

Weather-Induced Degradation in Magnetorheological Elastomers: Tropical Climatic Conditions on The Rheological and Mechanical Properties

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Abstract. Integrating advanced materials into engineering has made significant strides in developing innovative applications that support future technologies and enhance human convenience, both in the present and in the coming years. Among these, smart materials like magnetorheological elastomers (MREs) have emerged as promising candidates for replacing traditional materials such as rubber due to their unique ability to alter their mechanical properties in response to external magnetic fields. This capability opens up new possibilities in various fields, from automotive to robotics. Despite these advancements, the full potential of MREs to replace rubber in all its functions remains unfulfilled, particularly when considering their performance in real-world conditions. One critical challenge is their durability and resistance to climatic environmental factors, such as UV radiation, temperature fluctuations, and humidity. These factors can cause significant degradation in the material's mechanical and magnetic properties over time, limiting its long-term functionality. This paper focuses on the degradation of MREs under an outdoor tropical climate and weathering effects. Two types of silicone rubber (SR)-based MREs were developed, containing 70 wt% micron-sized carbonyl iron particles (CIP) and 60 wt% micron-sized electrolyte iron particles (EIP). These samples were exposed to natural weathering conditions for 30 days. The natural weathering process led to significant changes in the material's properties. Mechanical testing, rheological analysis, and morphological evaluation revealed increased storage modulus, indicating enhanced stiffness, while flexibility decreased. These changes suggest that the material became more rigid and less flexible over time due to exposure to environmental conditions, which is important for

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understanding its long-term performance and durability. These assessments provided a comprehensive understanding of MRE degradation under prolonged exposure to climatic conditions. Unpredictable climatic variations, particularly variations in weather, may induce uncharacterized behavior in MREs. Investigating these emergent behaviors is essential for optimizing their performance and expanding their applicability in dynamic and complex operational environments.

Key words: Climatic Degradation, Magnetorheological Elastomer, Morphology, Rheology, Smart Materials

1 INTRODUCTION

The study on Magnetorheological Elastomers (MREs) has demonstrated their potential to emerge as a significant smart material in various engineering applications, ranging from vibration control in automotive systems to adaptive structures in advanced industries [1], [2]. As a composite material, MREs consist of magnetic particles embedded within an elastomeric matrix, exhibiting tunable mechanical properties under the influence of a magnetic field. This unique characteristic makes them highly valuable for dynamic response applications [3], [4]. With these capabilities, the automotive sector, in particular, is expected to leverage MREs to develop advanced suspension systems and engine mounts, integrating them into structural components that require adjustable stiffness and damping properties to adapt to existing environmental conditions.

Although the use of MREs is expanding and holds promising benefits, their long-term performance in tropical climates presents significant challenges that remain largely unaddressed and not yet fully understood. Tropical environments are characterized by high temperatures often exceeding 35°C, relative humidity above 80%, and intense ultraviolet (UV) radiation exposure, creating highly aggressive conditions for polymeric materials, including MREs. These environmental factors can trigger complex degradation mechanisms in MREs, potentially compromising their mechanical properties and magnetic responsiveness. The elastomeric matrix in MREs is particularly susceptible to accelerated oxidation and chain scission due to the combined effects of heat and UV exposure, while high humidity levels may affect the interfacial interactions between magnetic particles and the polymer matrix [5].

Recent literatures [6], [7], [8] highlight a critical gap in understanding the degradation mechanisms of MREs under tropical environmental conditions. While previous studies [9], [10], [11], [12], [13] have investigated the effects of temperature and UV exposure on conventional elastomeric materials, comprehensive research on the synergistic impact of natural tropical conditions—including high temperature, humidity, and UV radiation—on MRE performance remains scarce. Existing studies [14], [15], [16] often focus on distinct environmental settings, such as marine or non-tropical climates, which may not fully capture the degradation dynamics specific to tropical regions. Moreover, the implications of these

degradation mechanisms on the magneto-mechanical coupling behavior of MREs, which is essential for their functional performance, are not yet well understood. This knowledge gap hinders the ability to predict long-term reliability and optimize MRE formulations for use in harsh environments. Exploring various particle shapes could offer a potential solution by mitigating the degradation process [17], [18], [19], [20], [21], [22]. While spherical particles are the most commonly used due to their uniformity and ease of dispersion, other shapes, such as ellipsoidal, platelet, rod-like, cubic, and irregular geometries, are less popular but worth investigating. These alternative shapes could influence the stress distribution within the MRE matrix, impact particle-matrix interactions, and potentially enhance durability by altering load transfer mechanisms and reducing localized stress concentrations. Understanding the role of particle morphology in degradation resistance can provide valuable insights for designing more robust MREs suitable for demanding applications.

