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Tensile and viscoelastic characterization of magnetorheological elastomers with varying carbonyl iron particle concentration

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ABSTRACT (10 PT)

Magnetorheological elastomers (MREs) are smart composite materials whose mechanical properties can be tuned under magnetic fields, making them ideal for adaptive vibration control. This study examines the viscoelastic behavior of MREs containing 0%, 10%, 20% 30%, 40% and 50% carbonyl iron particles (CIPs) through uniaxial tensile testing. Key mechanical parameters, including tensile stress at 0.2% strain, modulus, and load at yield, were evaluated across twelve samples. The storage modulus was determined using both Rubber Elasticity Theory and the Maxwell–Kelvin viscoelastic model to compare their predictive accuracy. Results revealed that the storage modulus increased with CIP content up to 30% (1.5 MPa, Rubber Elasticity Theory) before slightly declining at 50% (0.6 MPa), likely due to particle agglomeration. The Rubber Elasticity Theory consistently predicted higher moduli than the Maxwell–Kelvin model. Qualitatively, damping improved with higher CIP content, indicated by greater load at yield. These findings highlight the crucial role of filler concentration in tailoring MRE stiffness and damping performance, while emphasizing the need for dynamic mechanical testing to validate energy dissipation mechanisms. The study provides insights into optimizing MRE formulations for engineering applications such as vibration isolation and adaptive control systems.

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Introduction

Magnetorheological elastomers (MREs) are composite materials comprising a polymer matrix embedded with magnetic particles, such as carbonyl iron particles (CIPs), whose mechanical behaviour can be dynamically and actively tuned when exposed to magnetic fields. This tunability enables MREs to serve in vibration isolation mounts and adaptive damping devices and reconfigurable structural components. Prior research investigations has primarily focused on shear-mode performances, demonstrating that increasing CIP concertration enhances the improvement for both stiffness and damping capacity (Dargahi et al., 2019; Sun et al., 2008). For instance, Li et al. (2023) observed and documented approximately a 50% rise in shear modulus for MREs with 30 wt.% CIP system under a moderate magnetic field. However, the tensile mode viscoelastic response across broad CIP loadings remains insufficiently characterized.

Viscoelastic responses, particularly the storage modulus, which quantifying elastic energy storage, and the loss or damping modulus which indicative of energy dissipation govern MRE efficacy in vibration-control application designs. Theoretical frameworks such as classical rubber elasticity and Maxwell–Kelvin viscoelastic models have been applied to predicting these moduli. However, their assumptions often fail at higher filler contents where particle interactions and network heterogeneity dominate the response (Kallio, 2005; Nam et al., 2020). Recent analyses indicate that beyond roughly 15–25 vol.% CIP, discrepancies between modeled and experimental stiffness become pronounced owing to particle clustering and imperfect matrix–filler coupling (Nam et al., 2022; Dhakad et al., 2023).

The present study systematically evaluates isotropic MREs containing 0 - 50 vol.% CIP under uniaxial tensile loading to elucidate how filler content affects viscoelastic performance. Storage and loss moduli are computed via both Rubber Elasticity Theory and the Maxwell–Kelvin model, enabling comparison between ideal-elastic and time-dependent predictions. Additionally, damping capability is qualitatively assessed using yield-load behavior as an indicator of internal energy dissipation. By correlating experimental findings with model predictions, this work aims to establish empirical guidelines for optimizing CIP concentration in MREs intended for real-world vibration-control and adaptive-stiffness applications.

Method

Sample Preparation

Eighteen magnetorheological elastomer (MRE) samples were fabricated by incorporating carbonyl iron particles (CIPs) into a room-temperature vulcanized (RTV) silicone rubber matrix at concentrations of 0%, 10%, 20%, 30%, 40% and 50% by weight, with three samples per concentration. Carbonyl iron particles with an average diameter below 5 µm were mechanically dispersed into the silicone base using high-speed stirring to ensure uniform particle distribution. The mixture was subsequently degassed under vacuum and cured at ambient temperature for 24 h to achieve full crosslinking. This isotropic dispersion technique follows recent best practices for optimizing filler–matrix homogeneity and minimizing agglomeration (Cheng et al., 2022; Siti Nor et al., 2023; Liang et al., 2024).

