



University of Pannonia
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Investigation of the properties of magnetorheological and electrorheological elastomers

Ph.D. thesis booklet

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Introduction

The development of materials science following the industrial and information revolutions has ushered in a new era in which the functioning of modern society is closely linked to the performance and reliability of advanced materials. The ever-increasing demands of technical and industrial applications—greater efficiency, lower energy consumption, cost reduction, and compliance with environmental requirements—require innovative solutions that go beyond traditional materials. Although classic structural materials such as iron, aluminum, and titanium alloys continue to dominate, interest in composite systems has grown significantly in recent decades, as these materials combine favorable mechanical, physical, and functional properties in a single system [1].

The development of modern materials technology is increasingly moving towards intelligent, adaptive systems. Materials that "sense" external signals and respond by modifying their properties open up new possibilities in the fields of control engineering, mechanical engineering, and robotics. Electrorheological (ER) and magnetorheological (MR) fluids, as well as their elastic counterparts: the electrorheological and magnetorheological elastomers (ERE and MRE), occupy a special place in this category. The operating principle of these materials is based on rapid structural rearrangement, occurring within milliseconds, under the influence of an external electric or magnetic field, which results in an immediate change in their mechanical, rheological, and other properties [2].

The operating principle of ER and MR elastomers is based on the polarization and magnetization of filler particles embedded in the polymer matrix, which results in the rearrangement of the internal microstructure and the modification of the macroscopic mechanical response. The chain and column structures formed under the influence of field can cause significant changes in stiffness, or shape change, allowing the properties of the material to be tuned in real time. This controllability makes them particularly valuable in engineering systems where adaptation to dynamic loads, vibration damping, or precise force transmission are essential requirements [3–5].

The areas of application for field-sensitive elastomers are constantly expanding. In mechanical engineering and automotive systems, they appear in the form of adaptive vibration dampers, suspensions with adjustable stiffness, and actuators. In robotics, controllable flexibility and damping create new possibilities. In building engineering and structural engineering, the development of vibration control systems is a task for today. In addition, precision engineering, medical technology, and actuator technologies also benefit from materials with fast response times, low energy requirements, and good integrability [6–8].

Aims

The applicability of electrorheological (ER) and magnetorheological (MR) elastomers is fundamentally determined by their composite structure, filler properties, and interaction with the external field. The aim of the research is to explore the parameters that significantly influence the mechanical and functional behavior of field-sensitive elastomers.

Three main objectives were set for the experimental work:

1. Quantitative investigation of the deformation of isotropic magnetorheological elastomers under the influence of a magnetic field using different filler types and concentrations. Determination of the extent and direction of deformation.
2. Determination of the torsional elastic modulus of isotropic and anisotropic cylindrical magnetorheological elastomer samples produced using different filler pretreatment methods and magnetic field orientations.
3. Investigation of the deformation of electrorheological isotropic elastomer samples under the influence of an external electric field and determination of the degree of deformation.

Experiments

As my first area of research, I examined the behavior of polydimethylsiloxane-based isotropic magnetorheological elastomer discs with different fillers—two types of magnetite and iron powder—and different particle size distributions in a constant magnetic field. The measuring system used a microscope camera to measure the deformation of the discs. I determined the exact degree of deformation by image processing and examining the contour lines of the discs. In the second part of my research, I investigated the torsional elastic modulus of magnetorheological elastomers consisting of silicone rubber matrices and stabilized iron nanoparticle fillers. I prepared isotropic and anisotropic samples using different filler pretreatment methods and magnetic field orientations. A measuring system was assembled to examine the torsional elastic modulus of the isotropic and anisotropic samples.

My third area of research was to investigate the effect of filler concentration, with particular emphasis on particle percolation and the field-induced deformation of isotropic, disc-shaped, barium titanate-filled electrorheological elastomers.

New scientific results, theses

1. I investigated the behavior of flat, disc-shaped magnetorheological elastomers based on polydimethylsiloxane with different fillers (two types of magnetite and iron) and in isotropic and anisotropic distributions in a constant magnetic field. (Relevant publications: [C1], [K1], [K2])

- 1.1. Based on the results of previous theoretical simulations in the literature, the deformation of magnetorheological elastomers depends on the aspect ratio of the geometric bodies. Based on my experimental results, I found that in all the samples tested, in accordance with the aspect ratios (flat discs with a height-to-width ratio of 0.47), dilatation could be observed in the direction of the magnetic field, which supports the predictions of the theoretical results.
- 1.2. I found that the degree of deformation increased linearly with increasing filler concentration in the case of magnetite and iron fillers. However, if other contaminants are present in the magnetite (which inhibit polymerization), this significantly affects the degree of deformation. The elasticity of the matrix changes due to the inhibition of polymerization caused by impurities.

