

A MORPHOLOGY OF THE EFFECT OF THE MAGNETORHEOLOGICAL ELASTOMER MATERIAL IN THE ADDITION OF COBALT FERRITE NANOMATERIAL

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ABSTRACT

Smart materials have been defined as functional substances that have the ability to respond to a variety of stimuli from the environment. Magnetorheological elastomers (MREs) are a class of advanced materials. They consist of magnetic particles dispersed in an elastomeric matrix. These particles have the ability to tune the mechanical properties of the material through a tunable response to applied magnetic fields. The purpose of this research is to investigate the effect of adding Cobalt Ferrite nanomaterial, which has strong magnetic properties, to MRE material at a specified weight percent by volume. For vibration damping, the materials show promising characteristics for vibration reduction applications due to their high carbon content and favorable mechanical properties. Specifically, carbon-based composites are known for their ability to absorb vibrations effectively. Based on both the elemental composition data and current research findings, MRE-2 is identified as the most suitable material for vibration reduction applications due to its optimal carbon content and balanced elemental composition that supports effective damping characteristics. Where MRE-2 is a mixture of materials consisting by weight of 5% silicone oil, 65% silicone rubber, up to 29.5% carbonyl magnetic particles (CIPs), and up to 0.5% cobalt ferrite.

Keywords Nanomaterial; Cobalt Ferrite; Magnetorheological Elastomers; Vibration;

Paper type Research paper

INTRODUCTION

Functional materials capable of sensing and responding to a variety of environmental stimuli have been defined as smart materials. This stimulus may include light, electricity, magnetism, mechanics, heat, and chemicals [1]. They have the potential to alter the properties of the material considerably [2]. Wearable devices, neuromorphic computing, and biomimetic robotics [3]. These materials can be engineered and customized for specific functional applications, with notable examples including shape memory polymers, smart liquid metals, and flexible conductive polymers [3]. Due to the aforementioned characteristics of smart materials, namely self-sensing, self-adaptability, and memory, the aerospace industry has a keen interest in smart materials [4]. To fabricate smart micro/nanodevices using smart materials, a variety of printing methods have been employed, including inkjet and three-dimensional printing [1]. With the advancement of research in this field, the integration of smart materials will play a key role in the development of a smart society [3].

Magnetorheological elastomers (MREs), a class of advanced materials, consist of magnetic particles distributed throughout an elastomer matrix. These particles have an adjustable response to an applied magnetic field, enabling them to control mechanical properties [4], [5], [6], [7]. An extensive review of existing literature reveals an extensive body of research that identifies significant factors affecting MRE performance, including manufacturing process, particle type and size, matrix material, and additives [8]. MREs exhibit field-dependent rigidity and attenuation characteristics, making them suitable for many applications, including damping, isolation, soft actuation, and sensing [4], [9]. MRE performance depends on several factors, including the magnetic field strength, how the MRE works, and how the particles are dispersed within the material [10]. When designing adaptive structures and systems, it is imperative to model the behavior of MREs. Several approaches have been used, such as physically based and phenomenological models [9]. The improvement of MRE performance and the development of characterization methods have been the focus of recent research

efforts. In addition, the potential applications of MREs in areas such as biomedical engineering have been investigated in these studies [5], [9], [10].

A nanomaterial is a particle or substance with one or more dimensions between 1 and 100 nm [11], [12]. Due to their unique properties, which include their tiny dimensions, surface effects, and quantum tunneling effects, these materials have attracted considerable interest [13]. From traditional materials and medical devices to electronic components and coatings, the potential applications of nanomaterials cover a wide spectrum [13]. Nanomaterials have a history that goes back to the universe itself. However, it was not until the mid-1990s that the term "nanotechnology" began to catch on and become established. The main reason for this is the considerable progress made in imaging technologies. Nanomaterials synthesis methods have advanced considerably over time, allowing specific properties to be incorporated by modulating scale, morphology, and composition. However, research is underway to understand their potential toxicities, risks, and regulatory frameworks to ensure their safe use in various industries [14].

