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An examination of the Fe_3O_4 nanomaterial impact in conjunction with Magnetorheological Elastomer material

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Abstract
Magnetorheological elastomer (MRE) is an advanced material class that can be used for vibration damping. This material possesses the ability to reduce vibration disturbances through adjustment of its mechanical properties in response to a magnetic field applied from an external source. The objective of this study is to ascertain the effect of incorporating Magnetite (Fe_3O_4) nanomaterials into MRE. It is expected that this new material will be more sensitive to magnetic fields in damping vibrations, which would be a significant improvement. MRE is composed of carbonyl iron powder (CIP), silicone oil, and silicone rubber, with weight proportions of 30%, 5%, and 65%, correspondingly. The addition of magnetite nanomaterials to MRE occurred at weight ratios of 0.5%, 1%, 1.5%, and 2%. Observations of this new material included elemental composition analysis and viscoelastic testing of various mixture formulations in the laboratory. From this research, it can be concluded that an MRE containing Fe_3O_4 nanomaterials has been created. For the attenuation of vibrations within the 1–100 Hz frequency range. MRE-2 (MRE with 0.5% Fe_3O_4 added) is the best choice as the primary material, as it exhibited the highest tan delta value and strong damping performance at an intermediate frequency. MRE-1 sample was used as a base material mixture without added Magnetite also an excellent choice, offering high stiffness and good damping capability at low frequencies. It is shown by the results of this experiment that the effectiveness of MRE in reducing vibration can be increased by adding Magnetite, even in the limited mid-frequency range of 0 to 100 Hz.

Keywords:
Magnetite;
Magnetorheological Elastomer;
Nanomaterial;
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INTRODUCTION

Smart materials have been defined as functional substances that are able to sense and respond to a variety of environmental stimuli. These stimuli may include optical, electrical, magnetic, mechanical, thermal, and chemical signals [1]. These materials can significantly change their properties under controlled conditions [2]. The utilization of smart materials has been instrumental in propelling advancements across a diverse array of disciplines, including but not limited to wearable devices, neuromorphic computing, and biomimetic robotics [3][4]. These materials can be engineered and customized for particular functional applications, with notable examples including shape memory polymers, intelligent liquid metals, and flexible conductive polymers [3]. The aerospace industry has a

marked interest in smart materials due to the aforementioned properties that are characteristic of such materials, namely, self-sensing, self-adaptability, and memory capabilities [5]. A wide array of printing methodologies, including inkjet printing and three-dimensional printing, have been employed to manufacture intelligent micro/ nanodevices that utilize smart materials [1]. As research in this field continues to advance, the integration of smart materials is poised to play a pivotal role in the development of a smart society [3].

Magnetorheological elastomers (MREs), a type of advanced material, consist of magnetic particles dispersed in an elastomer matrix. These particles exhibit an adjustable response to an applied magnetic field, enabling the adjustment of the material's mechanical properties. Previous research findings indicate that when the current applied to the insulated coil is increased, the magnetic field strengthens, and the stiffness of the MRE also increases [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]. The potential applications of nanomaterials encompass a broad spectrum, ranging from traditional materials and medical devices to electronic components and coatings [11]. Fe_3O_4 is a magnetic material with a unique set of properties that make it the mineral with the strongest magnetic properties found in nature. Its magnetic properties are influenced by a variety of factors, including oxidation level, particle size, and method of synthesis [12, 13, 14, 15, 16].

The purpose of this research is to investigate the effect of adding Fe_3O_4 nanoparticles, which have strong magnetic properties, to MRE [17]. Meanwhile, MRE, which is often studied by authors, is a vibration damper. With the addition of Fe_3O_4 nano-material, it is expected that the new MRE will be more sensitive to magnetic fields. This opens up the potential for MRE-based vibration dampers by providing varying magnetic fields, which significantly reduce unwanted vibrations by altering the stiffness of the MRE.

MATERIAL AND METHODS

MREs are made using a variety of materials, including silicone oil, carbonyl iron powder (CIP) and silicone rubber [18, 19, 20, 21, 22]. In the present research, the material mixture of MR elastomer was modified with the addition of Fe_3O_4 nanomaterial. This modified material is henceforth referred to as the new MRE. The procedure for producing new MREs is outlined in Figure 1 and generally encompasses three steps.

