

## Research Article

# Magnetodielectric Effects in Magnetorheological Elastomers Based on Polymer Fabric, Silicone Rubber, and Magnetorheological Suspension

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Received 3 November 2018; Revised 24 December 2018; Accepted 2 January 2019; Published 23 January 2019

Academic Editor: Martin Zatloukal

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We fabricate a hybrid magnetorheological elastomer (hMRE) based on a microfiber cloth soaked with a mixture containing magnetorheological suspension (MRS) and silicone rubber (SR). Two parallel copper electrodes are attached to the hMRE and the capacitance  $C$  is measured as a function of time  $t$ , for fixed values of magnetic flux density  $B$ . We show that  $C$  is stable in time and is sensibly influenced by  $B$ , while the relative dielectric permittivity increases up to two orders of magnitude when  $B$  reaches 340 mT. We explain the physical mechanism which leads to the observed magnetodielectric effects. The obtained results can be used for various biomedical applications such as in fabrication of active biomagnetic membranes used in dental implantology.

## 1. Introduction

Magnetorheological elastomers (MRE) together with magnetorheological suspensions (MRS) and gels (MRG) belong to the class of active magnetic materials. They consist of an elastic matrix, (i.e., natural/silicone rubber, etc.) in which ferro/ferrimagnetic nano/microparticles [1–8] and additives [9–11] are dispersed. In a magnetic field the elasticity state and electrical properties of MRE can be sensibly changed due to formation of aggregates inside the elastic matrix. This property of MRE is often used in automotive industry for manufacturing of dampers of magnetic shocks and vibrations [12, 13].

Formation of parallel metallic particles chains with increasing the magnetic field intensity leads to significant changes in the electrical conductivity of MRE [14], and this effect can be used in fabrication of materials aimed at shielding the electromagnetic radiation [15, 16]. However, achieving preestablished values of electrical properties of

MRE is not an instantaneously process, since the magnetic dipoles have to move inside a viscous or viscoelastic media [17]. By using absorbing sponges, in [18] a high stability of electrical properties during application of an external magnetic field has been reported. It is well-known that MRS are successfully used in fabrication of dynamic prostheses in oral surgery [13], since it increases the positioning precision of implants [19] and it isolates the patient's bone from the oral cavity [20, 21].

Here, we propose a low-cost approach for fabrication of hybrid MRE (hMRE) in which the electrical properties are stable when a magnetic field is applied. We present the fabrication process of hMRE, and we describe the experimental setup used to reveal the magnetodielectric effects. It is shown that the relative dielectric permittivity increases up to two orders of magnitude when magnetic flux density reaches 340 mT. The obtained results can be used for fabrication of bioactive membranes useful for dental implantology and maxillofacial surgery [22, 23] by replacing

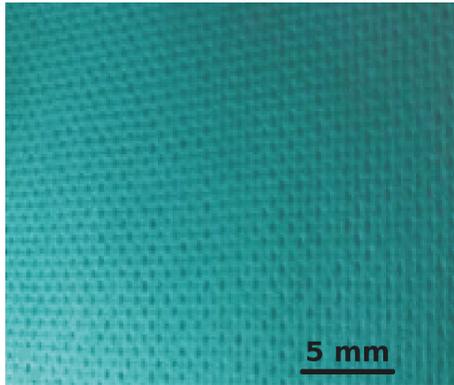


FIGURE 1: Absorbent microfiber cloth with thickness 0.45 mm.

the microfiber cloths with organic membranes from Poly (D, L-lactide). To this aim, a first step has been performed in [24], where it has been shown that by dissolving of 0.5 g of Poly (D, L-lactide) in 30 ml of chloroform, followed by a dispersion of 0.10 g of bioglass, a bioactive membrane can be obtained. Addition of ferro/ferrimagnetic powders leads to formation of biomagnetic active membranes, which can reduce significantly the time of the bone growth as well as the quality of the added bone.

## 2. Materials and Methods

The materials used for fabrication of hMRE are silicone oil (SO) from Silicone Commerciale SpA, with viscosity 100 cSt, density  $0.97 \text{ g/cm}^3$  at 298 K, and ignition temperature 583 K; carbonyl iron (CI) powder from Sigma Aldrich with particle diameters between 4.5 and  $5.4 \mu\text{m}$ ; and Fe content of min. 97 %, silicone rubber (SR), type Globasil AL/40 from Globalsimchimica, catalyst (C), type Rhodosil Cata 6H, from Bluestars Silicones, and absorbent microfiber cloth, type Scotch-Brite from Emag, with thickness 0.45 mm.

The preparation of MRE is performed according to the following procedure. Initially, three squared-shape microfiber cloth are cut at dimensions  $30 \text{ mm} \times 30 \text{ mm}$  (Figure 1). Inside one of the three microfiber clothes, two parallel copper conductors with a diameter of 0.24 mm, situated at a distance of 20 mm apart from each other, are introduced (Figure 2).

Then, the three microfiber cloths are placed on top of each other, with the one containing the copper electrodes in the middle, and then they are sewed with cotton fibers (absorbent/resistor body; Figure 3). Third, a volume of  $10 \text{ cm}^3$  of MRS is prepared at 523 K for about 10 minutes containing 30 % mass conc. of SO and 70 % mass conc. of CI, and then it is homogenized until it reaches 353 K. The absorbent body is weighted and then it is immersed for about 30 minutes in the MRS. The obtained system soaked with MRS is kept at room temperature for about 1 hour while the MRS excess is drained. Then, the body is again weighted and the quantity absorbed is found to be 3.8 g (i.e.,  $2 \text{ cm}^3$ ).

Finally, a volume of  $20 \text{ cm}^3$  is prepared consisting of 20 % vol. conc. of MRS, 70 % vol. conc. of SR, and 10 % vol.

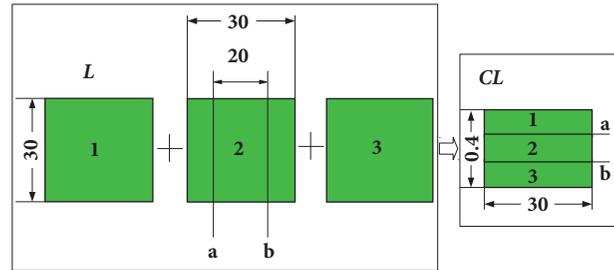


FIGURE 2: Fabrication of the absorbent body CL: L, microfiber cloth; 1 and 3, microfiber cloths without copper electrodes; 2, microfiber cloth with copper electrodes a and b. The values of the lengths are in mm.

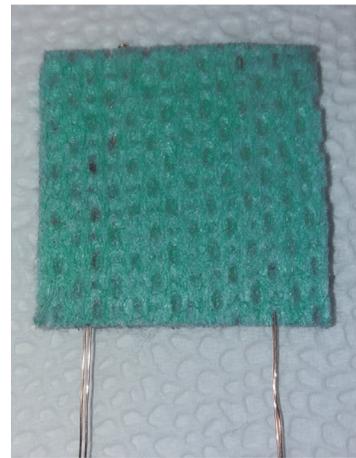


FIGURE 3: Resistor body consisting from the microfiber cloth (turquoise) and two parallel copper wires (reddish brown). Dimensions are the same as in Figure 1.

conc. of C and then is poured over both sides of the system soaked with MRS obtained in step (6). The MRE becomes polymerized after about 24 hours, and it has a rough surface. Several layers of SR (90 % vol. conc.) mixed with C (10 % vol. conc.) are poured on the MRE, thus obtaining smooth surfaces. Finally, after polymerization (about 24 hours) one obtains the hMRE as shown in Figure 4.

The overall configuration of the experimental setup used for investigating the electrical capacitance of hMRE in a static magnetic field is shown in Figure 5, while an image of the setup is shown in Figure 6.

## 3. Results and Discussions

The hMRE is introduced between the dipoles of the electromagnet, and by using an RLC bridge the electrical capacitance is measured as a function of time  $t$ , with and without an external magnetic field. In the latter case the capacitance of hMRE is  $C_{\text{exp}}^0 = 0.085 \text{ nF}$ . However, when  $B \neq 0$  the capacitance increases with  $B$ , but it remains stable with time, as shown in Figure 7.

The average values of the capacitance ( $C_m$ ), calculated from the variations  $C = C(t)$  at fixed values of  $B$  in Figure 7,



FIGURE 4: Image of the hMRE (E). Dimensions are the same as in Figure 1.

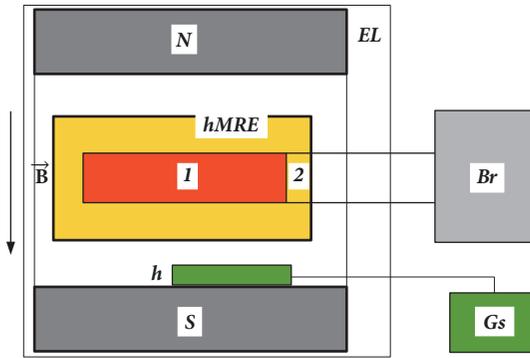


FIGURE 5: Experimental setup (overall configuration): EL, electromagnet; N and S, magnetic poles; hMRE, measuring cell; 1 and 2, MRE body based on SR and, respectively, MRS; Br, RLC bridge; Gs, Gaussmeter; h, hall probe;  $\mathbf{B}$ , magnetic flux density vector.

show that they are sensibly influenced by magnetic flux density  $B$ , with the highest value corresponding to  $B = 340$  mT (see Figure 8(a), black dots).

Empirically, we found that the capacitance can be approximated by

$$C_m = C^0 + KB^n, \quad (1)$$

where  $C^0$  is the capacitance of hMRE at  $B = 0$  mT. By performing the fit we obtain  $C^0 = 0.0885$  nF,  $K = 88 \times 10^{-14}$  nF/mT, and  $n = 5$ . Thus, by introducing them in (1), one obtains the variation  $C_m = C_m(B)$  as shown in Figure 8(a) (continuous black line), which approximates very well the experimental data (black dots). The results show also that the experimentally measured value of the capacitance  $C_{\text{exp}}^0$  is very close to the theoretical one  $C^0$ , which supports the empirical formula given by (1). Also, at  $B = 340$  mT, the average capacitance is about 4.2 nF, and thus magnetodielectric effects are induced inside hMRE.

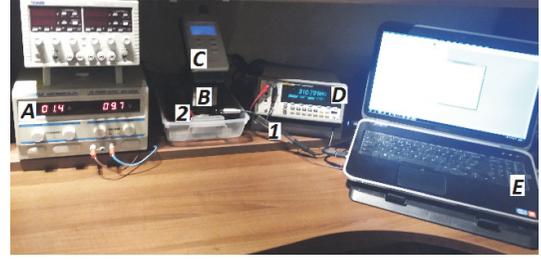


FIGURE 6: Image of the experimental setup: A, source of continuous current; B, electromagnet; C, Gaussmeter; D, RLC bridge; 1, hall probe; 2, hMRE; E, computing unit.

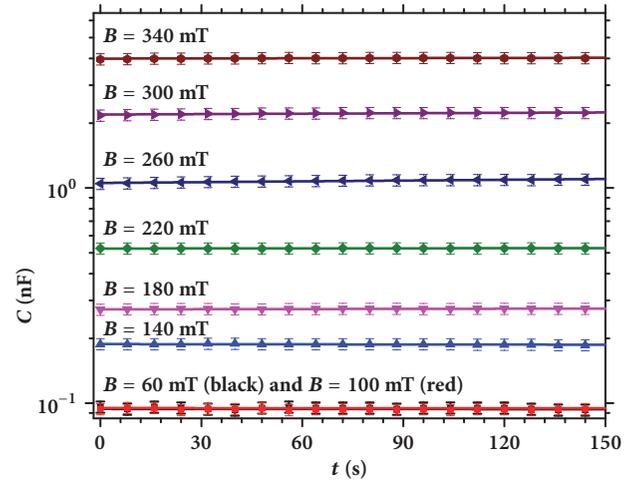


FIGURE 7: Electrical capacitance  $C$  of hMRE as a function of time  $t$  for fixed values of magnetic flux densities  $B$ . Dots, experimental data; continuous lines, linear fit.

In order to evaluate quantitatively these effects, we assimilate hMRE to an electrical plane capacitor, whose capacitance is given by the well-known expression:

$$C^0 = \frac{\epsilon_0 \epsilon_r^0 S}{h} \quad \text{at } B = 0, \quad (2)$$

and

$$C^m = \frac{\epsilon_0 \epsilon_{rm}^0 S}{h} \quad \text{at } B \neq 0, \quad (3)$$

where  $\epsilon_0$  is the vacuum dielectric constant, while  $\epsilon_r^0$  and  $\epsilon_{rm}$  are the relative dielectric permittivities of hMRE without and, respectively, with a magnetic field,  $S$  is the common surface area between the plates of the capacitor, and  $h$  is the distance between the plates. Thus, by using (2) and (3) one obtains a measure of the magnetodielectric effects induced inside the hMRE by the magnetic field, through

$$\gamma = \left( \frac{C_m}{C^0} - 1 \right) \times 100. \quad (4)$$

Introducing (2) and (3) in (4), one obtains the expression

$$\gamma = \left( \frac{\epsilon_{rm}}{\epsilon_r^0} - 1 \right) \times 100. \quad (5)$$

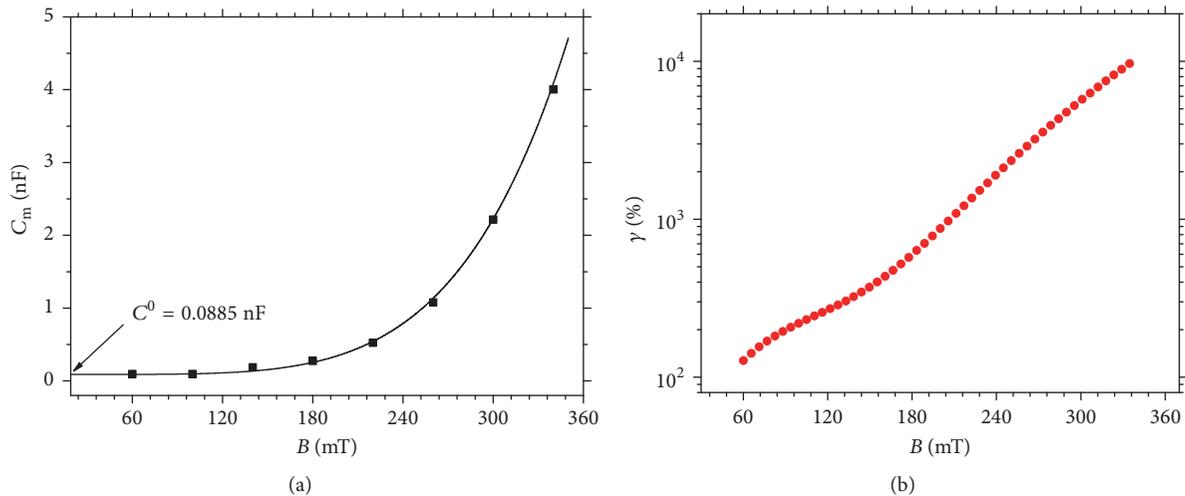


FIGURE 8: Average electrical capacitance  $C_m$  (a) and the ratio  $\gamma = (C_m/C^0 - 1) \times 100$  (b) of hMRE as a function of magnetic flux density  $B$ . Dots, experimental data; continuous black curve, fit using (1).

By using the dependence  $C_m = C_m(B)$  and the value  $C^0 = 0.0885$  nF inside (4) we obtain in Figure 8(b) the variation of  $\gamma$  with magnetic flux density. The results show that the relative dielectric permittivity of hMRE is strongly dependent on the magnetic flux density, with magnetodielectric effects increasing from  $\gamma = 127\%$  at  $B = 60$  mT, to  $\gamma = 10465\%$  at  $B = 340$  mT.

#### 4. Conclusion

A new hMRE based on polymeric fabric, silicone rubber, and MRS has been manufactured. We show that its dielectric function is stable in time in the presence of an external magnetic field. We show that the relative dielectric permittivity of hMRE can be controlled in a magnetic field. Its values increase about two orders of magnitude when the magnetic flux density increases from 0 mT to 340 mT.

The obtained effect can be used in biomedical applications for fabrication of magnetic field sensors for patients wearing cardiac pacemakers and prostheses. In particular, by replacing the microfiber cloth with Poly (DL-lactide)-based membranes consisting of electrolytic iron particles and MimetikOss granules, the hMRE is a biomagnetic active material which opens possibilities towards new trends in dental implantology.

#### Data Availability

The processed data required to reproduce these findings are available to download from Figshare or from the corresponding author upon request.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

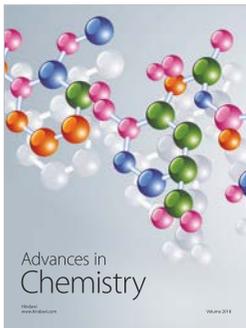
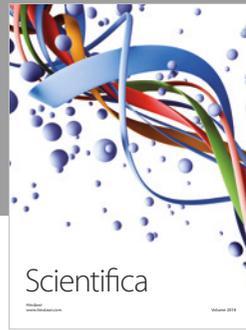
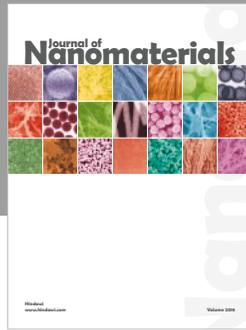
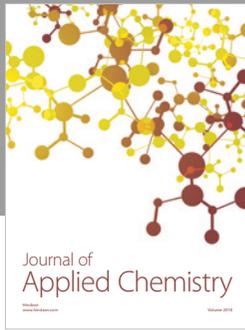
#### Acknowledgments

The paper is a result of the collaboration between JINR (Dubna, Russia) and the partner Universities/Institutes from Romania. Financial support from PN-III-P1-1.2-PCCDI-2017-0871 (CNDI-UEFISCDI) project is acknowledged.

#### References

- [1] Y. Han, *Mechanics of Magneto-Active Polymers [Ph. D. thesis]*, Iowa University, 2012.
- [2] I. Bica, E. M. Anitas, and L. M. E. Averis, "Tensions and deformations in composites based on polyurethane elastomer and magnetorheological suspension: Effects of the magnetic field," *Journal of Industrial and Engineering Chemistry*, vol. 28, pp. 86–90, 2015.
- [3] V. Birman and G. A. Kardomateas, "Review of current trends in research and applications of sandwich structures," *Composites Part B: Engineering*, vol. 142, pp. 221–240, 2018.
- [4] A. K. Bastola and L. Li, "A new type of vibration isolator based on magnetorheological elastomer," *Materials & Design*, vol. 157, pp. 431–436, 2018.
- [5] T. Hu, S. Xuan, L. Ding, and X. Gong, "Stretchable and magneto-sensitive strain sensor based on silver nanowire-polyurethane sponge enhanced magnetorheological elastomer," *Materials & Design*, vol. 156, pp. 528–537, 2018.
- [6] D. Leng, K. Xu, Y. Ma, G. Liu, and L. Sun, "Modeling the behaviors of magnetorheological elastomer isolator in shear-compression mixed mode utilizing artificial neural network optimized by fuzzy algorithm (ANNOFA)," *Smart Materials and Structures*, vol. 27, no. 11, article 115026, 2018.
- [7] S. A. Aziz, S. A. Mazlan, N. I. Ismail et al., "A comparative assessment of different dispersing aids in enhancing magnetorheological elastomer properties," *Smart Materials and Structures*, vol. 27, no. 11, article 117002, 2018.
- [8] L. