polymerization process, especially during the final stage, when a magnetic field is applied to the composite matrix. This causes the iron particles in the sample to align in a regular, parallel arrangement. On the other hand, a random and irregular arrangement of iron particles within the sample results from the polymer curing process occurring in the absence of an external magnetic field. Fig. 2 shows the dimensions of the MRE used in this study, with a diameter of 3 cm and a thickness of 0.5 cm.

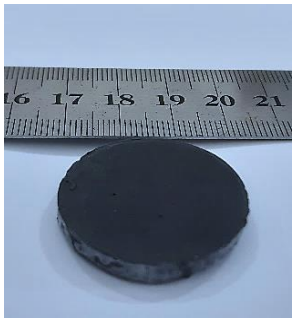

Fig. 2. The dimension of the new MRE sample.

The new MRE sample's shape and dimensions were determined, after which several sample tests were conducted. First, the morphological properties of the new isotropic MRE were explored. The FEI brand Scanning Electron Microscope-Energy Dispersive X-ray spectroscopy (SEM-EDX) microscope was used. Inspect-S50 was used to take high-resolution images of the sample surface and analyze its elemental composition. The SEM is a FEI brand. Inspect-S50. Begin the process by configuring the SEM. Place the sample in the SEM chamber. In this study, a 12 mm specimen was used. Then, the sample was dried with vacuum equipment to remove H_2O. Once this step was complete, the sample could be observed using the SEM.

Knowledge of the dynamic properties of materials used in equipment subjected to vibration is required. The efficacy of damping is characterized by a set of parameters, including the loss angle (tan δ), storage modulus, and loss modulus. Viscoelastic materials have two main modulus components. The first is the storage modulus, which indicates the material's ability to store elastic energy. The second is the loss modulus, which indicates the energy lost as heat due to internal friction within the material. The higher the loss modulus, the more energy is absorbed and lost as heat. If the loss modulus increases with temperature, the material undergoes viscoelastic relaxation. The ratio of the loss modulus to the storage modulus is called the tan δ (damping factor) and indicates how effectively the material dampens mechanical energy. The second test used a Discovery Hybrid Rheometer (DHR) series, a rheometer manufactured by TA Instruments that determines the rheological properties of samples in response to certain forces. In this research, the axial force used to compress the samples was 1 N, and the frequency ranged from 0 to 100 Hz. This investigation measured the loss modulus, storage modulus, and tan δ (damping factor) of the material.

3 Results

SEM has been used to observe the microstructures of the new MRE. This observation mainly concerns magnetic particle dispersion in the matrix. Typically, new MRE samples were cut perpendicular to the disk surface after being immersed in liquid nitrogen prior to SEM observation. Additionally, EDX spectroscopy with iron mapping image analysis was used to characterize the orientation of magnetic particles within the rubber matrix. Fig. 3 and Fig. 4 show the randomly dispersed particles of various volume fractions of the isotropic new MRE observed by SEM-EDX. The weight and atomic percentage compositions of the isotropic new MRE are listed in Tables 2 and 3, respectively.

Fig. 3 shows the elemental distribution map of the new MRE sample. The distribution of carbon is indicated by the green color. Its presence extends nearly across the entire sample surface. The distribution of oxygen is indicated by red. Oxygen is also widely distributed. The cyan color indicates the distribution of silicon. This element is distributed uniformly and appears to be the primary component of the sample matrix. The presence of iron is indicated by magenta. Unlike the other elements, iron does not spread evenly; rather, it accumulates in small, specific areas.