The initial stage in creating MRE is mixing the substances, which are specifically silicone rubber, silicone oil, micrometer-sized iron carbonyl magnetic particles (CIPs), and Fe_3O_4 nanomaterial. The weight percentage of each material can be found in Table 1.

The first step in developing this new type of MRE was to select the appropriate materials. The materials selected were CIPs, compounds with low magnesium and manganese content from Sigma-Aldrich. Sigma-Aldrich supplied Dow Corning Corporation's 200® liquid silica oil, which has a viscosity of 60,000 cSt at 25°C. Sigma-Aldrich. Transparent RTV (100% silicone rubber) was produced by Permatex. The Fe_3O_4 used in this study was produced by the researchers themselves.

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%

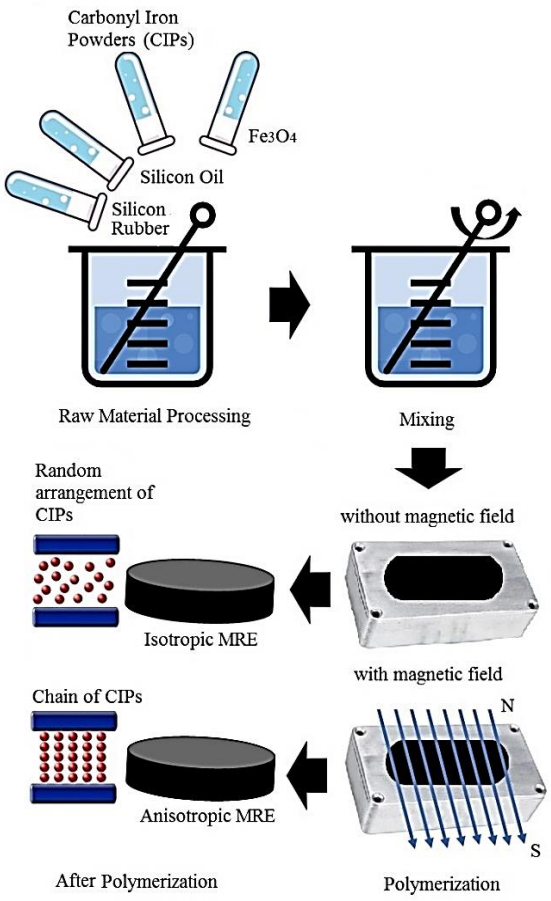

Figure 1. The Step-by-step new MRE Fabrication

The mixture was prepared at room temperature. The next step was to add CIP to the polymer matrix during mixing. This resulted in the formation of air bubbles. The new MRE sample had to have its air bubbles removed. The last step is moving the MRE substance into a mold of a particular measurement. Thereafter, the mold is left for several hours to facilitate the drying of the sample. Next, the MRE sample mixture is polymerized for 2–3 hours at a high temperature (200–500 °C) [19, 20, 23, 24, 25].

The new classification of MRE samples is based on the distribution of the particles produced. In the isotropic type, the nano-sized iron particles are arranged randomly, whereas in the anisotropic type, the nano-sized iron particles are arranged in a chain-like configuration. The anisotropic composition emerges because of the polymerization procedure, especially during the last stage, when a magnetic field is used on the composite matrix, causing the iron particles in the specimen to line up in a consistent, parallel configuration. 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. The dimensions of the MRE used in this study are shown in Figure 2, where the diameter is 3 cm and the thickness is 0.5 cm.

After obtaining the shape and dimensions of the new MRE sample, several sample tests were conducted. First, this test was used to explore the morphological properties of the new isotropic MRE.