Tensile Testing

Uniaxial tensile tests were conducted at 298 K using a universal testing machine under displacement control. Specimens were elongated until failure, while the modulus (G), tensile stress at 0.2% strain, and yield load were recorded. The 0.2% strain was chosen to represent the linear viscoelastic region (LVR), consistent with established testing standards for elastomeric composites (Pavel et al., 2022; Asadi et al., 2023). The average of three samples per CIP level was used for subsequent analysis to ensure repeatability and statistical reliability.

Storage Modulus Calculation

Rubber Elasticity Theory

The shear modulus was estimated using the Rubber Elasticity Theory, expressed by

$$G = \frac{\rho RT}{M_C}$$

with assumed material density ($\rho \approx 1000$ kg·m^{-3}), gas constant ($R = 8.314$ J/mol·K), and temperature ($T = 298$ K) and Mc, represents the molecular weight between crosslinks. Assuming Poisson's ratio of 0.5, The storage modulus, E' was derived as

$$E' = 3G$$

This method has been validated in studies relating crosslink density to viscoelastic stiffness in silicone-based composites (Li et al., 2022; Safaei et al., 2023).

Maxwell-Kelvin Model:

For comparison, the Maxwell–Kelvin viscoelastic model approximates the storage modulus as,

$$E' \approx \frac{\sigma}{\varepsilon}$$

at small strain (0.2%), representing the elastic component of the composite response. Although this approach neglects frequency dependence, it remains widely adopted for quasi-static assessments when dynamic mechanical analysis (DMA) data are unavailable (Wang et al., 2023; Singh & Zhang, 2025).

Damping Evaluation

Because direct measurement of the loss modulus, E was unavailable, damping performance was qualitatively inferred from the load at yield, which correlates with internal energy dissipation due to particle matrix friction. The relative loss modulus was estimated from

$$E'' \approx E' * \tan \delta$$

assuming small damping factors derived from quasi-static stress–strain behavior. While approximate, this indirect approach is accepted for preliminary damping characterization of MREs lacking DMA data (Rosdi et al., 2023; Lu et al., 2023).

Results and Discussions

Tensile Test Data

The tensile behavior of all MRE samples is summarized in Table 1. Each data point represents the average of three specimens for a given carbonyl iron particle (CIP) concentration. As the CIP content increased, both tensile stress at 0.2% strain and yield load generally rose up to 30 wt.% CIP, indicating progressive stiffening of the matrix. Beyond this concentration, a slight reduction in these parameters was observed, likely due to particle agglomeration and localized stress concentrations.

Table 1 <Summary of Average Tensile Data for MRE Samples at Varying CIP Content>

CIP %	Modulus (GPa)	Tensile Stress at 0.2% (MPa)	Load at Yield (kN)
0	0.00027 ± 0.00005	0.00053 ± 0.0001	0.000021 ± 0.000004
10	0.00037 ± 0.00007	0.00073 ± 0.0002	0.000029 ± 0.000006
20	0.00038 ± 0.00008	0.00077 ± 0.0002	0.000027 ± 0.000005
30	0.00037 ± 0.00006	0.00073 ± 0.0001	0.000029 ± 0.000004
40	0.00035 ± 0.00005	0.00070 ± 0.0001	0.000028 ± 0.000004
50	0.00030 ± 0.00005	0.00060 ± 0.0001	0.000024 ± 0.000005

The overall trend reveals an optimum mechanical response around 20 to 30 wt.% CIP. Similar results have been reported by Zhang et al. (2024) and Gomez-Color et al. (2025), who found that intermediate filler loadings enhance stiffness without compromising matrix continuity.