Cobalt ferrite, is a semi-hard magnetic material that exhibits unique physical and magnetic properties, making it suitable for various technological and medical applications. It has high saturable magnetic and thermal stability, customizable via different synthesis routes. There are several distinctive properties of cobalt ferrite nanoparticles. The magnetic properties of cobalt ferrite exhibit high coercivity and magnetocrystalline anisotropy. These properties are advantageous for applications requiring stable magnetic materials. Its magnetic performance is enhanced by the presence of nanoscale single-domain properties [15], [16]. The material is suitable for harsh environments due to its excellent thermal and chemical stability [17]. In terms of morphological control, various synthesis techniques such as sol-gel methods, co-precipitation and green synthesis using plant extracts can be used to control the size and shape of cobalt ferrite nanoparticles. Due to their unique properties, cobalt ferrite nanoparticles have a wide range of applications. In biomedical applications, they are used as contrast agents in magnetic resonance imaging, as drug delivery systems, and as antibacterial agents. Their magnetic properties enable targeted drug delivery and enhanced imaging capability. In energy storage, due to its electrochemical properties, cobalt ferrite is being investigated as an electrode material in supercapacitors and batteries. In photocatalysis applications, particularly in environmental remediation processes, are being investigated with modified cobalt ferrite nanoparticles. In sensors and actuators area, high magnetostrictive properties make them ideal for sensors and actuators requiring precise control of magnetic fields [15], [16], [17]. Recent studies have focused on enhancing the functionality of cobalt ferrite nanoparticles by ion substitution, Further tuning the magnetic properties of cobalt and iron ions by modifying them with rare earth elements or other transition metals. In synthesis innovations, the use of environmentally friendly synthesis methods to produce cobalt ferrite with controlled morphology and improved performance characteristics. In hybrid materials, the combination of cobalt ferrite with other materials, such as graphene or silica, creates composite materials that take advantage of the strengths of both components for advanced applications. Due to its versatility and potential for innovation, cobalt ferrite continues to be a major focus of materials science research [10], [16], [17]. The purpose of this research is to investigate the effect of adding nano cobalt ferrite material, which has strong magnetic properties, to MRE material in order to minimize vibration. Through the combination, it will be observed the spread and material content that will occur after the mixing.

METHOD

Several materials are used in MRE manufacturing, including CIP, silicone oil, and silicone rubber [2], [6], [7], [10]. The material blend of MR elastomer was modified with the addition of cobalt ferrite nanomaterial in this research. This modified material will be called MRE+. The process for the preparation of MRE+ is shown in Figure 1 and is generally a three-step process.

The first steps involve fusing materials, namely silicone rubber, silicone oil, micron-sized iron carbonyl magnetic particles (CIP), and cobalt ferrite. The weight percentages for each material are listed in Table 1. Choosing the right materials is the first step in developing MREs. The materials of choice are CIPs, a compound from Sigma-Aldrich that is low in magnesium and low in manganese. Dow Corning Corporation 200® silica oil liquid with a viscosity of 60,000 cSt (25 oC) was supplied by Sigma-Aldrich. Sigma-Aldrich. Clear RTV (100% silicone rubber) was provided by Permatex. Mixing is done at room temperature. The next step is to incorporate the CIP into the polymer matrix. This process takes place during the stirring procedure and results in the presence of air bubbles. Air bubbles must be eliminated from the MRE+ sample. The final step involves transferring the mixture results from the previous steps into a mold of a specified size. To facilitate the hardening of the

sample, the mold is left for several hours. Subsequently, the mold is filled with the mixture of the sample material and polymerized for 2 to 3 hours at an elevated temperature (200 to 500 °C). At room temperature, polymerization continues for up to 24 hours.

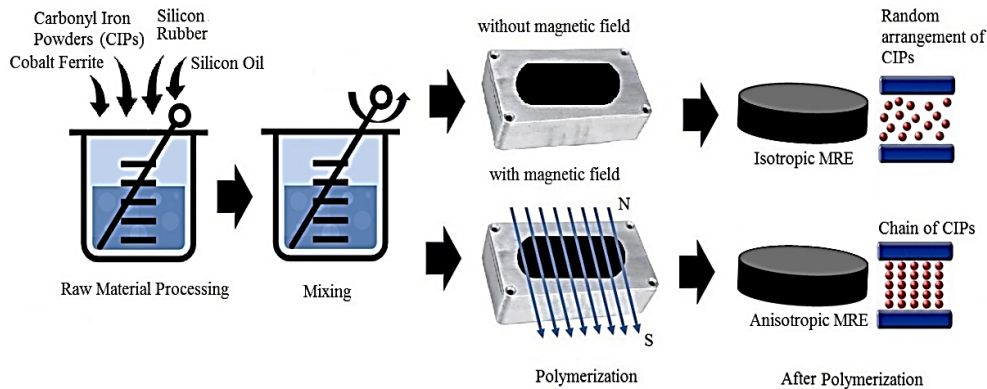


Figure 1. The Step-by-step MRE Fabrication

TABLE I. THE WEIGHT PERCENTAGE FOR EACH MATERIAL

Name	Silicone oil	Silicone rubber	CIPs	Cobalt Ferrite
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%