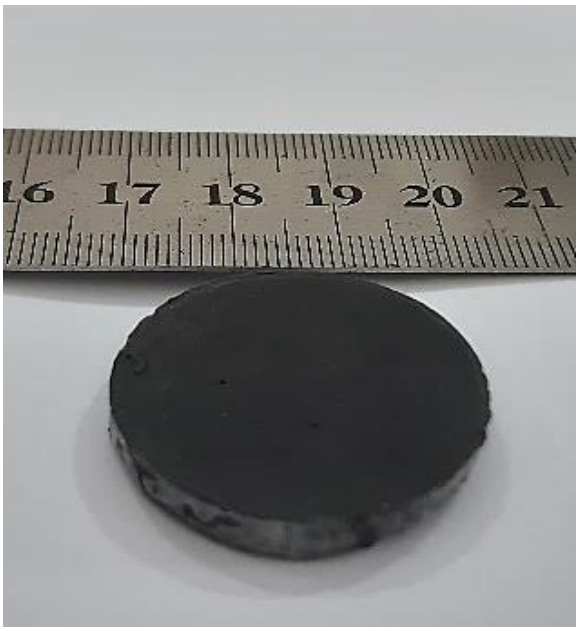

Figure 2. The Dimension of New MRE Sample

The FEI SEM-EDX (Scanning Electron Microscope-Energy Dispersive X-ray spectroscopy) microscope is used to take high-resolution images of sample surfaces and analyze their elemental composition. Taking high-resolution images of sample surfaces and analyzing their elemental composition is what the Inspect-S50 is used for.

The SEM is an FEI brand, type: Inspect-S50. Initiate the process by configuring the SEM. This entails ascertaining that the Power On indicator is illuminated on both the SEM and the computer. Then, click the XT Microscope Server menu. Press the Start button, followed by XTM Log On. Place the sample in the SEM chamber. Then pump (high or low vacuum) is used, and the SEM will be ready for use. Subsequently, the 12 mm specimen undergoes a thorough cleansing procedure. Conductive double-sided tape is used to attach the sample, and it works best when the tape is applied in a precise, even layer. The sample is first dried under a vacuum to remove H_2O. Then, it is placed into the SEM chamber. Next, pumping is performed (either high vacuum or low vacuum). Once this is done, the SEM is ready for use.

Materials used in equipment subjected to vibration require knowledge of their dynamic properties. The efficacy of damping is characterized by a set of parameters, including the loss angle tan δ, the storage modulus, and the loss modulus. Two main modulus components are present in viscoelastic materials. 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 will undergo viscoelastic relaxation. The proportion between the loss modulus and the storage modulus is known as tan δ (damping factor), which demonstrates how efficiently the substance mitigates mechanical energy. The second test used a rheometer, namely the Discovery Hybrid Rheometer (DHR) series manufactured by TA Instrument, a device used to determine the rheological properties of samples in response to certain forces. The axial force used to compress the samples in this research was 1 N. The frequency used ranged from 0 to 100 Hz. In this investigation, the loss modulus, storage modulus, and tan δ (damping factor) of the material were measured.

RESULTS AND DISCUSSION

Microstructures of the new MRE have been observed by SEM mainly regarding magnetic particle dispersion in the matrix. Typically, new MRE samples were first cut perpendicular to the disk surface after immersion in liquid nitrogen before SEM observation. Characterization of the orientation of the magnetic particles within the rubber matrix was achieved by using energy-dispersive X-ray spectroscopy (EDX) with Fe-mapping image analysis. The randomly dispersed particles of the various volume fractions of the isotropic new MRE observed by SEM-EDX are shown in Figures 3-4. Meanwhile, the weight % and atomic % elemental composition of the isotropic new MRE are listed in Tables 2-3.

The elemental distribution map of the new MRE sample is shown in Figure 3. The distribution of carbon is indicated by the green color. The distribution of carbon across the sample's surface is evident, with its presence extending to nearly the whole sample. The distribution of oxygen is designated by the red color. Oxygen is also widely distributed. The distribution of silicon is shown by the cyan color. This element is also distributed uniformly and appears to be the primary component of the sample matrix. The presence of iron is pointed out by the magenta color. Unlike the other elements, iron does not spread evenly; it accumulates in small, specific areas.

