

## STUDIES ON TORSION MODULI OF MAGNETORHEOLOGICAL ELASTOMERS

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This study investigates the torsion modulus of elasticity in magnetorheological elastomers (MREs) composed of silicone rubber matrices and stabilized iron nanoparticle fillers. Isotropic and anisotropic samples were prepared using different filler pre-treatment methods and magnetic field orientations. A measurement system for testing the torsion modulus of elasticity for isotropic and anisotropic samples was developed. The results show that both particle dispersion and alignment significantly affect the mechanical properties. In particular, the torsion modulus increased in the presence of a magnetic field with transverse anisotropic samples exhibiting the most pronounced response. These findings highlight the potential of MREs for applications in adaptive mechanical systems such as tunable vibration dampers, soft robotic actuators or controllable stiffness components where mechanical properties can be dynamically adjusted using an external magnetic field.

**Keywords:** intelligent materials, magnetorheological elastomer, determination of torsion modulus, magnetic susceptibility

### 1. Introduction

Advances in research methods and instrumentation are creating more opportunities for the development of new materials. Within multifunctional materials, research into smart materials, which first appeared in the late 1980s and continue to evolve in the field of materials science, is gaining importance. Such material systems as biological systems can adapt to changes in external or internal parameters, meaning that they can “sense” one or more features of the physical or chemical state of their immediate environment before responding to them rapidly and unambiguously by changing their state significantly. Sensory function is most often the result of a dynamic (chemical, mechanical or thermodynamic) equilibrium between a substance and its environment. A change in the environment produces a change in the equilibrium state, providing the material with different properties. An important aspect is the relationship between the effect that creates the change and the response to it. Intelligent materials are characterized by an effect-response relationship where the magnitude of the response is not proportional but much larger than the magnitude of the stimulus. The basic property of these materials is reversibility, i.e. the original state is restored after the stimulus is removed. Furthermore, their

response time is also fast. Smart materials can be divided into two broad groups in terms of this effect-response relationship. One group includes materials that react to changes in the natural environment, e.g. temperature, chemical environment, mechanical action, light, etc. In contrast, the other group includes materials that respond to stimuli controlled by an electronic signal generated by a computer. The material properties of the latter category are limited by the relationship that can be established between the computer and material. In terms of control technology, electrical and/or magnetic fields can be created, changed and eliminated practically instantaneously by computer-controlled electronics. Depending on their mechanical properties, smart materials can be hard or soft [1]-[5].

In these composite materials, solid fillers are embedded in a cross-linked polymer matrix where, depending on the magnetic or dielectric properties of the solid particles, the macroscopic response, e.g. rheological, mechanical, etc., can be stimulated by an external magnetic or electric field [6],[7] or a combination of both. The macroscopic response is mainly due to the relationship between the dipole-dipole interactions of the embedded particles (which carry dipole moments - magnetic or electric - induced by the external field) [8] and the particle-matrix interactions, which determine the mobility of the solid phase.

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Therefore, the response is highly dependent on the elasticity of the polymer matrix.

One group of smart materials is magnetorheological elastomers (MREs), which contain magnetizable particles (usually micrometer-sized iron particles) embedded in a flexible polymer matrix that can change their physical or mechanical properties under the influence of a magnetic field. The properties of such particles, e.g. type of material, average particle size, size distribution, shape, arrangement, etc., significantly influence the mechanical properties of the composite material. These materials change their rheological properties depending on the external magnetic field. In MRE materials, magnetic particles are bound to matrices with a high degree of polymerization and a relatively high elastic modulus, so that their field-induced mechanical response is reduced by a few percent [9]-[13].

In a magnetic field, particles tend to align parallel to magnetic field lines [14]. This tendency has been applied to the preparation of many MREs with chain-like microstructures since the elastomer matrix retains the alignment of the particles after the curing process. In a magnetic field, the elastic modulus of MREs can be increased, moreover, this mechanical property may make them potentially suitable for the shock and vibration control of structures as well as systems [15].

Regarding their application, it is therefore important to consider the elastic properties of MREs in addition to deformation. From an engineering perspective, these properties can be expressed in terms of elastic modulus indices.

The modulus of elasticity, also known as Young's modulus, is a constant value for a material that dictates the degree of stiffness of that material. In the Hooke model of a linearly elastic material, the tensile or compressive mechanical stress ( $\sigma$ ) is directly proportional to the strain ( $\epsilon$ ). This proportionality factor is referred to as the elastic modulus ( $E$ ).

It is important to note that the modulus of elasticity refers only to tension or compression. In terms of shear, the relationship regarding the shear modulus of elasticity applies:

$$\tau = G \cdot \gamma \quad (1),$$

where:

- $\tau$  - shear stress,
- $\gamma$  - shear strain,
- $G$  - shear modulus of elasticity.

