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RESEARCH ARTICLE

# Tensile Properties of Isotropic and Anisotropic Magnetorheological Elastomer With and Without Magnetic Field Application

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**ABSTRACT -** In this study, two variations of magnetorheological elastomer (MRE) tensile specimens were fabricated, differing in their isotropic and anisotropic configurations. The isotropic MRE exhibited randomly dispersed carbonyl iron particle (CIP), whereas the anisotropic featured longitudinally aligned CIP particles along the gauge length of the tensile sample. The formation of the anisotropic MRE involved utilizing an electromagnetic curing chamber, which facilitated the alignment of CIP particles during the elastomer curing process. A mold was specifically designed to produce samples conforming to the dimensions outlined in ASTMD412-F. Subsequently, a Finite Element Method Magnetics (FEMM) analysis was conducted to examine the magnetic flux within the curing device for the anisotropic MRE. Uniaxial tensile tests were conducted on both MRE types, both in the absence and presence of a 30 mT magnetic field applied transversely to the direction of CIP alignment. Results indicated that without a magnetic field, the anisotropic sample exhibited a slightly higher tensile strength, lower elongation, and higher modulus at 100% strain. However, when a magnetic field was introduced, the isotropic sample demonstrated a more pronounced increase in tensile strength, showing an 18.4% improvement compared to the 5.6% increase observed in the anisotropic sample. Similar trends were observed in the reduction of elongation, with a 14% decrease for isotropic and a 7% decrease for anisotropic samples. Additionally, the data on modulus at a 100% strain revealed a 22.3% increase in stiffness for the isotropic sample, while the anisotropic sample showed a 10.6% increase.

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## 1.0 INTRODUCTION

The aspiration for an enhanced quality of life is increasingly prominent in contemporary culture, aligning closely with advancements in science and technology. This surge in demand has led to the evolution of smart materials, specifically engineered to exhibit controlled and reversible behaviors in response to external stimuli such as mechanical force, temperature, or magnetic fields. An exemplary instance of such smart material is magnetorheological (MR) material, comprising micron-sized magnetic particles suspended within a non-magnetic medium. Among these materials, MR elastomer (MRE) stands out as a smart material capable of reversible alterations in its rheological and mechanical properties when subjected to a magnetic field. This transformative shift in properties post-magnetic application is commonly referred to as the 'MR effect'. The MR effect is achieved through the induced interaction of magnetic particles within the non-magnetic medium, thereby modifying the overall system's stiffness. [1]. MRE samples represent multifunctional materials endowed with diverse capabilities, including the dynamic adjustment of stiffness, natural frequency, and damping capacity in reaction to an external magnetic field. The potential applications of MREs can be categorized into three main areas: vibration and noise control devices [2]–[4], sensing devices [5], [6], and actuators [7], [8]. The practical implementation of MREs in real-world scenarios hinges on the operational model of the device. A crucial aspect lies in comprehending the various functioning modes of an MRE, as this understanding is an essential prerequisite in the design of MRE devices [9].

MREs are categorized into two types: isotropic MRE, characterized by randomly dispersed particles, and anisotropic MRE, also known as aligned MRE, which undergoes specific curing methods [10]. While investigations have explored particle concentrations in MREs as high as 90 wt.%, most researchers opt for 70 wt.% as it yields optimal MR performance. However, the use of larger loading particles (beyond 70% by weight) significantly raises composite viscosity and may lead to particle aggregation due to non-uniformities [11]. In the case of anisotropic MRE, the magnetic particles within the matrix can be reconfigured into various orientations [12]. In previous studies, curing devices for anisotropic treatment were often fabricated using molds consisting of two separate pieces—an upper and a lower portion—created from non-magnetic materials [9], [13]–[15].