Based on the observed particle distribution and subsequent analysis of the resulting architectures, the MRE+ samples are classified as follows. In the isotropic form, the particles are arranged in a random pattern, while in the anisotropic form, the particles are arranged in a chain-like arrangement. Anisotropy occurs during the polymerization process, particularly in the final stage when a magnetic field is applied to the composite matrix, causing the iron particles in the sample to align. Conversely, the isotropic shape results from a random and irregular arrangement of the iron particles within the sample in the absence of an external magnetic field during the polymer curing process. The dimensions of the MRE used in this study are 2 cm in diameter and 0.5 cm in thickness.

DISCUSSION

MRE+ microstructures were observed by SEM mainly for magnetic particle matrix dispersion. Usually, MRE+ samples were first sliced perpendicular to the wafer surface following immersion in liquid nitrogen before SEM examination. In addition, the orientation of the magnetic particles within the rubber matrix was characterized by energy dispersive X-ray spectroscopy (EDAX) with Fe-mapping image analysis. The SEM observations of the randomly distributed particles are shown in Figures 3-4. Meanwhile, Figure 5 shows the sum spectrum of sample MRE+. Tables 2-3 list the weight percent and atomic percent elemental composition of the isotropic MRE+.

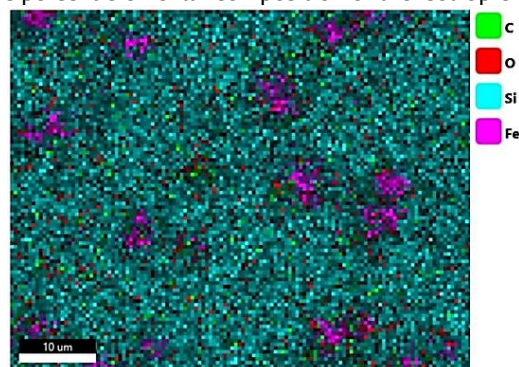


Figure 3. Element Overlay of Sample MRE+

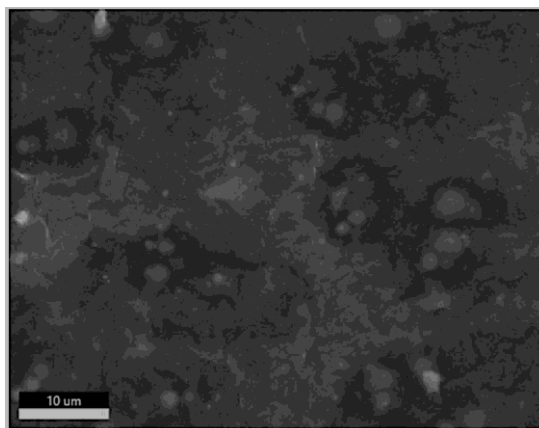


Figure 4. Surface Image of Sample MRE+

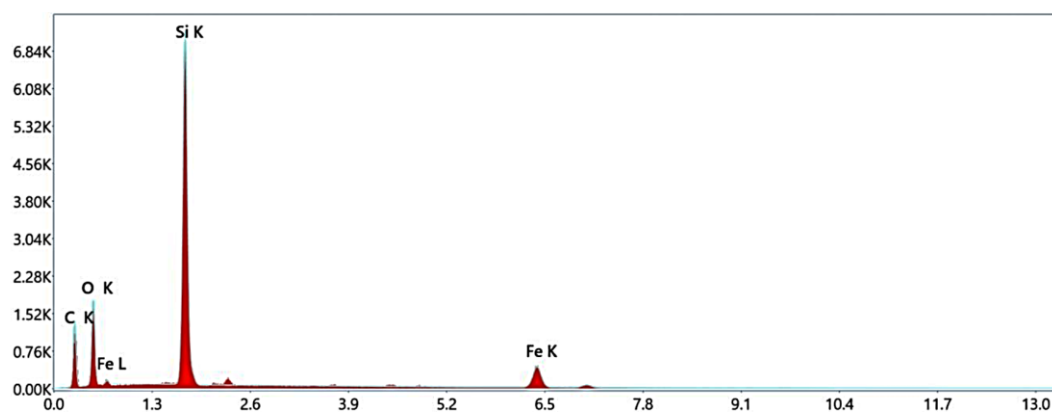


Figure 5. Sum Spectrum of Sample MRE+

TABLE II. 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 III. 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