To bridge this knowledge gap, this study systematically investigates the combined effects of elevated temperature, high humidity, and UV exposure on the degradation mechanisms of MREs, incorporating both spherical and flaky-shaped embedded particles. Additionally, it seeks to quantitatively assess the evolution of mechanical and rheological properties under natural tropical weathering conditions. This study focuses exclusively on the effect of tropical climatic exposure on the rheological and mechanical properties of MREs. Although magneto-mechanical behavior under similar conditions is also of great interest, it lies beyond the scope of this work and will be considered in future investigations. The insights gained from this investigation will serve as a fundamental basis for improving the environmental resilience of MREs and optimizing their performance for advanced applications in tropical climates.

2 METHODOLOGIES

2.1 Sample Preparation

The fabrication of isotropic silicone-based MREs was conducted using a closed-mold method. Two types of MREs were prepared: one incorporating 70 wt.% soft carbonyl iron particles (CIPs) (BASF, Germany) and another with 60 wt.% electrolyte iron particles (EIP) (Industrial Metal Powders Pune, India PVT.LTD), both embedded in a silicone rubber matrix (Nippon Steel Co., Japan). The fabrication process involved mixing iron particles into silicone rubber at 25°C using a mechanical stirrer (200 rpm) until a visually homogeneous dispersion was achieved, followed by the addition of NS625B curing agent (0.1 wt.% for MRE-CIP and 1.5 wt.% for MRE-EIP). The mixtures were then poured into a rectangular aluminum mold (150 mm × 150 mm × 1 mm) and cured for 4 hours. The cured samples were cut into strips (25 mm × 150 mm) and systematically labeled based on exposure duration (0 to 30 days) for weathering studies. For dynamic oscillatory shear testing, circular MRE specimens (20 mm diameter, 1.0–1.3 mm thickness) were prepared using a hollow punch tool. Additionally, mechanical testing was conducted using a tensile testing machine, with samples prepared based on standard test geometry to ensure accurate evaluation of mechanical properties.

2.2 Exposure to Environmental Conditions

The tropical climate exposure was conducted at the Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, to evaluate the environmental degradation of MRE samples. MRE strips underwent a 30 days exposure following ASTM G7/G7M standards, placed in a caged rack facing south, with periodic retrieval for evaluation. The recorded 24-hour mean temperature was 27.0°C, with 19 rainy days over the period. After retrieval, samples were cleaned with acetone and conditioned at room temperature in a desiccator for 24 hours before further testing. Weather data, including rainfall, humidity, wind speed, and temperature, were obtained from the Malaysian Meteorological Department. In this study, only mean values of temperature, relative humidity, and wind speed during the exposure period are reported. The present study was designed to capture the net effect of tropical exposure, and future work will aim to address this aspect.

2.3 Morphological, Rheological, and Mechanical Analysis

To assess the effects of tropical climate on MRE samples, morphological analysis was conducted using scanning electron microscopy (SEM). SEM Tescan Vega 3 (Brno, Czech Republic) was used to examine the degradation characteristics of aged and unaged samples, including surface defects, discoloration, and structural modifications. Cross-sectional analysis provided insights into particle distribution within the matrix. Before SEM imaging, visually identified degraded areas were cut into 10 mm × 10 mm sections, and a conductive coating was applied using sputter coaters (NS800, Novatic Scientific, Singapore) to minimize charging effects and enhance image quality. Gold and platinum coatings of approximately 1–2 nm was applied to improve resolution.

Rheological testing was conducted using an oscillation parallel plate rheometer (Physica MCR 302, Anton Paar, Austria) to evaluate viscoelastic properties, storage modulus, and the absolute magnetorheological (MR) effect. Circular MRE samples (20 mm diameter, 1 mm thickness) were prepared using a hollow punch and placed between parallel plates, preloaded with a consistent normal force of 5.7 N. Magnetic flux densities from 0 to 0.73 T were generated by varying the applied current from 0 to 4 A, measured using a Tesla meter. Strain amplitude sweep tests were performed by varying strain from 0.01% to 10% at a constant frequency of 1 Hz. The temperature was maintained at 25°C using a Viscotherm VT2 temperature control unit.