The shear modulus of elasticity is also used for torsional loads and can be used to impose a torsional moment:

$$M_{cs} = G \cdot I_p \cdot \frac{\varphi}{l} \quad (2),$$

where:

- $G$  - torsional modulus of elasticity,
- $M_{cs}$  - torsional moment (torque),
- $I_p$  - polar second-order torque,
- $l$  - twist length,
- $\varphi$  - twist angle.

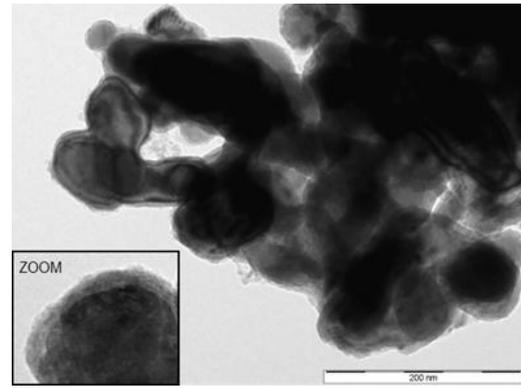


Figure 1: TEM images of the NANOIRON NANO FER STAR stabilized iron particles from the material data sheet

The torsional modulus of elasticity for a cylindrical sample:

$$G = \frac{32 \cdot M_{cs} \cdot l}{d^4 \cdot \pi \cdot \varphi} \quad (3),$$

where  $d$  denotes the diameter of the twisted cylindrical body.

## 2. Experimental

For the elastic modulus test, cylindrical samples with a silicone rubber matrix and stabilized iron grain filler were prepared. To take measurements, a measuring system was set up to which a data acquisition card and a torque gauge were connected as well as a coil placed around the specimen. A stepper motor-driven table was also installed to enable automatic rotation, the details of which can be found in the following sections.

### 2.1. Samples and measurements

Elastosil RT 640-type two-component silicone rubber (A) and crosslinker (B) were used to form the matrix for the cylindrical composite elastomer. The samples contained 6 m/m% crosslinker and 1 m/m% surfactant.

The elastomeric composite filler used was NANOIRON NANO FER STAR stabilized iron (nZVI, nanoscale zero-valent iron) powder which forms large particles by itself as presented in Figure 1. To avoid such aggregation, a surfactant was used.

The average particle size of the iron particles used was  $59.8 \pm 1.3$  nm and the average thickness of the surface oxide layer was  $4.30 \pm 0.53$  nm according to the manufacturer. Since caking was observed while the powder was being stored, the aforementioned filler could not be used for sample preparation without pre-treatment. Two different pre-treatment methods were chosen as a solution. In one pre-treatment, silicone rubber component A and surfactant Triton X-100 were mixed with the filler particles before being ground in a RETSCH MS micro mill for 1, 2, 3 and 4 hours, after which the crosslinker was added. In the other pre-

Table 1: Data regarding preparation of the samples

Sample	Pre-treatment time	Pre-treatment method
26,2-1	1h	with component A
26,2-2	2h	with component A
26,2-3	3h	with component A
26,2-4	4h	with component A
26,2-0,5	0.5h	dry
40-0,5	0.5h	dry

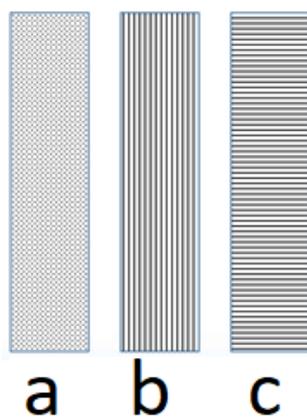


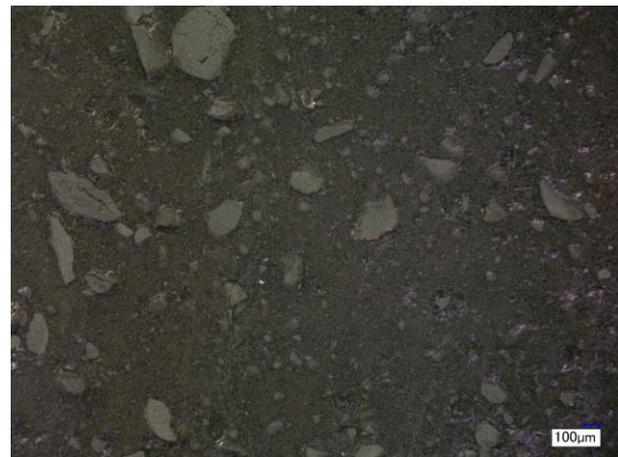
Figure 2: Location of the filler in the isotropic composite matrix (a), anisotropic samples containing longitudinal (b) and transverse chains (c)

treatment, the iron particles were ground into a powder in the RETSCH micro mill for half an hour under constant conditions before the other components were added. Filler concentrations in the samples were between 26.2 and 40.0 m/m%. The samples for the measurements were prepared as shown in Table 1.

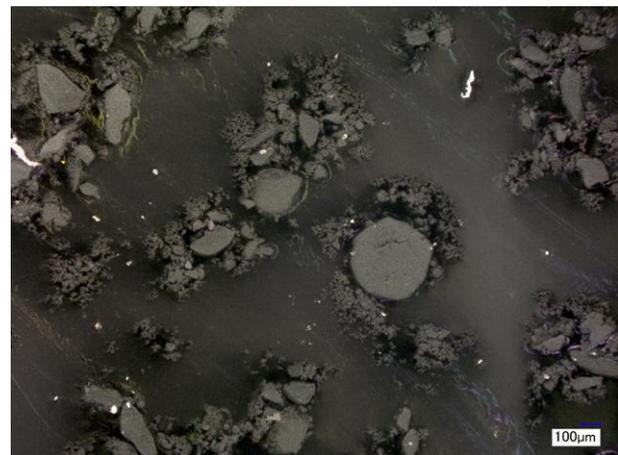
From the silicone rubber in liquid state and stabilized iron composite mixture, residues of trapped air were removed in a vacuum oven to prevent the formation of possible air inclusions.

In the case of the isotropic samples, the prepared liquid silicone rubber was poured into a cylindrical mold and treated with air at 200 °C for 10 mins using a heat gun. Samples containing anisotropic (longitudinal and transverse) magnetite particle chains (Figure 2) were prepared by holding the mold containing the liquid mixture between the poles of an electromagnet in a homogeneous magnetic field of 350 mT which solidified by heating them with air at 200 °C.

Microscopic studies of the structure of the filler in the matrix were carried out using a Keyence VHX-2000 high-resolution digital microscope (Figure 3).



a) Isotropic sample



b) Anisotropic (longitudinal) sample



c) Anisotropic (transverse) sample

Figure 3: Results from light microscopy

## 2.2. Measurement method

To measure the torsion modulus of the samples, a measurement system was set up consisting of Labview software, an NI data acquisition card, a torque sensor, a stepper motor-driven table and a coil around the sample (Figure 4).

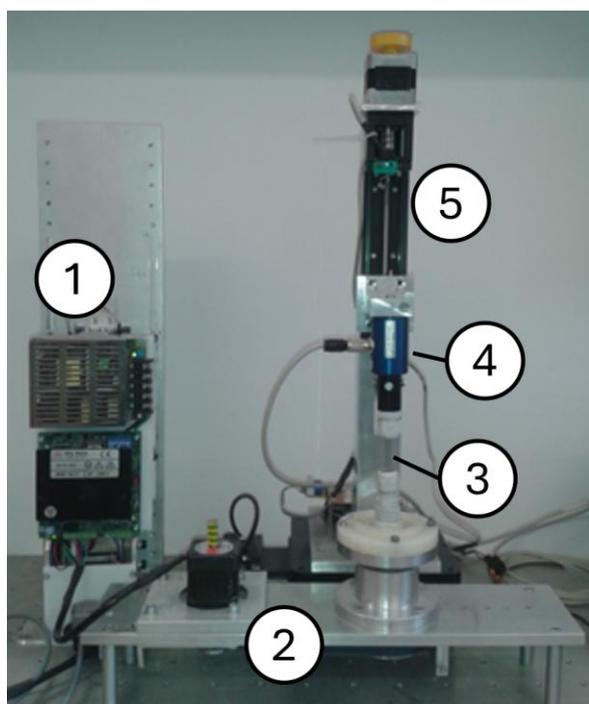


Figure 4: The device assembled for measuring the torsion modulus of the sample: 1) Driver of the stepper motor, 2) Stepper motor-driven table, 3) Sample, 4) Torque sensor and 5) Linear unit to adjust the height

The torsion modulus of the prepared cylindrical samples was determined according to Equation 3 using the measured torque.

The torsion torque was measured with a Burster 8625-4200 torque sensor. Since this measuring instrument can be equipped with an electromagnetic coil, it is possible to measure in a magnetic field with a magnetic induction of up to approximately 80 mT. During our measurements, the change in the torsion modulus was determined in a magnetic field with a magnetic induction of 70 mT.

On our user interface, which was created using the Labview software, the desired rotation angle in degrees, the diameter of the sample, the clamping length and the number of rotation steps were set before taking the measurements. The measuring device automatically rotated the sample while recording the torque as a function of the rotation angle in radians. Once the sample had stopped rotating, a trendline was fitted to the data and the torsion modulus calculated based on the entered parameters for samples with different compositions and positions of the filler.

During measurements in a magnetic field, the coil was cooled using a thermostat.