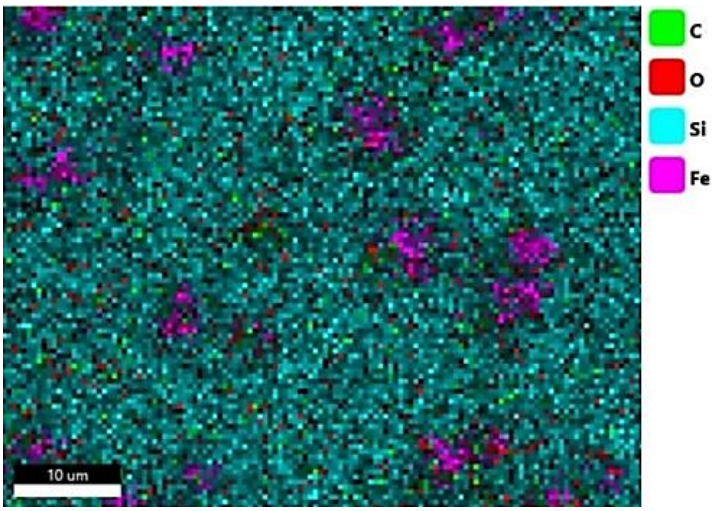

Fig. 3. Dispersed particles of the new MRE sample.

Fig. 4 shows the EDX spectrum of the new MRE material. The horizontal axis, labeled X, shows the X-ray energy level in kiloelectron volts, or keV for short. The vertical axis, labeled Y, shows the intensity of the X-rays that were detected. Each element emits X-rays at a characteristic energy level. The graph's peaks

identify the elements present in the sample. The detected peaks are silicon (Si), oxygen (O), carbon (C), and iron (Fe). The presence of a prominent, elevated silicon peak further substantiates this observation, indicating silicon's dominance. A significant oxygen peak was also observed. There is also a significant carbon peak. Two iron peaks were identified, indicating its presence, though they were significantly lower compared to the peaks for silicon, oxygen, and carbon.

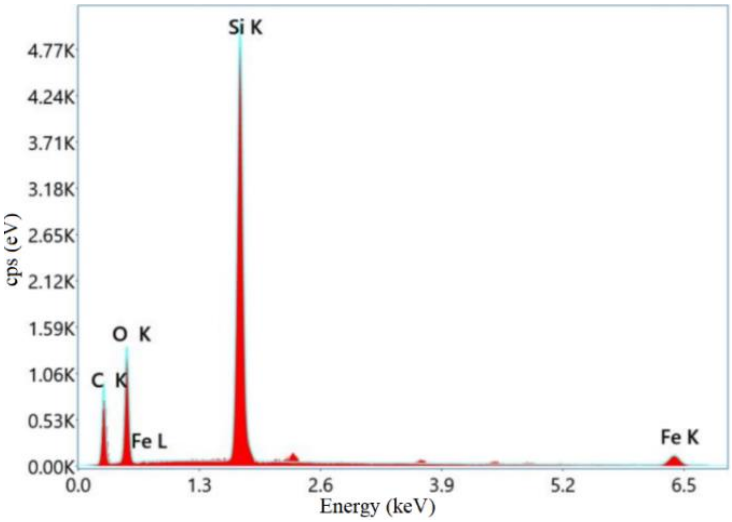

Fig. 4. Spectrum of the sample new MRE.

In accordance with the data presented in Tables 2 and 3, a multitude of patterns of compositional alteration were identified. MRE production before the addition of Fe_3O_4 involves various materials, including CIP, silicone oil, and silicone rubber. Meanwhile, the CIP used in this study contains Fe. Therefore, the MRE before the addition of the Fe_3O_4 nanomaterial contains iron elements, as shown in Tables 2 and 3. Carbon (C) remained relatively stable at about 50-52% in all samples, indicating that it is the dominant component. Oxygen (O) increased in MRE-2 and then decreased slightly in MRE-3 and MRE-4, indicating increased oxidation in MRE-2. The silicon (Si) content decreased slightly in MRE-2 but increased again in MRE-3 and MRE-4, indicating variation in silica content between samples. The iron (Fe) content decreased slightly from MRE-1 to MRE-4, possibly due to the addition of Fe_3O_4 redistributing iron within the material. Overall, the observed changes in elements were relatively small, with no significant trends. The most notable changes were in oxygen and iron content, which may be related to the modifications made to each sample.