Recognizing shortcomings in conventional curing devices, Khairi et al. [10] conducted research to enhance the alignment capability of such devices. Additionally, as noted by Tian et al. [15] and Samal et al. [16], simulations indicated

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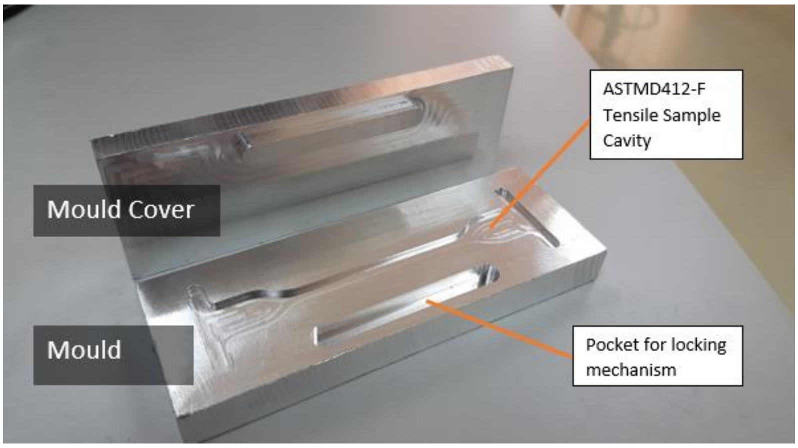
a minimum magnetic flux density of 0.3 T is required to align particles within the matrix phase. Soria-Hernández et al. [17] investigated the impact of carbonyl iron particle (CIP) and their alignment on the mechanical and rheological properties of MRE made with polydimethylsiloxane (PDMS) elastomer and 24 wt % silicone oil (SO). Results indicated that, at a CIPs concentration of 70 wt %, the material samples exhibited the highest shear modulus, stress-softening effects, and engineering stress values under specific conditions. This study utilized a custom-designed device to fabricate MRE samples, aligning CIP along the longitudinal axis of the manufactured parts. Due to limitations in the induced magnetic forces (up to 52.2 mT), the samples containing 63 and 70 wt % of CIPs did not achieve particle alignment. The experimental characterization focused on assessing the morphology, distribution, and alignment of particles within MRE samples. researchers [18], [19] also discovered that particle alignment at an angle of 30 degrees with respect to the magnetic field direction exhibited the highest storage modulus, followed by alignments at 45 and 90 degrees, which corresponds to a perpendicular alignment of particles relative to the magnetic field direction. The investigation also delved into the impact of particle orientation on the storage modulus of MRE samples. During the curing process, the MRE samples were positioned at angles of 0, 5, 10, and 15 degrees from the perpendicular direction of the magnetic field. The findings revealed that the initial storage modulus and the magnetic field-induced shear modulus were higher for the MRE sample with a 15-degree particle orientation.

The magnetorheological behavior of MRE has been investigated through various magneto-mechanical analysis methods, including shear deformation, uniaxial compression, and tensile testing. These analyses utilize an external magnetic field to measure the magnetorheological effect in elastomer-based composites. The researcher also conducted a comparative study involving three magneto-mechanical analysis methods—uniaxial compression, uniaxial tension, and pure shear deformation—to examine the magnetorheological effect of their matrix-CIP composites. Notably, the choice of the testing method significantly influenced the observed magnetorheological properties of the material [20]. The extensive examination of MRE's large strain behavior has primarily focused on compression and simple shear tests[21]. In a typical tensile test, anisotropic MRE is longitudinally aligned with the direction of tensile loading to maximize reinforcement, and the applied magnetic field is oriented to intersect the particle alignment for optimal MR effect. To the author's knowledge, the behavior of anisotropic MRE under the perpendicular application of magnetic flux lines remains unexplored. While Sandesh et al. [22] conducted a tensile study in this regard, it did not delve into the impact of different particle alignment distributions. The orientation of particles plays a pivotal role in determining the mechanical properties of the polymer [23]. Hence, it is essential to elucidate the effects resulting from CIP alignments on the mechanical properties of MRE by examining diverse outcomes of tensile tests for various MRE alignments, both in on-state and off-state conditions. A more comprehensive understanding of CIP orientation enables the fabrication of MREs with enhanced control over their properties, whether or not a magnetic field is applied.

## 2.0 EXPERIMENTAL

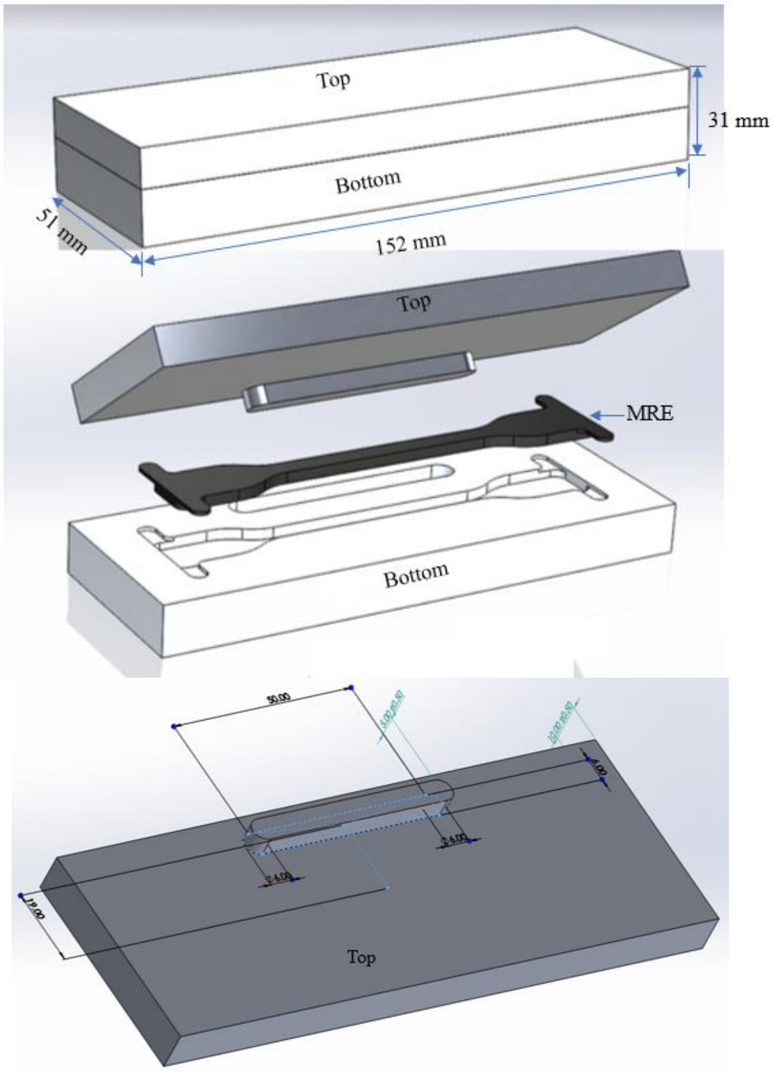
### *2.1 Mold*

A specialized mold was created to facilitate the production and curing of MRE, constructed from Aluminum 6061. The mold's dimensions were meticulously designed to ensure a proper fit within the curing chamber, particularly for anisotropic configurations, where the gauge area is centered on the electromagnetic field lines. The mold features two distinct cavities: one accommodates the sample, while the other houses the locking mechanism pocket. As depicted in Fig. 1, the fabricated mold conforms to the shape outlined in ASTM D412 type F standard for the cavity. The sample's thickness is deliberately set at approximately 2.2 mm. Precision machining of the mold was executed using a Bridgeport VMC 2216 CNC milling machine.

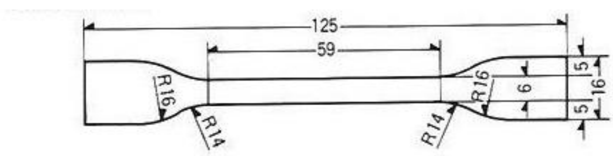



(a)

Figure 1. MRE mold (a) fabricated from aluminium




(b)




(c)

Figure 1. (cont.) (b) design and (c) with tensile measurement ASTM-D412

### *2.2 Sample Preparation and Curing Device Mold*

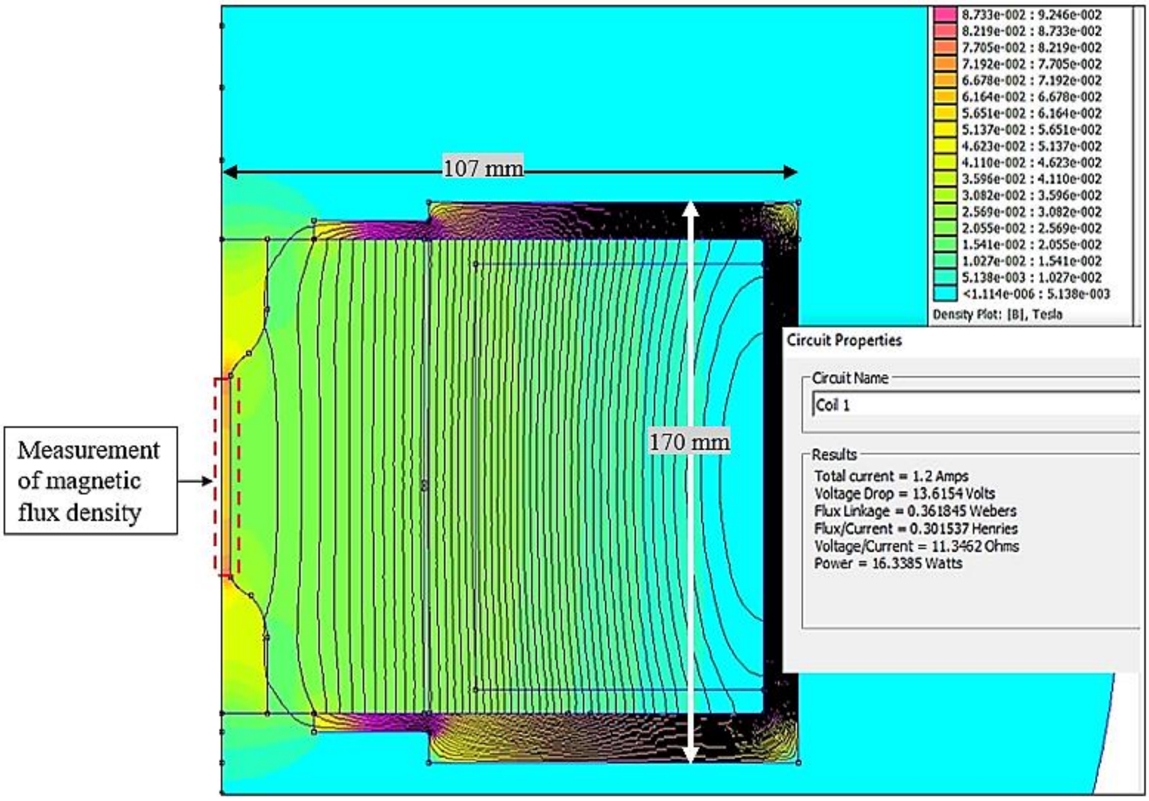
The preparation of MRE samples is a two-step process. The initial phase involves the mixing of liquid MRE, where silicone liquid and CIPs are combined. Subsequently, the second phase encompasses the curing process of MRE, conducted in accordance with ASTM D6411 standards. The CIP and silicone are mixed in a 70:30 weight percentage ratio for 25 minutes. Room-temperature curing is achieved using RTV silicone rubber, with the CIP-Silicone mixture further enhanced by the addition of 1 wt.% hardener[15]. This treated mixture is applied to the mold before undergoing the curing process, whether in isotropic or anisotropic conditions. Two sample groups, each comprising eight samples, are generated under isotropic and anisotropic conditions. In the case of anisotropic MRE, the CIPs are aligned longitudinally. The curing device utilized for producing anisotropic MRE involves a setup with 1250 turns of 1.11mm copper coil, 18 AWG in diameter, wound around a non-magnetic bobbin (polyethylene), enclosed with a steel cover as illustrated in Fig. 2. A FEMM simulation of the setup reveals a magnetic flux density of approximately 70 mT penetrating through the MRE sample gauge area, given a current of 1.2 A, which is the output of the electromagnetic device power source.


(a) (b)

Figure 2. (a) Electromagnetic Curing device (b) MRE sample produced by the mold.

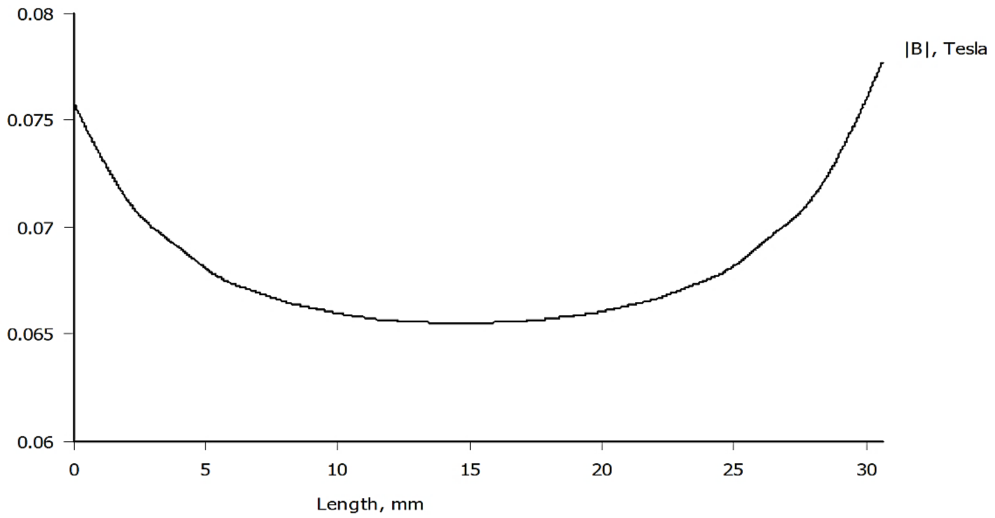
### *2.3 Finite Element Method Magnetic*

In the simulation of the magnetic flux density passing through the sample, researchers [24], [25] commonly employ Finite Element Method Magnetics (FEMM), a methodology also utilized in the present study. However, the power source for the curing device in this investigation was capable of producing only 1.2A of current, which represents approximately 40% of the reported 3A requirement for generating 300 mT necessary for the vertical alignment of the MRE sample [26]. Consequently, due to this limitation, the curing device is constrained to provide only around 65 to 70 mT, as determined by the FEMM analysis presented in Fig. 3. This output accounts for only about 23% of the targeted value of 300 mT. The simulation also includes a magnetic flux density plot along the gauge length.




(a)

Figure 3. (a) FEMM simulation for 1.2 Amps with the area of magnetic flux measurement

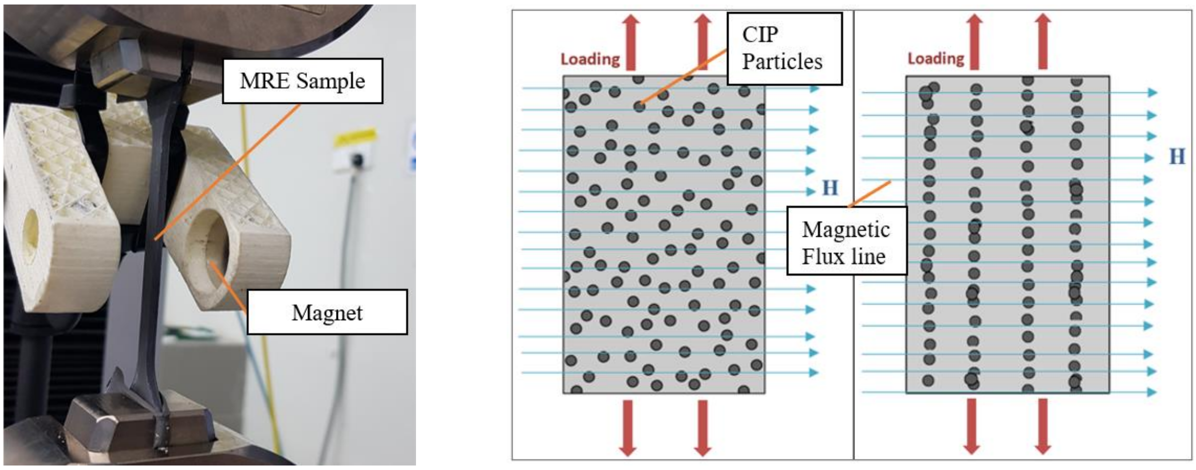



(b)

Figure 3. (cont.) (b) Magnetic flux density plot along the gauge length

### *2.4 Tensile Properties Characterization*

A Uniaxial static tensile test was conducted using the AG-X PLUS 20KN Universal Testing Machine, employing a grip separation rate of 500 mm/min in accordance with the ASTM D412 Standard. Each set of data involved an average of four samples. The experiment incorporated two types of particle configurations, with each configuration subjected to testing both in the presence and absence of magnetic fields. A neodymium magnet housed in a 3D-printed enclosure delivered an approximate magnetic intensity of 30 mT, intersecting the gauge area horizontally. The testing machine recorded key parameters, including tensile strength (stress at break), strain (percentage of elongation), and Modulus 100 (stress at 100% strain, indicative of elasticity). As depicted in Fig. 4, the arrangement of the tensile sample during testing is illustrated. In the 'Off' condition, the magnet is simply removed. For the anisotropic sample, CIP alignment is longitudinal to the loading direction. It is important to note that, in this study, the magnetic field lines traverse the sample perpendicular to the loading direction. Fig. 4(b) provides a visual representation of the experimental setup, outlining the loading direction and magnetic field lines for both isotropic and anisotropic samples.




(a) (b)

Figure 4. Tensile testing (a) Set-up configuration with magnet (b) Schematic of Isotropic (left) and Anisotropic (right) tensile testing configuration for 'ON' condition

## 3.0 RESULTS & DISCUSSION

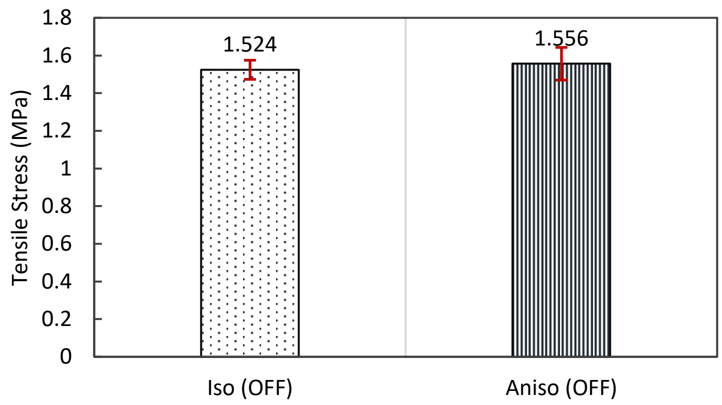
### *3.1 Results Without Magnetic Field*

In the absence of a magnetic field, discernible variations emerge among sets of particle alignments regarding tensile strength, strain, and elasticity. According to composite theory, aligned fibrous composites inherently display anisotropic characteristics, wherein optimal strength and reinforcement occur along the alignment (longitudinal) direction [27]. Conversely, in the transverse direction of loading, the presence of fibre reinforcement is minimal, leading to fractures typically occurring at relatively low tensile stresses. For stress orientations other than longitudinal or transverse, the composite strength falls between these extremes. Despite this study using particles as reinforcement, its behaviour mirrors that of fibrous composites. For instance, Gao et al. [28] demonstrated that aligning CIP particles transversely in tensile tests results in the lowest tensile strength and elongation, aligning with composite theory. This section presents data acquired from randomly oriented CIPs (isotropic) and aligned CIPs (anisotropic) within the silicone matrix, emphasizing the longitudinal direction of loading and the reinforcing effect induced by a magnetic field in the anisotropic configuration.

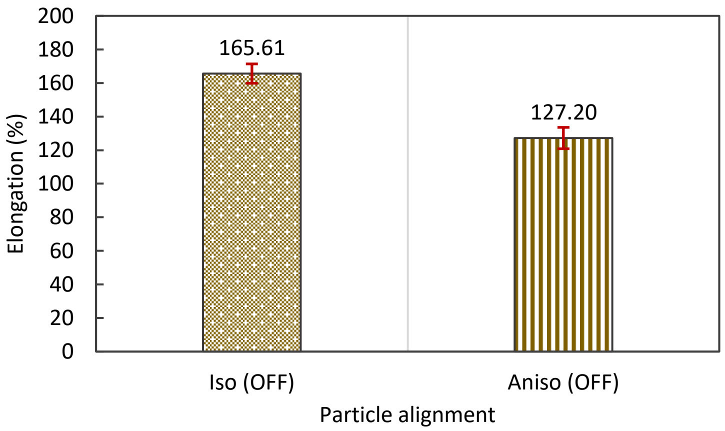
The findings from Table 1 and the graph depicted in Fig. 5 highlight notable differences in the Anisotropic sample, demonstrating an increase in both strength and stiffness. This enhancement is attributed to the alignment of Carbonyl Iron Particles (CIP) within the Magnetorheological Elastomer (MRE) system, aligning parallel to the direction of tensile loading. The chain-like structure of the anisotropic sample revealed effective performance even in the absence of magnetic stimulation. However, it's noteworthy that as the sample's stiffness increased, there was a compromise in strain percentage, indicative of a brittle behaviour associated with the particle distribution in the MRE. This suggests that the mechanical response becomes more rigid, leading to reduced strain tolerance, which is a crucial consideration in the evaluation of the material's overall performance.

Table 1. Summarization of isotropic and anisotropic data for OFF-state

| Alignment | Tensile Strength (MPa) | Strain (%) | Modulus 100 (MPa) |
|---|---|---|---|
| Isotropic | 1.524 | 165.61 | 0.918 |
| Anisotropic | 1.556 | 127.2 | 1.105 |




(a)




(b)

Figure 5. Isotropic vs Anisotropic (a) OFF-state Tensile Stress (b) OFF-state elongation

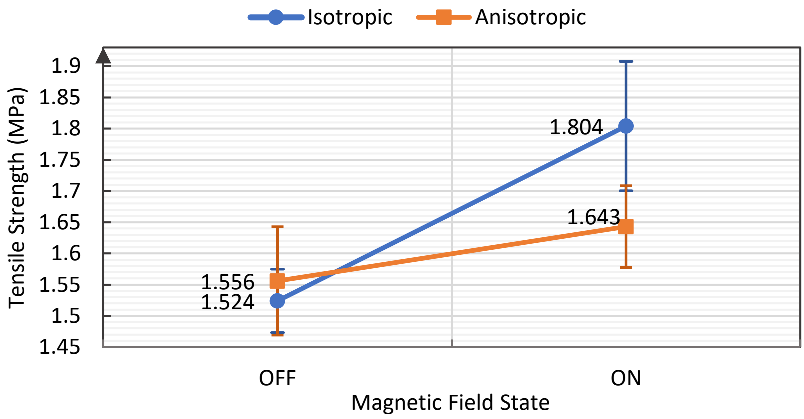
### 3.2 *Result with Application of Magnetic Field*

Due to increased interaction among the CIPs, the isotropic sample demonstrates a more pronounced impact of the magnetic field on its mechanical properties, as illustrated in Table 2.

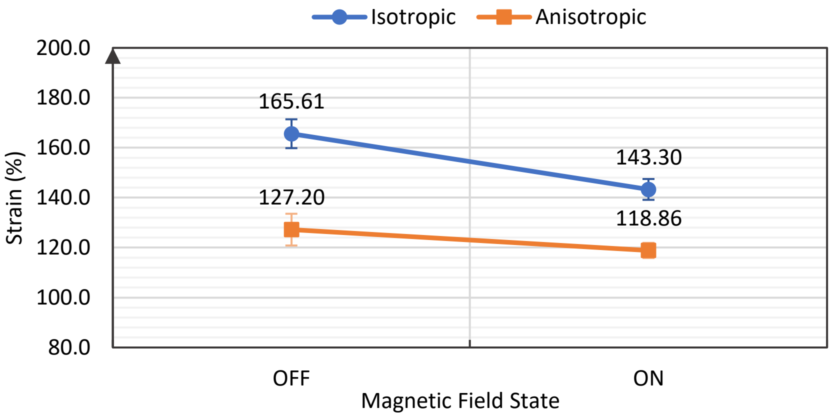
Table 2. Summarization of the effect of the magnetic field on MRE samples

| Alignment | State | Tensile Strength (MPa) | | Strain (%) | | Modulus 100 (MPa) | |
|---|---|---|---|---|---|---|---|
| Isotropic | OFF | 1.524 | +18.4% | 165.61 | -13.5% | 0.918 | +22.3% |
| | ON | 1.804 | | 143.3 | | 1.123 | |
| Anisotropic | OFF | 1.556 | +5.6% | 127.2 | -6.6% | 1.105 | +10.6% |

The tensile strength recorded a notable increase of 18.4% for the isotropic sample, in contrast to the 5.6% observed for the anisotropic counterpart. Furthermore, the change in elongation was more pronounced in the isotropic sample, exhibiting a 13.5% increase compared to the 6.6% recorded for the anisotropic sample. In terms of elasticity, the isotropic sample showcased a substantial 22.3% increase in stiffness, whereas the anisotropic sample showed a 10.6% increase. These findings indicate a more significant MR effect for the isotropic sample in comparison to the longitudinally aligned sample under the perpendicular direction of a magnetic field. The distinctions in the effects of magnetic field application on the two sample types are visually depicted in Fig. 6. As previously noted, the anisotropic sample demonstrates elevated mechanical properties, particularly at higher modulus values, signifying an increased level of elasticity. In more straightforward terms, the modulus quantifies a material's deformation (strain) in response to applied force (stress). A higher modulus indicates that the material demands more stress to induce a given level of strain, highlighting greater stiffness and, consequently, enhanced elasticity. To sum up, a higher modulus generally implies a more elastic material capable of withstanding higher stress levels with minimal deformation.




(a)

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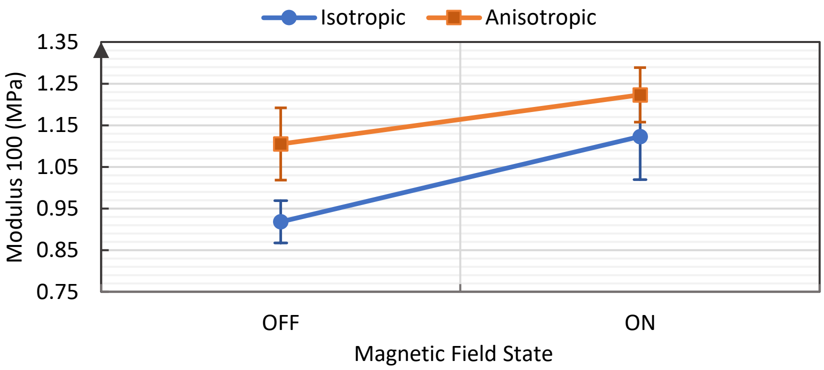


(c)

Figure 6. (cont.) (c) Modulus 100 (MPa)

This study distinguishes itself from others in the field by applying the magnetic field perpendicularly to the longitudinal alignment of CIPs. Conventionally, magnetic field lines align with the direction of an anisotropic MRE sample, leading to reinforcement through the interaction of ferromagnetic particles within the material. In this case, the absence of longitudinal particle alignment appears to yield a more significant impact in terms of increased tensile strength, reduced elongation, and heightened stiffness when the magnetic field is introduced. The application of a magnetic field enhances the force of attraction between particles in the lateral direction, resulting in heightened resistance to loading and an elevation in tensile modulus at lower strain values. The dipole effect reduces the spacing between particles in the lateral direction. In isotropic samples, where particle alignment in the longitudinal direction creates a smaller gap between neighboring CIP particles laterally, there is a stronger lateral attraction. This, in turn, amplifies resistance to longitudinal elongation, increasing stiffness and rendering the material more brittle yet higher in tensile strength.

Based on the findings of this study, it is crucial to highlight the significance of employing FEMM for early prediction of how alterations in material properties, particularly those pertaining to magnetic characteristics, impact the mechanical behavior of the system in relation to sample fabrication. This predictive capability holds considerable value in applications within the fields of materials science and engineering. Furthermore, FEMM offers a computational framework that aids in comprehending and analyzing the interplay between magnetic fields and mechanical properties within materials and structures. This capability proves particularly advantageous in the design, optimization, and performance prediction of devices and systems that encompass both magnetic and mechanical components. The experiments conducted unveil the authentic behavior of the MRE sample, with results influenced by various factors such as the curing process and defects arising from fabrication. The impact of magnetic stimulation during the tests also emerges as a crucial aspect in comprehending MREs with different types of particle alignment.

## 4.0 CONCLUSIONS

In summary, this study involved the fabrication of two types of magnetorheological elastomer (MRE) tensile samples: isotropic, characterized by a random dispersion of ferromagnetic particles, and anisotropic, with particles aligned longitudinally along the gauge length. The production of these samples employed a meticulously designed and machined aluminum mold conforming to ASTM D412 standards. Subsequent uniaxial tensile tests were conducted using a universal testing machine on both types of MRE samples, under conditions both with and without the presence of a 30 mT magnetic field oriented transversely to the direction of CIP alignment. The findings revealed that in the absence of a magnetic field, the anisotropic sample displayed slightly higher tensile strength, lower elongation, and higher Modulus at 100% elongation. However, with the introduction of a magnetic field, the isotropic sample exhibited a more substantial increase in tensile strength compared to the anisotropic sample. This trend was mirrored in the reduction of elongation, with a more significant decrease observed in the isotropic sample. The Modulus 100% elongation data highlighted a 22.3% increase in stiffness for the isotropic sample, as opposed to a 10.6% increase for the anisotropic sample. This study underscores the importance of understanding the orientation of ferromagnetic particles in MRE, offering insights into the manufacturing process. By gaining deeper knowledge about the CIP orientation, MREs can be engineered with enhanced control over their properties, both in the presence and absence of a magnetic field.

## 5.0 ACKNOWLEDGEMENT

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