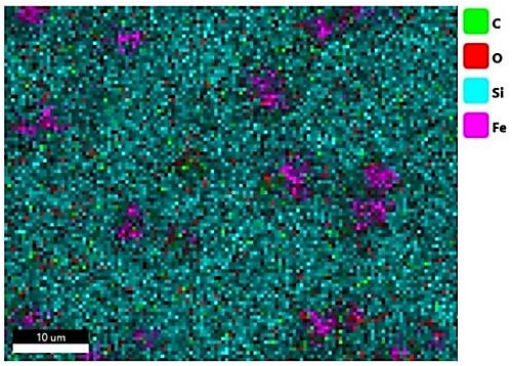

Figure 3. Dispersed Particles of Sample new MRE

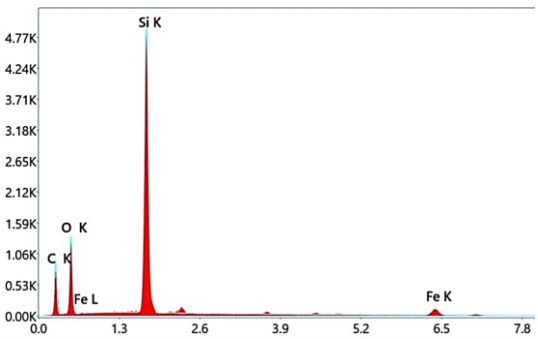

Figure 4. Spectrum of the Sample new MRE

The EDX spectrum of the new MRE material is shown in Figure 4. The horizontal axis, designated as X, signifies the X-ray energy level in kilo electron volts (keV), while the vertical axis, denoted as Y, denotes the intensity of the detected X-rays. X-rays are emitted by each element at a characteristic energy level. The components present in the specimen are distinguished by the highs on the chart. The peaks seen are silicon (Si), oxygen (O), carbon (C), and iron (Fe). The presence of a prominent and elevated peak, indicative of silicon's dominance, further substantiates this observation. A significant oxygen peak was observed. There is also a significant carbon peak. Two peaks for iron were identified, indicating its presence, though these peaks were significantly lower compared to those for Si, O, and C.

Based on Tables 2-3, several patterns of compositional change were observed, and these patterns will be discussed in more detail in the following section. The fabrication of MRE prior to the incorporation of Fe_3O_4 entails the utilization of an array of materials, encompassing carbonyl iron powder (CIP), silicone oil, and silicone rubber. Meanwhile, the CIP used in this study already contains Fe. Thus, the MRE before the addition of Fe_3O_4 nano material already contains Fe elements as presented in Tables 2-3. Carbon (C) remained relatively stable at about 50-52% in all samples, indicating that it is the major component. Oxygen (O) showed an increase in MRE-2, followed by a slight decrease in MRE-3 and MRE-4, indicating increased oxidation in MRE-2. Silicon (S) content decreased slightly in MRE-2, but increased again in MRE-3 and MRE-4, marking variation in silica content between samples. Iron (Fe) content showed a slight decrease from MRE-1 to MRE-4, which may be due to the addition of Fe_3O_4 causing a redistribution of iron in the material.

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. Composition of the Elements 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

Overall, the changes in elements observed were relatively small with no significant trends. The most notable changes were in oxygen and iron, possibly related to the modifications made in each sample.