Table 2. Elemental composition weight%

Element	MRE-1	MRE-2	MRE-3	MRE-4
C	52.02	50.65	50.00	50.30
O	25.96	30.62	25.47	23.64
Si	16.22	13.61	15.53	18.13
Fe	5.80	5.12	9.00	7.93
Total	100.00	100.00	100.00	100.00

Table 3. Elemental composition atomic%

Element	MRE-1	MRE-2	MRE-3	MRE-4
C	65.28	62.88	64.36	64.90
O	24.45	28.53	24.60	22.90
Si	8.70	7.22	8.55	10.00
Fe	1.57	1.37	2.49	2.20
Total	100.00	100.00	100.00	100.00

As shown in Tables 2 and 3, there is a decrease in weight percentage from MRE-1 to MRE-3. The percentage of carbon decreased slightly from 52.02% to 50.00% in MRE-3. This could be due to an increase in other elements, such as oxygen (O) and silicon (Si). In MRE-4, the carbon percentage increased slightly back to 50.30%, suggesting that the performed modification may not have significantly changed the carbon content. Although the percentage by weight of carbon decreased slightly, the atomic percentage remained high (62.88%-65.28%). This indicates that, even though the mass of carbon decreased slightly, carbon atoms still dominate the material structure. Therefore, it can be concluded that carbon remains the dominant element in all samples. The decrease in weight percentage may be offset by an increase in other elements, such as oxygen and silicon. The relatively stable atomic percentage indicates that changes in mass distribution are more significant than changes in the number of carbon atoms.

MREs are composites typically made of a polymer matrix embedded with magnetic particles, in this case, magnetite (Fe_3O_4). When a material is subjected to vibrations, some of the mechanical energy is converted into heat or other forms of energy, thereby reducing the amplitude of the vibrations. Magnetite is a ferromagnetic material, meaning it is strongly attracted to a magnet. When dispersed within the elastomer matrix, these magnetic particles can interact with each other and with the matrix under dynamic loading and/or an applied magnetic field. When an external magnetic field is applied, the magnetite particles can form chain-like structures or agglomerates. As the MRE deforms, these structures can be rearranged or broken, leading to energy dissipation. Even without an external field, the magnetic interactions between magnetite particles can contribute to internal friction and energy loss during deformation. The soft magnetic nature of magnetite (low remanence) means it responds readily to changes in the magnetic field, which can be advantageous for tunable damping. A higher tan δ value indicates greater energy dissipation and stronger damping potential. The results of the second test, which used a TA instruments DHR rheometer to determine the rheological properties of a sample in response to a given force, are shown in Fig. 5, Fig. 6 and Fig. 7. These results are the storage modulus, loss modulus, and tan δ (damping factor) of the material.

The performance of MRE-1 is shown in Fig. 5, Fig. 6 and Fig. 7. These figures contain the storage modulus, loss modulus, and tan δ data. The tan δ values for MRE-1 vary. The maximum values are at low frequencies. The maximum values are 217,869 at 1,167 Hz. It exhibits good attenuation at low frequencies. MRE-2 performance exhibits the highest tan δ at mid-frequencies (242,524 at 1,167 Hz), indicating strong damping potential. It is effective at absorbing energy in this frequency range. MRE-3 performance shows the lowest tan δ at most frequencies, indicating less attenuation and effectiveness in vibration-damping applications. MRE-4 has a fairly good tan δ, but it degrades at high frequencies. While it can still perform well in damping, it is not as effective as MRE-2. For vibration damping in the 1–100 Hz frequency range, MRE-2 is the best choice, as it has the highest tan δ at intermediate frequencies, indicating strong damping capability. MRE-1 also performs well at low frequencies. MRE-4 is viable but less optimal than MRE-2. MRE-3 is not recommended for this application due to its lowest value. Therefore, MRE-2 should be selected as the primary material for effective vibration-damping applications in this frequency range.

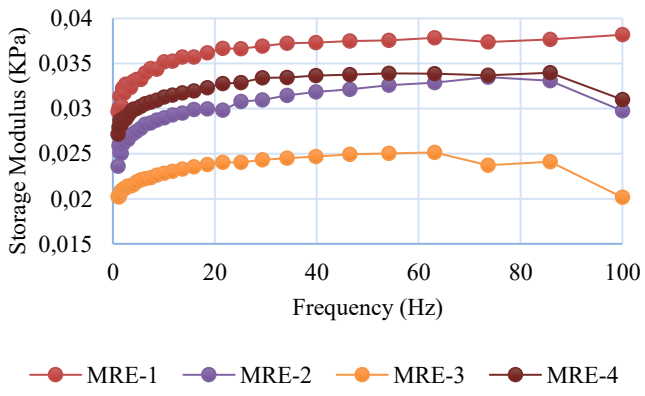

Fig. 5. Storage modulus.

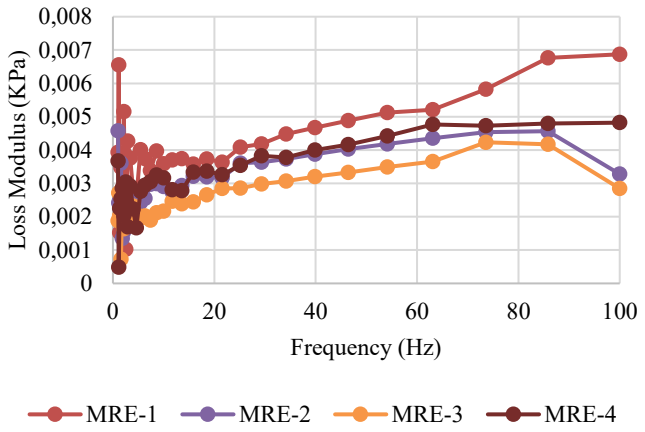

Fig. 6. Loss modulus.

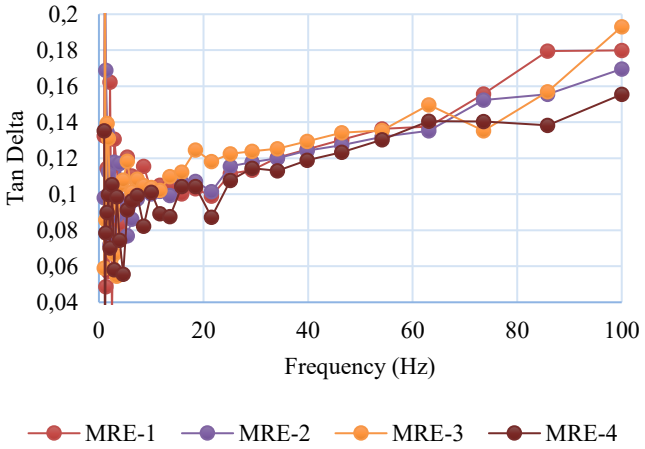

Fig. 7. Tan δ.

4 Conclusions

This research concludes that an MRE with the Fe_3O_4 nanomaterial has been created. For vibration damping in the 1-100 Hz frequency range, MRE-2 (with 0.5% added Fe_3O_4) is the best choice. Based on the experiment, it has the highest tan delta value and strong damping performance at intermediate frequencies (1,167 Hz). MRE-1 is a very good alternative at low frequencies, offering high stiffness and good damping capability. MRE-4 is feasible but less optimal than MRE-1 and MRE-2. MRE-3 is not recommended for this application due to its low tan delta and storage modulus values. Therefore, MRE-2 should be selected as the primary material for optimal vibration-damping applications in the 1-100 Hz frequency range, especially at intermediate frequencies.

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