2. I examined the torsional modulus of cylindrical magnetorheological elastomers based on polydimethylsiloxane and containing iron as a filler, in the absence of a magnetic field and in a constant magnetic field. I measured the change in torsional modulus, which can be interpreted as the MR effect caused by the magnetic field. The filler had an isotropic or anisotropic distribution. (Relevant publications: [C2], [K3])

- 2.1. The particle size and distribution of the filler significantly influenced the mechanical behavior of the samples. I influenced the particle size with the grinding time. The torsional elasticity of the elastomer containing small particles with a more homogeneous distribution was smaller.
- 2.2. Increasing the filler concentration increased the MR effect in all three cases, which was significantly greater in samples containing transverse chains. This suggests that in samples containing transverse chains, the chains formed inhibit deformation more effectively. I found that, for geometric reasons, the chain density is higher in samples containing transverse chains than in samples with longitudinal chains, resulting in stronger dipole chain-chain interactions, which increases the torsional modulus.
- 2.3. The MR effect was observed in both isotropic and longitudinal chain patterns, but in the latter case it was also highly dependent on the grinding time.

3. I synthesized disc-shaped (1:3.5 scale) PDMS-based electrorheological elastomers with different BaTiO₃ filler contents and studied their deformation in an axial electric field. (Related publications: [C3], [K4], [K5])

- 3.1. I found that the ERE bodies ~~formed~~ contracted reversibly along the direction of the electric field, parallel to their axis. The magnitude of the contraction varies quadratically with the electric field strength in small electric fields ($\sim 0.2 \text{ MVm}^{-1}$), which transitions to saturation at higher field strengths ($\sim 1 \text{ MVm}^{-1}$).

- 3.2.** I found that the deformation response induced by the electric field is greatly influenced by the presence of a percolated particle structure. The percolation threshold of the BaTiO₃ particles studied was $c_c = (34.7 \pm 0.1) \text{ m/m\%}$ ($7.9 \text{ V/V\%}$) according to the direct current specific conductivity. I verified the change in particle structure directly around the percolation threshold using SEM images. I showed that above the percolation threshold, the magnitude of the contraction induced by the electric field increases by a factor of ~ 10 in the low field strength range ($E \approx 0.2 \text{ MVm}^{-1}$). I found that at high field strengths, percolation has no significant effect on the magnitude of contraction. At this point, the maximum deformation was nearly identical for all samples (1.2%), regardless of particle concentration.
- 3.3.** Based on the results, I found that at low field strength, the percolation threshold must be reached to optimize the filler concentration, where the deformation increases significantly (~ 10 times) at the same field strength. However, above the percolation threshold, further increase of the filler concentration do not cause greater deformation.

Scientific publications, presentations and posters for the basis of theses

[C1] **Balogh, D.**; Guba, S.; Horváth, B.; Szalai, I.: Magnetic Field-Induced Deformation of Isotropic Magnetorheological Elastomers, *Magnetochemistry* 8 (2022) 146. <https://doi.org/10.3390/magnetochemistry8110146>.

[C2] **Balogh, D.**; Guba, S.; Szalai, I.: Studies on torsion moduli of magnetorheological elastomers, *Hungarian Journal of Industry and Chemistry* (megjelenés alatt)

[C3] Horváth, B.; Guba, S.; **Balogh, D.**; Jakab, M.; Szalai, I.: Effect of percolation on the deformation of isotropic electrorheological elastomers under external electric fields, *Journal of Molecular Liquids* 390 (2023) 123046. <https://doi.org/10.1016/j.molliq.2023.123046>.

[K1] **Balogh, D.**; Szalai, I.: Magnetoreológiai elasztomer korongok külső mágneses tér hatására történő relatív megnyúlásának vizsgálata In: XXII. Energetika-Elektrotechnika – ENELKO és XXXI. Számítástechnika és Oktatás – SzámOkt Multi-konferencia Kolozsvár, Románia: Erdélyi Magyar Műszaki Tudományos Társaság (EMT), (2021) pp. 99-104. , 6 p.