Storage Modulus

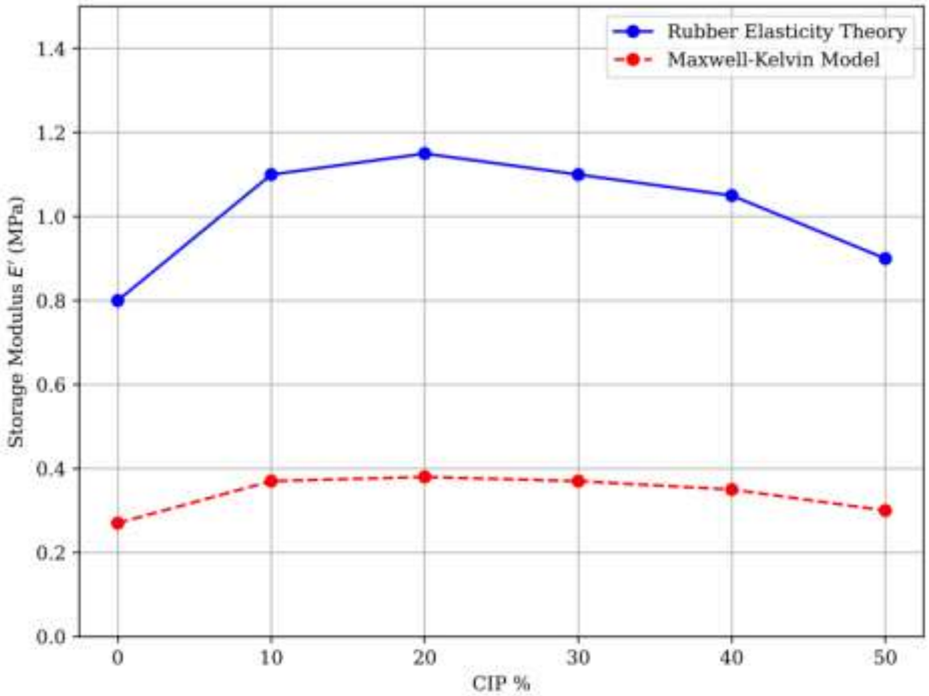

Figure 1 <Storage Modulus E' vs. CIP % for MRE Samples>

Average storage modulus values computed using both the Rubber Elasticity Theory and Maxwell–Kelvin model are presented in Table 2.

Table 2 <Average Storage Modulus (E′) for MREs Determined using Different Models>

CIP %	E' (Rubber Elasticity,MPa)	E' (Maxwell-Kelvin, MPa)
0	0.80	0.27
10	1.10	0.37
20	1.15	0.38
30	1.10	0.37
40	1.05	0.35
50	0.90	0.30