The quasi-static uniaxial tensile properties of the samples were evaluated before and after tropical climate conditions using a universal testing machine (Shimadzu AGX-S, Kyoto, Japan), following ASTM D412. Dumbbell-shaped specimens were precisely cut from the MRE sheets using standardized tensile cutting dies. The tensile tests were conducted at a controlled room temperature of 25°C, with a constant crosshead speed of 50 mm/min.

3 RESULTS AND DISCUSSION

3.1 Morphological Analysis

The SEM image of MRE-CIP before aging in Figure 1(a) reveals a clean and smooth surface, indicating a uniform dispersion of its constituents without significant irregularities. In contrast, the SEM image of MRE-EIP of Figure 1(c) exhibits a slightly rough texture with visible protruding particles on the surface. This roughness can be attributed to the larger surface area of EIP, which enhances matrix-particle interactions. A possible explanation, the increased interaction between the elastomer matrix and EIP particles contributes to greater interfacial adhesion, thereby improving load transfer efficiency and increasing the stiffness of the MRE. However, the presence of protruding particles may also indicate potential stress concentration points, which could influence long-term durability and aging behavior.

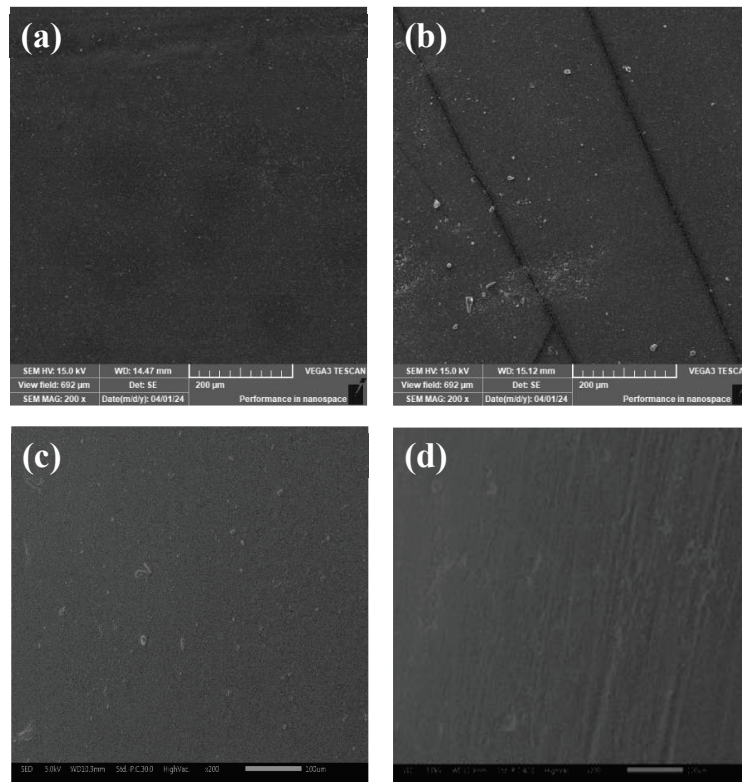


Figure 1: SEM images of (a) unaged MRE-CIP, (b) MRE-CIP after 30 days of exposure, (c) unaged MRE-EIP, and (d) MRE-EIP after 30 days of natural tropical climate aging.

The SEM analysis of the MRE-EIP sample after 30 days (Figure 1(d)) of natural weathering exposure reveals early-stage surface degradation. The micrograph shows a relatively smooth surface with faint linear striations, likely attributed to the stress from environmental exposure. Unlike MRE-CIP samples subjected to prolonged weathering (Figure 1(b)), no significant microcracks, deep voids, or severe surface roughening are observed at this stage. However, subtle textural changes suggest the onset of degradation, potentially influenced by UV radiation, humidity, and temperature fluctuations. UV-induced oxidation of the silicone rubber matrix may have initiated minor surface roughening, while cyclic thermal expansion and contraction could be contributing to the gradual evolution of surface stress. Additionally, prolonged moisture exposure from rainfall may have started affecting the matrix, though no evident water-induced swelling or delamination is detected. These preliminary findings may be attributed to observation that while short-term environmental exposure does not drastically alter the surface morphology, extended exposure may accelerate degradation.