Based on Tables 2-3, several patterns of compositional change were observed in weight percentages for four samples labeled MRE-1, MRE-2, MRE-3, and MRE-4. The elements analyzed include Carbon (C), Oxygen (O), Silicon (Si), and Iron (Fe). Below is a detailed analysis of the data. The carbon content is relatively high across all samples, with MRE-2 showing the highest value at 49.89%. MRE-4 has the lowest carbon content at 48.36%, which may suggest a difference in composition or processing conditions affecting carbon retention. Carbon Levels for the material are high and consistent across all samples, with slight variations. Oxygen levels vary significantly, with MRE-4 having the highest oxygen content at 28.34%. This could indicate a higher degree of oxidation or the presence of more oxidized compounds in this sample compared to others. Oxygen

Levels for the material are significant variation, particularly higher in MRE-4. Silicon content is relatively consistent among the samples, with MRE-2 displaying the highest at 17.83% and MRE-3 the lowest at 15.88%. Silicon content is relatively consistent among the samples, with MRE-2 displaying the highest at 17.83% and MRE-3 the lowest at 15.88%. The variations in silicon content may reflect differences in mineralogical composition or processing methods. The variations in silicon content may reflect differences in mineralogical composition or processing methods. Silicon Levels for the material are moderately consistent, with a noticeable dip in MRE-3. Iron content is notably higher in MRE-3 at 8.07%, which could suggest a greater presence of iron-bearing minerals or compounds in this sample compared to others. The other samples show relatively similar iron levels, with MRE-2 slightly higher than MRE-1 and MRE-4. Iron Levels for the material are highest in MRE-3, indicating potential differences in mineral composition. The elemental composition analysis reveals distinct differences among the samples that could be attributed to variations in their source materials or processing methods. Understanding these differences can provide insights into their potential applications or behaviors in various environments, such as chemical reactivity, stability, or suitability for specific uses in industry or research contexts.

As shown in Tables 2-3, the elemental composition in atomic percentages for four samples labeled MRE-1, MRE-2, MRE-3, and MRE-4. The elements analyzed are Carbon (C), Oxygen (O), Silicon (Si), and Iron (Fe). Below is a detailed analysis of the data. Carbon constitutes a significant portion of the atomic composition across all samples, with MRE-2 having the highest carbon content at 63.94%. MRE-4 shows the lowest carbon content at 61.89%, which may suggest a variation in the organic or carbonaceous material present in this sample. Carbon Levels: High and consistent across all samples, with slight variations. Oxygen levels exhibit notable variation, particularly with MRE-4 having the highest oxygen content at 27.22%. This increase may indicate a higher degree of oxidation or the presence of more oxygen-containing compounds in this sample compared to others. Oxygen Levels: Significant variation, particularly higher in MRE-4. Silicon content is relatively consistent among the samples, with MRE-2 showing the highest value at 9.77% and MRE-3 the lowest at 8.70%. These variations could reflect differences in mineralogical composition or processing methods. Silicon Levels: Moderate consistency, with a noticeable dip in MRE-3. Iron content is highest in MRE-3 at 2.22%, indicating a greater presence of iron-bearing minerals or compounds in this sample compared to others. The other samples have relatively similar iron levels, with MRE-2 being slightly higher than MRE-1 and MRE-4. Iron Levels: Highest in MRE-3, suggesting potential differences in mineral composition. The atomic composition analysis reveals distinct differences among the samples that could be attributed to variations in their source materials or processing methods. The high carbon content across all samples suggests a carbon-rich material, while variations in oxygen and iron levels indicate differing degrees of oxidation and mineral presence. Understanding these differences can provide insights into their potential applications or behaviors in various environments, such as chemical reactivity, stability, or suitability for specific uses in industry or research contexts.