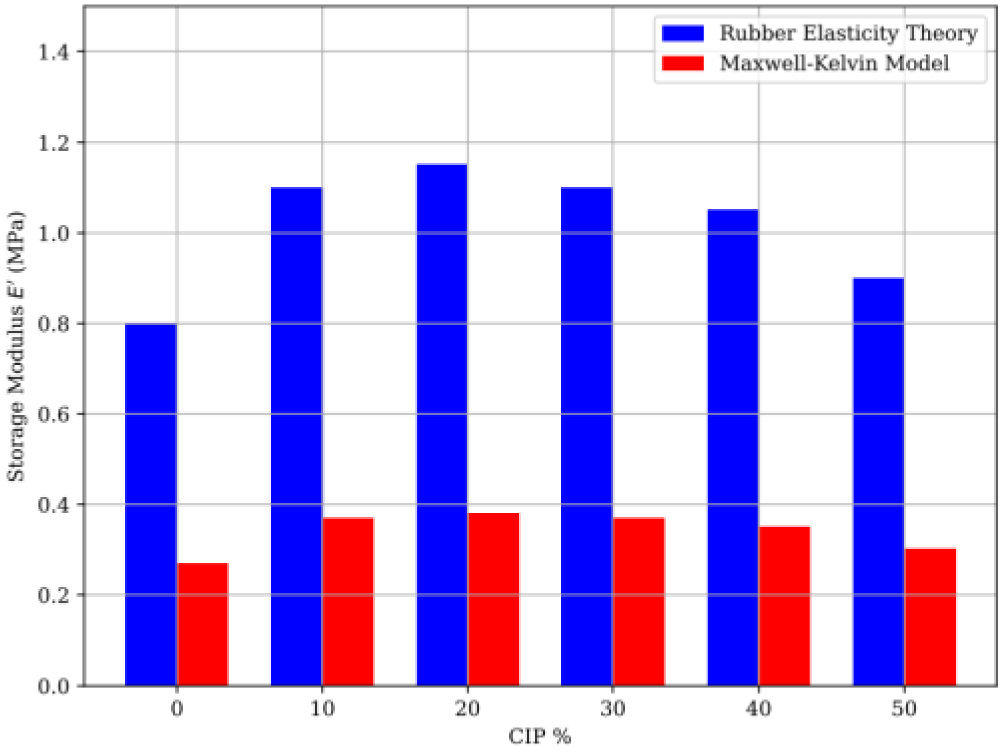

Figure 2 <Comparison of Storage Modulus, E' for Rubber Elasticity Theory and Maxwell-Kelvin Model>

Figures 1 and 2 illustrate the variation of E"" with CIP content. Both models show a rise in storage modulus up to approximately 20 - 30 wt.% CIP, followed by a gradual decline. The Rubber Elasticity Theory consistently predicts higher E"" values than the Maxwell–Kelvin model due to its assumption of ideal elasticity and neglect of viscoelastic relaxation effects. The maximum modulus (1.15 MPa for the Rubber Elasticity model) corresponds to a critical particle concentration at which magnetic interactions and filler–matrix bonding synergistically enhance stiffness. The subsequent decline at higher filler loadings is attributed to particle agglomeration, which disrupts stress transfer within the elastomeric matrix (Patel et al., 2024; Dhakad et al., 2023). Similar nonlinear trends have been observed in other elastomeric composites with magnetic or rigid inclusions (Liang et al., 2024).

Viscoelastic Behavior

The evolution of storage modulus with increasing CIP concentration demonstrates a nonlinear viscoelastic response, confirming that particle–matrix interactions significantly influence the microstructural rigidity of the material. The peak E′ between 20 - 30 wt.% CIP represents an optimal percolation threshold, where interparticle magnetic coupling forms a semi-continuous reinforcing network (Zakaria, 2024; Kim et al., 2025). Beyond this threshold, excessive particle clustering hinders deformation uniformity, reducing effective stiffness. This trend highlights a balance between reinforcement and matrix flexibility, aligning with observations from shear-mode dynamic studies (Nam et al., 2022; Gomez-Color et al., 2025). Moreover, the discrepancy between theoretical predictions indicates that classical elasticity models are inadequate for describing highly filled viscoelastic composites, where non-linear and frequency-dependent mechanisms dominate (Singh & Zhang, 2025).

Damping Characteristic

The load at yield serves as a qualitative proxy for damping capability in the absence of dynamic mechanical data. As shown in Table 3.1, the yield load increased with CIP concentration up to 30 wt.% ($\approx 2.93 \times 10^{-5}$ kN), reflecting enhanced internal friction and interfacial energy dissipation. Beyond this concentration, a decline was observed at 40–50 wt.%, consistent with particle agglomeration and poor stress transfer across interfaces. The increase in damping up to moderate filler loadings suggests improved internal hysteresis and magneto-mechanical coupling, phenomena also reported by Lu et al. (2023) and Salim & Matlack (2024). However, since the present evaluation is quasi-static, these results should be interpreted cautiously. Frequency-dependent dynamic mechanical analysis (DMA) is required to accurately determine the loss modulus E″ and damping factor (tan δ). Future studies should therefore incorporate field-dependent DMA testing to quantify magneto-viscoelastic damping under operational conditions.