### 3. Results and analysis

Measuring the torsion modulus, it was observed that the modulus of the samples almost always exhibited a decreasing trend as the grinding time increased (Figure 5A). For the longitudinal and transverse

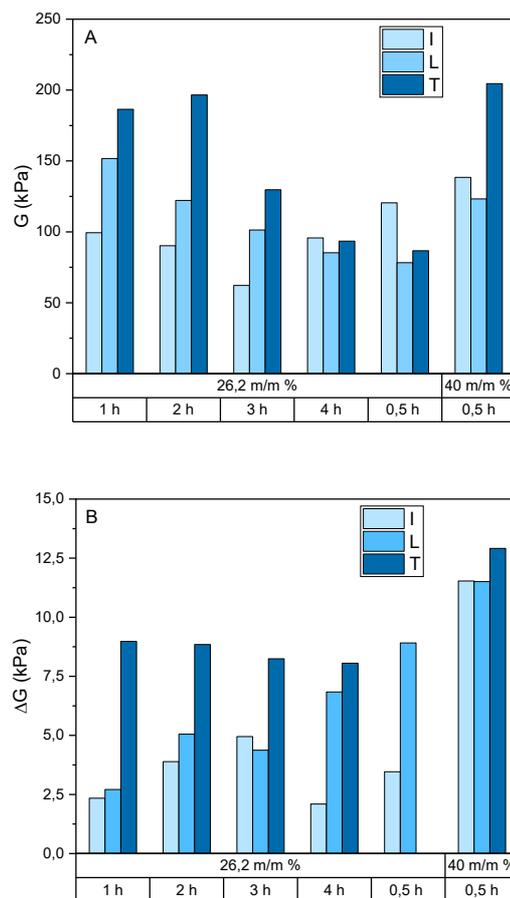


Figure 5: Change in the torsion modulus (A) due to the magnetic field (B) for different samples (I: isotropic; L: longitudinal anisotropic; T: transverse anisotropic)

anisotropic samples ground for 4 h, their moduli did not differ significantly. Based on previous observations, it was concluded that the smaller particles produced by grinding are better dispersed in the matrix of the composite. Therefore, the structure of the silicone rubber-stabilized composite consisting of iron particles was weakened. The torsion modulus of the isotropic samples varied irregularly. For these samples, no correlation between the grinding time and the change in torsion modulus was observed. For samples containing iron particles ground for half an hour under the same dry conditions, the torsion modulus increased in proportion to the filler concentration.

The difference between the torsion moduli of the samples measured in the absence of a magnetic field and in one with a magnetic induction of 70 mT is shown in Figure 5B. It was observed that the samples with transverse chains are more affected by the magnetic field given that the change in torsion modulus is higher on average compared to the other samples. While for the samples containing longitudinal chains, an increasing trend was observed as the grinding time increased. The isotropic samples also exhibited an increasing trend up to

a grinding time of 4 hours. The reason for this difference can be explained by the fact that small particles distributed homogeneously may be less affected by the magnetic field than the larger aggregates of particles. For samples ground for half an hour under the same conditions, it can be concluded that at higher concentrations, the effect of the magnetic field is greater than expected.

#### 4. Conclusions

The torsional modulus of elasticity of composite elastomers containing nanoparticles of NANOFER STAR stabilized iron was investigated. Samples containing between 26.2 and 40.0 m/m% of iron particles were investigated. Isotropic and anisotropic samples were prepared. In the anisotropic samples, longitudinal and transverse chains were created using an external magnetic field of 350 mT.

The results showed that the particle size and distribution of the filler, which is influenced by the grinding time and pre-treatment method, significantly affected the mechanical behavior of the samples. Longer grinding times generally led to smaller, more homogeneously distributed particles, which reduced the overall torsional stiffness of the matrix. In the isotropic samples, the relationship between the grinding time and torsion modulus was irregular, indicating a more complex interaction between distribution of the filler and the surrounding matrix.

It was found that transverse anisotropic samples typically exhibited the highest torsion modulus, especially under the influence of a magnetic field, suggesting that chains of particles oriented perpendicular to the torsional axis provide greater mechanical resistance to deformation. The difference in torsion modulus due to exposure to a magnetic field was consistently larger in the transverse anisotropic samples, indicating that they respond better to it. In contrast, isotropic samples exhibited smaller and less consistent changes in torsion modulus, while longitudinal anisotropic samples yielded moderate values with a gradual increase in response to the field over longer grinding times.

The results clearly demonstrate that transverse anisotropic samples consistently exhibited the highest torsion moduli both in the presence and absence of a magnetic field, confirming their enhanced stiffness and magnetic responsiveness. This indicates that chains of particles oriented perpendicular to the torsional axis resist deformation better. Therefore, such MREs are particularly promising for applications requiring high direction-dependent rigidity and magnetic tunability such as adaptive vibration damping systems and tunable mechanical components.

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