The elemental composition data presented in both weight percentages and atomic percentages for the samples MRE-1, MRE-2, MRE-3, and MRE-4 can provide insights into their potential effectiveness in vibration reduction applications. Carbon materials, especially in composite forms like carbon fibers, are known for their excellent mechanical properties, including high stiffness and strength-to-weight ratios. They also exhibit good damping characteristics due to their ability to absorb vibrations, making them suitable for applications in reducing vibrations in structures and instruments. The presence of oxygen can indicate the potential for oxidation reactions that may affect the material's structural integrity or damping capabilities. However, moderate oxygen content can enhance the bonding characteristics in composites, potentially improving their overall performance in vibration reduction. Silicon can contribute to the thermal stability and mechanical strength of composite materials but may not directly influence vibration-damping capabilities. While iron is not typically associated with vibration damping, its presence could enhance the material's density, which may contribute to overall stability and vibration resistance [3], [13], [18], [19], [20]. The materials analyzed show promising characteristics for vibration reduction applications due to their high carbon content and favorable mechanical properties. Specifically, carbon-based composites are known for their ability to absorb vibrations effectively, making them suitable candidates for various engineering applications where noise and vibration control are paramount. Carbon is known for its excellent mechanical properties and damping capabilities, making it a prime candidate for vibration-reduction materials. All samples have high carbon content, which is beneficial. MRE-2 has the highest carbon content (both weight and atomic percentages), which correlates with superior

mechanical properties and damping capabilities. Oxygen levels are highest in MRE-4, which could indicate a higher degree of oxidation that might affect structural integrity but could also enhance bonding in composites. Silicon contributes to thermal stability and mechanical strength but does not directly influence vibration damping. Iron levels are relatively low across all samples but are highest in MRE-3, which may contribute to density and stability under dynamic loads. MRE-2 maintains a balanced composition with moderate levels of oxygen and silicon, potentially enhancing its structural integrity while still providing effective damping properties [18], [20], [21], [22]. Based on both the elemental composition data and current research findings, MRE-2 is identified as the most suitable material for vibration reduction applications due to its optimal carbon content and balanced elemental composition that supports effective damping characteristics. Where MRE-2 is a mixture of materials consisting by weight of 5% silicone oil, 65% silicone rubber, up to 29.5% carbonyl magnetic particles (CIPs), and up to 0.5% cobalt ferrite.

CONCLUSION

From observing, analyzing, and discussing the data, we know that the materials we studied have high carbon content and favorable mechanical properties that make them attractive for vibration damping. In particular, carbon-based composite materials are known for their ability to effectively absorb vibration, which makes them suitable candidates for a variety of engineering applications where noise and vibration control are of paramount importance. The performance of these materials in practical vibration reduction applications could be further enhanced through further research to optimize the structure and composition of these materials. Based on both the elemental composition data and current research findings, MRE-2 is identified as the most suitable material for vibration reduction applications due to its optimal carbon content and balanced elemental composition that supports effective damping characteristics. Where MRE-2 is a mixture of materials consisting by weight of 5% silicone oil, 65% silicone rubber, up to 29.5% carbonyl magnetic particles (CIPs), and up to 0.5% cobalt ferrite.

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REFERENCES

- [1] M. Su and Y. Song, "Printable smart materials and devices: strategies and applications," *Chemical reviews*, vol. 122, no. 5, pp. 5144–5164, 2021.
- [2] T. Ramakrishnan *et al.*, "Recent developments in stimuli responsive smart materials and applications: an overview," *Journal of Nanomaterials*, vol. 2022, no. 1, p. 4031059, 2022.
- [3] W. Hu, H. Zhang, K. Salaita, and H. Sirringhaus, "SmartMat: Smart materials to Smart world," *SmartMat*, vol. 1, no. 1, 2020.
- [4] A. A. Basheer, "Advances in the smart materials applications in the aerospace industries," *Aircraft Engineering and Aerospace Technology*, vol. 92, no. 7, pp. 1027–1035, 2020.
- [5] V. G. Kamble, J. Thimmaiah, and S. Kolekar, "Magneto-sensitive elastomers—materials, fabrication, and characterisation: state of the art," *Emerging Materials Research*, vol. 13, no. 3, pp. 262–288, 2024.
- [6] G. Priyandoko, P. Suwandono, M. I. N. Sasongko, U. Ubaidillah, and S. T. Wicaksono, "Developing adjustable stiffness for smart material of magnetorheological elastomer to diminish vibration," *Sinergi*, vol. 28, no. 1, p. 163, Dec. 2023, doi: 10.22441/sinergi.2024.1.016.
- [7] G. Priyandoko, F. Hunaini, F. Imaduddin, U. Ubaidillah, P. Suwandono, and M. I. N. Sasongko, "Development of a Vibration Isolator on the Basis of a Magneto-Rheological Elastomer," *Adv. Sci. Technol. Res. J.*, vol. 18, no. 8, pp. 272–280, Dec. 2024, doi: 10.12913/22998624/194441.
- [8] S. S. Kang, K. Choi, J.-D. Nam, and H. J. Choi, "Magnetorheological elastomers: Fabrication, characteristics, and applications," *Materials*, vol. 13, no. 20, p. 4597, 2020.
- [9] A. Saber and R. Sedaghati, "The Modeling of Magnetorheological Elastomers: A State-of-the-Art Review," *Advanced Engineering Materials*, vol. 25, no. 16, p. 2300182, 2023.
- [10] A. K. Bastola, M. Paudel, L. Li, and W. Li, "Recent progress of magnetorheological elastomers: a review," *Smart Materials and Structures*, vol. 29, no. 12, p. 123002, 2020.