Comparison of Constitutive Models

The mechanical response of the magnetorheological elastomers (MREs) was analyzed using two theoretical frameworks: Rubber Elasticity Theory and the Maxwell–Kelvin viscoelastic model. As shown in Figures 3.1 and 3.2, the Rubber Elasticity Theory consistently predicted higher storage modulus (E′) values. For example, 1.15 MPa at 20 wt.% and 1.10 MPa at 30 wt.% CIP than those obtained from the Maxwell–Kelvin model (0.38 MPa and 0.37 MPa, respectively). This overestimation arises from the assumptions of perfect network elasticity and isotropic deformation inherent in Rubber Elasticity Theory, which neglects stress relaxation and time-dependent damping effects. Conversely, the Maxwell–Kelvin model integrates viscoelastic effects through a spring–dashpot configuration, allowing partial energy dissipation and delayed stress response. Although it better reflects viscoelastic phenomena, its predictive capacity remains limited at low-frequency or quasi-static conditions because it does not fully account for nonlinearities associated with particle–matrix interactions and field-dependent reinforcement (Qiao et al., 2021; Patel & Upadhyay, 2023).

The divergence between experimental data and theoretical predictions highlights the complex, nonlinear viscoelastic behavior of MREs. Factors such as interfacial adhesion, particle–particle magnetic coupling, and structural heterogeneity significantly influence stiffness and damping (Dhakad et al., 2023; Kim et al., 2025). Moreover, rigid inclusions disrupt the polymer network and generate microstructural anisotropy, resulting in behavior that departs from ideal elasticity (Puente-Córdova et al., 2018; Liang et al., 2024). These findings suggest that hybrid or fractional-order viscoelastic models may be more appropriate for accurately describing MREs with high filler concentrations.

Influence of CIP Content on Stiffness

The relationship between carbonyl iron particle (CIP) concentration and storage modulus (E′) exhibits a nonlinear profile, peaking at approximately 20–30 wt.% CIP. This behavior corresponds to a percolation threshold, beyond which particle–matrix and particle–particle interactions form semi-continuous networks that improve load transfer and enhance stiffness (Zakaria, 2024; Soria-Hernández et al., 2019). At these concentrations, the elastic network is optimally reinforced, leading to increased energy storage under deformation.

However, at higher concentrations (≥ 40 wt.%), agglomeration of CIPs reduces effective surface area and disrupts filler dispersion, resulting in microvoids and reduced mechanical synergy between matrix and inclusions. Consequently, the storage modulus declines, consistent with findings in highly filled composites where matrix continuity is compromised (Díez et al., 2021; Patel et al., 2024). Similar degradation patterns have been observed in nanocomposite MREs due to excessive magnetic clustering (Singh & Zhang, 2025). This nonlinear stiffness behavior underlines the trade-off between reinforcement and flexibility. It implies that moderate CIP concentrations (20–30 wt.%) achieve the best balance between mechanical rigidity and deformability—crucial for vibration isolation and adaptive structural applications (Gomez-Color et al., 2025).

Damping Characteristics and the Role of CIP

The increase in yield load with rising CIP content reflects improved energy dissipation due to enhanced interfacial friction and local viscoelastic deformation between particles and the elastomeric matrix. This enhancement results from increased micro-hysteresis during cyclic deformation, consistent with findings by Fan et al. (2011) and Lu et al. (2023). Nevertheless, at filler levels exceeding 30 wt.%, damping efficiency decreases due to particle agglomeration and reduced interfacial bonding, which limit frictional sliding and hinder stress transfer. Furthermore, quasi-static yield-based measurements capture only part of the total energy dissipation; dynamic loading is necessary to quantify the frequency-dependent damping factor (tan δ) and loss modulus (E″) (Salim & Matlack, 2024; Nam et al., 2022).