3.2 Rheological Behavior

The graphs in Figure 2 illustrate the variation in the storage modulus of MREs as a function of shear strain under different aging conditions and magnetic stimulation states. The data reveal that the storage modulus decreases with increasing shear strain, a characteristic behavior of viscoelastic materials subjected to deformation. Additionally, aging under a tropical climate has a significant impact on the rheological properties of MREs, as evidenced by the progressive increase in the storage modulus over time. As shown in Figure 2, the samples aged for 15 and 30 days exhibit a higher modulus compared to the unexposed (0-day) samples. This increase may be attributed to surface hardening and possible crosslinking reactions that occur during prolonged exposure to tropical climatic conditions. Such changes can make the material stiffer but potentially less flexible, indicating that aging affects the rheological response of the MREs. Furthermore, the effect of magnetic stimulation is evident, as samples tested under a 5A current, which produced 0.854 T, consistently display a higher storage modulus compared to those without magnetic stimulation (0A) across all aging durations. This suggests that the applied magnetic field enhances the stiffness of the MREs, potentially due to mechanical reinforcement effects that restrict the mobility of the particle in response to the magnetic field within the elastomer matrix. The comparison of both particle types confirms these trends, emphasizing the reliability of the findings. However, a more significant change can be observed in MRE-EIP. Although the unexposed sample has a low storage modulus value, its value increases drastically after exposure to the environment.

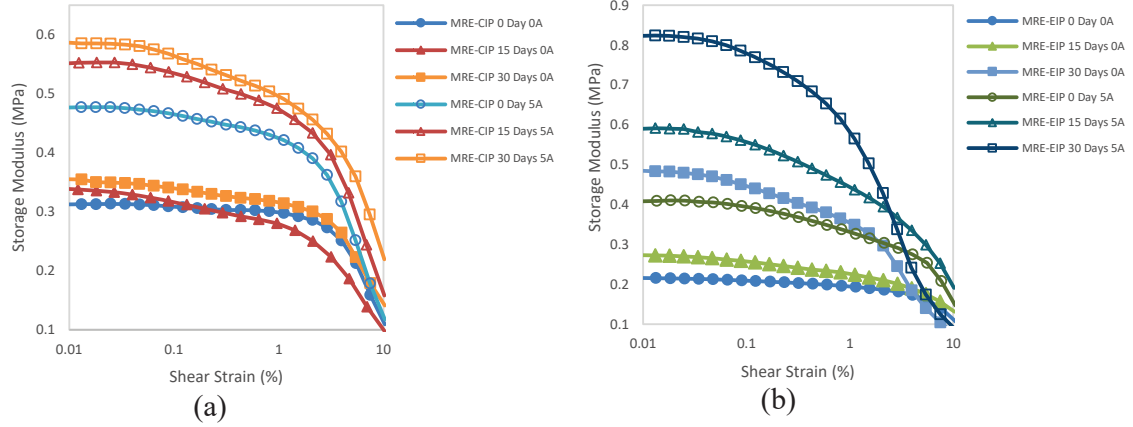


Figure 2: Storage modulus behavior for off-state and on-state at 5A of (a) MRE-CIP and (b) MRE-EIP, after 30 days of exposure to natural tropical climate aging conditions.

The pronounced increase in storage modulus after environmental exposure is more evident in MRE-EIP due to its material composition and susceptibility to environmental factors. This suggests that the higher surface area of the EIP may enhance moisture absorption and particle-matrix interactions, leading to increased stiffness. Additionally, the matrix in MRE-EIP may contain more reactive surface area, making it more prone to oxidation-induced crosslinking when exposed to oxygen, UV light, or heat. These combined mechanisms explain why MRE-EIP exhibits a more significant modulus increase after exposure.