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- [11] N. Baig, I. Kammakam, and W. Falath, "Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges," *Materials advances*, vol. 2, no. 6, pp. 1821–1871, 2021.
- [12] S. Caspani, R. Magalhães, J. P. Araújo, and C. T. Sousa, "Magnetic nanomaterials as contrast agents for MRI," *Materials*, vol. 13, no. 11, p. 2586, 2020.
- [13] Q. Wu, W. Miao, Y. Zhang, H. Gao, and D. Hui, "Mechanical properties of nanomaterials: A review," *Nanotechnology Reviews*, vol. 9, no. 1, pp. 259–273, 2020.
- [14] A. Barhoum *et al.*, "Review on natural, incidental, bioinspired, and engineered nanomaterials: history, definitions, classifications, synthesis, properties, market, toxicities, risks, and regulations," *Nanomaterials*, vol. 12, no. 2, p. 177, 2022.
- [15] A. Johan, D. Setiabudidaya, F. S. Arsyad, Ramlan, and W. A. Adi, "Strong and weak ferromagnetic of cobalt ferrite: Structural, magnetic properties and reflection loss characteristic," *Materials Chemistry and Physics*, vol. 295, p. 127086, Feb. 2023, doi: 10.1016/j.matchemphys.2022.127086.
- [16] A. Milutinović, Z. Ž. Lazarević, M. Šuljagić, and L. Andjelković, "Synthesis-Dependent Structural and Magnetic Properties of Monodomain Cobalt Ferrite Nanoparticles," *Metals*, vol. 14, no. 7, p. 833, Jul. 2024, doi: 10.3390/met14070833.
- [17] A. López-Ortega, E. Lottini, C. D. J. Fernández, and C. Sangregorio, "Exploring the Magnetic Properties of Cobalt-Ferrite Nanoparticles for the Development of a Rare-Earth-Free Permanent Magnet," *Chem. Mater.*, vol. 27, no. 11, pp. 4048–4056, Jun. 2015, doi: 10.1021/acs.chemmater.5b01034.
- [18] J. Zhao *et al.*, "Vibration Damping of Carbon Nanotube Assembly Materials," *Adv Eng Mater*, vol. 20, no. 3, p. 1700647, Mar. 2018, doi: 10.1002/adem.201700647.
- [19] L. Wang *et al.*, "Electromagnetic Absorption by Magnetic Oxide Nanomaterials: A Review," *ACS Applied Nano Materials*, vol. 6, no. 24, pp. 22611–22634, 2023.
- [20] S. Tosi and E. Marini, "Tracing the Evolution of the Emission Properties of Carbon-Rich AGB, Post-AGB, and PN Sources," *Astronomy*, vol. 4, no. 1, p. 2, Jan. 2025, doi: 10.3390/astronomy4010002.
- [21] M. Lv and J. L. Sun, "Effect of Vibration Characteristics for Carbon Fiber Composite Materials on Musical Instruments Making," *AMM*, vol. 508, pp. 66–69, Jan. 2014, doi: 10.4028/www.scientific.net/AMM.508.66.
- [22] X. Chen, P. Cheng, Z. Tang, X. Xu, H. Gao, and G. Wang, "Carbon-Based Composite Phase Change Materials for Thermal Energy Storage, Transfer, and Conversion," *Advanced Science*, vol. 8, no. 9, p. 2001274, May 2021, doi: 10.1002/advs.202001274.
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