Recent dynamic studies by Kim et al. (2025) and Singh & Zhang (2025) demonstrated that hybrid-field excitation or optimized filler orientation can amplify damping by 30–50%, emphasizing that magnetic field strength, strain amplitude, and particle dispersion collectively determine MRE energy dissipation. Therefore, a multi-physics approach integrating dynamic mechanical analysis (DMA) with microstructural modeling is recommended for comprehensive characterization.

Practical Implications for Vibration Control Applications

The observed results suggest that MREs with 20–30 wt.% CIP provide an optimal compromise between stiffness and damping. This balance makes them promising candidates for use in adaptive vibration isolators, semi-active mounts, and tunable stiffness components. In such systems, the ability to adjust modulus via external magnetic fields allows real-time control of vibration attenuation, as demonstrated by Zhang et al. (2024) and Park et al. (2022). At higher filler concentrations (≥ 40 wt.%), excessive magnetic interactions and particle clustering lead to mechanical degradation, reducing both elastic recovery and damping efficiency. Hence, maintaining uniform dispersion during fabrication is critical to preserving mechanical integrity. Future research should integrate frequency-sweep DMA, magnetic field modulation, and micro-CT imaging to link structural evolution with macroscopic mechanical behavior. Such multi-scale insights can guide the design of next-generation MREs for automotive, aerospace, and civil engineering applications requiring adaptive mechanical performance.

This study systematically investigated the viscoelastic and damping behavior of magnetorheological elastomers (MREs) with varying carbonyl iron particle (CIP) contents under uniaxial tensile loading. Two constitutive models—the Rubber Elasticity Theory and the Maxwell–Kelvin viscoelastic model—were employed to predict the storage modulus, providing complementary insights into elastic and time-dependent responses. The experimental results demonstrated that the storage modulus (E′) increased with CIP content up to 20–30 wt.%, reaching a maximum value of 1.15 MPa (Rubber Elasticity Theory) and 0.38 MPa (Maxwell–Kelvin model). Beyond this threshold, the modulus declined at higher filler loadings (40–50 wt.%), primarily due to particle agglomeration and loss of matrix uniformity. The Rubber Elasticity Theory consistently overestimated stiffness, reflecting its limitation in capturing viscoelastic relaxation at elevated filler concentrations.

Damping performance, inferred qualitatively from yield-load data, exhibited a similar non-linear trend improving up to 30 wt.% CIP before decreasing to higher loadings. This suggests that moderate filler concentrations enhance internal friction and interfacial energy dissipation, while excessive loading leads to microstructural saturation and reduced particle mobility.

Collectively, these results establish that 20-30 wt.% CIP represents an optimal concentration range for achieving a desirable balance between stiffness and damping in isotropic MREs. Such compositions are particularly suitable for adaptive vibration-control systems and semi-active isolators, where tunable mechanical behavior is essential. Overall, this research contributes to the growing body of knowledge on the mechanical design of smart MREs and provides a foundation for developing next-generation materials with tailored stiffness and damping properties for automotive, aerospace, and civil engineering applications.

Conclusion

This study demonstrates that the concentration of carbonyl iron particles (CIP) plays a significant role in determining the tensile, viscoelastic, and damping properties of magnetorheological elastomers (MREs). Results indicate that increasing the CIP content to 20–30 wt.% significantly improves stiffness and mechanical performance, as reflected by an increase in the storage modulus and related yield parameters. This improvement is attributed to effective particle-matrix interactions and the formation of a reinforcing network. However, at higher concentrations (≥ 40 wt.%), mechanical properties deteriorate due to particle agglomeration, reduced dispersion quality, and disruption of matrix continuity.

Furthermore, a comparison of constitutive models indicates that the Rubber Theory of Elasticity overestimates stiffness, while the Maxwell–Kelvin model provides a more realistic representation of viscoelastic behavior, albeit with limitations in capturing nonlinear effects. Damping performance follows a similar nonlinear trend, with optimal energy dissipation occurring at moderate CIP levels. Overall, the optimal range of 20–30 wt.% CIP offers the best balance between stiffness and damping, making it suitable for adaptive vibration control applications.

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