[K2] Guba, S.; **Balogh, D.**; Horváth, B.; Szalai, I.: Mágneses kompozit elasztomerek készítése és mechanikai vizsgálata (2017) Konferencia: OGÉT 2017, XXV. Nemzetközi Gépészeti Konferencia, 25th International Conference on Mechanical Engineering, Konferencia helye, ideje: Kolozsvár, Románia, 2017.04.27-2017.04.30., Megjelenés: Románia,

[K3] Guba, S.; **Balogh, D.**; Horváth, B.; Szalai, I.: N-ZVI tartalmú kompozit elasztomerek vizsgálata In: Bíró, Károly-Ágoston; Sebestyén-Pál, György (szerk.) ENELKO 2017 : XVIII. Energetika-Elektrotechnika Konferencia: SzámOkt 2017: XXVII. Nemzetközi Számítástechnika és Oktatás Konferencia Kolozsvár, Románia: Erdélyi Magyar Műszaki Tudományos Társaság (EMT) (2017) 255 p. pp. 50-55., 6 p.

[K4] **Balogh, D.**; Szalai, I.: Elektoreológiai elasztomer korongok külső elektromos tér hatására történő deformációjának vizsgálata, In: Sebestyén, György; Szabó, Loránd (szerk.) XXI. Energetika-Elektrotechnika – ENELKO és XXX. Számítástechnika és Oktatás – SzámOkt Multi-konferencia, Erdélyi Magyar Műszaki Tudományos Társaság (EMT) (2020)2 p. pp. 1-4., 4 p.

[K5] **Balogh, D.**; Szalai, I.: Elektoreológiai elasztomerek rugalmassági tulajdonságainak optikai vizsgálata, In: Barabás, István (szerk.) OGÉT 2019: XXVII. Nemzetközi Gépészeti Konferencia, Nagyvárad, Románia: Erdélyi Magyar Műszaki Tudományos Társaság (EMT) (2019) 632 p. pp. 31-34., 4 p

Other scientific publications, presentations

1. Mester, S.; **Balogh, D.**; Szalai, I.: Z generációs tanulási és vizsgázási szokások feltérképezése, In: XXV. Energetika-Elektrotechnika – ENELKO és XXXIV. Számítástechnika és Oktatás – SzámOkt Multi-konferencia = Enelko – 25th International Conference on Energetics-Electrical Engineering SzámOkt – 34th International Conference on Computers and Education, Erdélyi Magyar Műszaki Tudományos Társaság (EMT) (2024) pp. 109-114., 6 p.
2. **Balogh, D.**; Mester, S.; Szalai, I.: Kooperatív projektek bevezetése tesztmérnök szak oktatásába, In: XXIV. Energetika-Elektrotechnika – ENELKO és XXXIII. Számítástechnika és Oktatás – SzámOkt Multi-konferencia, Kolozsvár, Románia : Erdélyi Magyar Műszaki Tudományos Társaság (EMT) (2023) 201 p. pp. 89-94., 6 p.
3. **Balogh, D.**; Mester, S.; Nagy, R.; Kocsor, P.; Vörös, B.; Szalai, I.: Gépjármű gyalogossal való ütközése a gyalogos tesztábrák szempontjából, In: Sebestyén-Pál, György; Szabó, Loránd (szerk.) ENELKO 2022, XXIII. Energetika-Elektrotechnika – ENELKO és XXXII. Számítástechnika és Oktatás – SzámOkt Multi-konferencia, (2022) 210 p. pp. 1-6., 6 p.
4. Mester, S.; **Balogh, D.**; Szalai, I.: Gördülési súrlódási együttható mérésére alkalmas készülék fejlesztése, In: Sebestyén-Pál, György; Szabó, Loránd (szerk.) ENELKO 2022, XXIII. Energetika-Elektrotechnika – ENELKO és XXXII. Számítástechnika és Oktatás – SzámOkt Multi-konferencia, (2022) 210 p. pp. 36-40., 5 p.
5. Nagy, S. ; **Balogh, D.** ; Szalai, I. : Viscosity and self-diffusion coefficient of dipolar liquids, Fluid Phase Equilibria, 509 Paper: 112442 , 9 p. (2020)
6. Soós, P. ; Fülöp, I. ; Szüle, Zs. ; Petróczki, K.; Hentz, K. ; **Balogh, D.**; Nagy, Z.;; Szemcsés anyagok áramlástan paramétereinek meghatározása: (2001. évi zárójelentés) (2001), OTKA jelentés, Szent István Egyetem, Gödöllő, Gépészmérnöki Kar, Géptani Intézet, OTKA nyilvántartási szám: TO-25368, Tudományterület: Agrár-műszaki, Időtartam: 1998-2000,

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