3.3 Tensile Performance

The tensile test results in Figure 3 reveal significant changes in the mechanical behavior of SR and MREs over different aging periods. The Young's modulus at 100% strain increases progressively for both materials, may be attributed to the increased stiffness due to structural modifications such as polymer oxidation, crosslinking, and the evaporation of residual volatiles. In MREs, the modulus enhancement is more pronounced, attributed to stronger matrix-particle interactions that further restrict polymer chain mobility over time. Conversely, the elongation at break decreases with aging, may suggest that signifying a loss of material flexibility. In SR, this reduction is likely caused by polymer oxidation and molecular rearrangements that restrict chain movement. Polymer oxidation is a degradation process in which polymers react with oxygen, leading to structural changes such as additional crosslinking and chain scission. This phenomenon, likely accelerated by environmental exposure and mechanical stress, restricts polymer chain mobility, resulting in increased stiffness and reduced flexibility over time. The effect is more pronounced in MREs, where the presence of particles accelerates embrittlement by further limiting chain mobility. Additionally, particle-matrix detachment and microstructural degradation may contribute to the loss of elasticity and reduced elongation at break in aged

MREs.

A possible explanation is that these findings suggested the trend of the aging-induced trade-off between stiffness and flexibility, where increased stiffness enhances load-bearing capacity but reduces elasticity. This may explain that for the long-term mechanical performance of MREs, particularly in applications requiring durability and adaptive properties. It should be noted that the explanations provided are based on observed trends and previously reported mechanisms. Differences between MRE-CIP and MRE-EIP can be observed in terms of modulus trends, which are linked to the particle morphology and dispersion in the elastomer matrix. As shown in Figure 3, both MRE-CIP and MRE-EIP exhibit an increase in Young's modulus after tropical exposure, although the magnitude of change differs between the two. This difference may be attributed to the distinct particle morphology and dispersion characteristics of CIP and EIP, which influence the stiffness response of the elastomer matrix during aging.

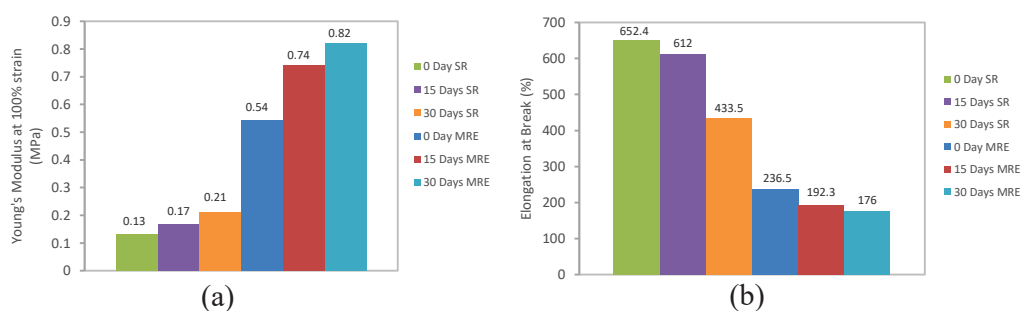


Figure 3: SR and MREs (a) Young's modulus and (b) Elongation at break properties changed after 30 days of exposure to natural tropical climate aging conditions.

4 CONCLUSIONS

This study confirms that MRE, like other rubber-based materials that have been extensively used in various applications, is susceptible to degradation when exposed to environmental conditions, particularly in tropical climates. The tendency for increased hardness after exposure was evident from mechanical and rheological testing, aligning with findings in the literature. This phenomenon is primarily attributed to ultraviolet UV exposure, which promotes cross-linking within the matrix, leading to increased stiffness. However, this hardening effect also contributes to a reduction in elongation at break due to increased brittleness. From a rheological perspective, all samples exhibited an increase in storage modulus, which correlates well with the observed mechanical property changes. This result was expected, as prolonged exposure to high temperatures and solar radiation plays a more dominant role in material degradation, despite the high humidity and frequent rainfall typical of tropical climates. Microstructural observations further support these findings, revealing surface alterations in the exposed

samples. Additionally, MRE with tunable stiffness under magnetic influence demonstrates enhanced properties, as evidenced by rheological evaluations. This characteristic provides a significant advantage over conventional rubber. This study makes a significant contribution to MRE materials research, providing new insights into a topic that has been rarely reported. For future studies, it is recommended to extend the exposure duration to better capture the long-term degradation effects, allowing for a more comprehensive understanding of material deterioration. The present work was limited to the non-magnetic influence of mechanical characterization. Future studies will extend this approach to investigate the influence of tropical climatic conditions on the magnetic and magneto-mechanical properties of MREs, which would provide a more comprehensive understanding of their performance in real environments. Additionally, the development of effective mitigation strategies can be further explored to enhance the durability of MRE under tropical environmental conditions.

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