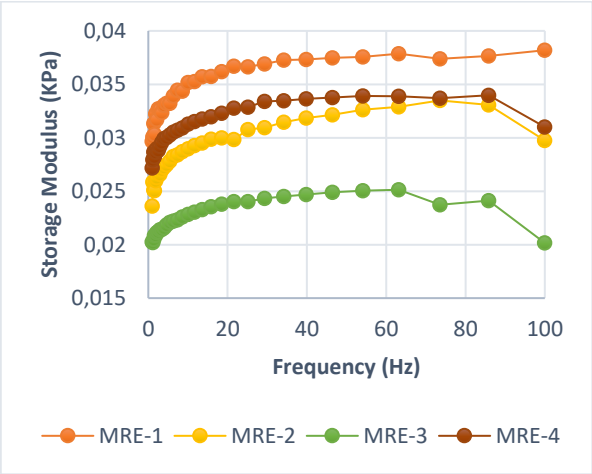

Figure 5. Storage Modulus

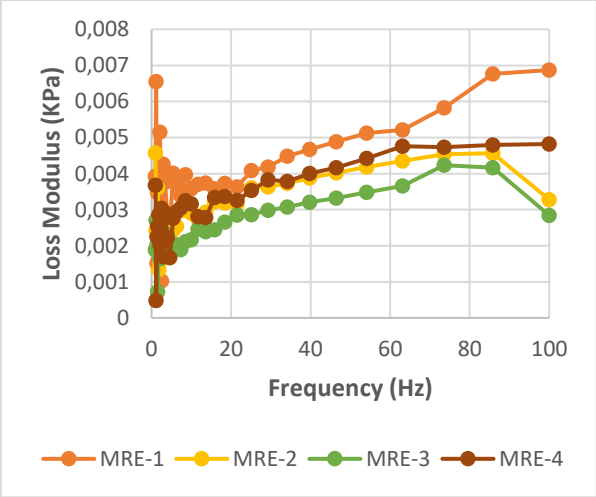

Figure 6. Loss Modulus

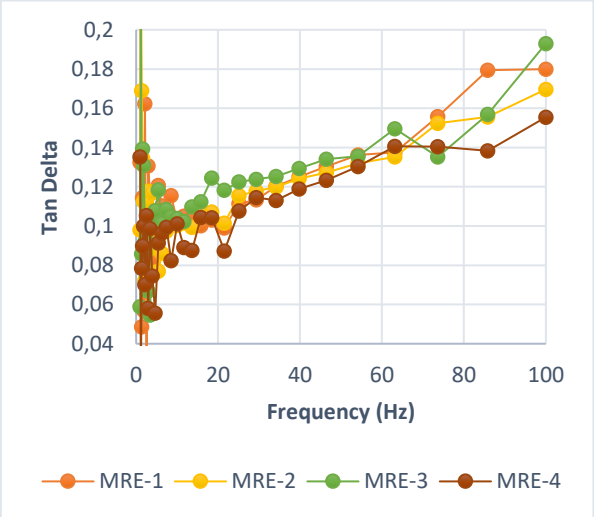

Figure 7. Tan δ

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

The findings from the second experiment, employing the TA Instrument DHR Rheometer, are presented in Figures 5-7. This instrument is utilized to ascertain the rheological characteristics of a specimen in response to a specified force. The figures depict the storage modulus, loss modulus, and tan δ (damping factor) of the material. In this research experiment, the MRE-1 sample was used as a base material mixture without added Magnetite, referring to previous research conducted by [26][7].

The performance of MRE-1 has been shown to have variable tan delta values, with maximum values occurring at low frequencies (217,869 at 1,167 Hz). These results are based on the Storage Modulus, Loss Modulus, and Tan δ data presented in Figures 5-7. It shows good attenuation at low frequencies. MRE-2 performance has the highest tan delta at mid-frequencies (242,524 at 1,167 Hz), indicating strong damping potential. It is shown effective at absorbing energy in this frequency range. MRE-3 performance has the lowest tan delta at most frequencies, indicating less attenuation and less effectiveness in vibration-damping applications. MRE-4 performance has a fairly good tan δ but degrades at high frequencies. It has shown that can still perform well in damping, but 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. The reference material, MRE-1, demonstrates effectiveness at low frequencies even without the incorporation of nanomaterials. MRE-4 is usable but less optimal than MRE-2. For this application, MRE-3, which has the lowest value, is not recommended. Therefore, to effectively damp vibrations in the 1-100 Hz frequency range, MRE-2 should be used as the primary material.

CONCLUSION

The research indicates that an MRE containing Fe_3O_4 nanomaterial has been developed. For vibration damping in the 1-100 Hz frequency range: MRE-2 (MRE is added 0.5% Fe_3O_4) is the best choice as it has the highest tan delta value and strong damping performance at intermediate frequencies (1,167 Hz) based on the experiment. MRE-1 without Magnetite nanomaterials is also an excellent choice with high stiffness and good damping capability at low frequencies. MRE-4 is still feasible, but less optimal than MRE-1 and MRE-2. MRE-3, with the lowest tan δ and storage modulus values, is not recommended for this application. Therefore, for optimal vibration damping applications in the 1-100 Hz frequency range, especially at intermediate frequencies, MRE-2 should be selected as the primary material. MRE-1 is a very good alternative at low frequencies. These experimental results indicate that incorporating Magnetite nanomaterial into MRE can enhance its effectiveness in mitigating vibration, even in the limited mid-frequency range of 0 to 100 Hz.

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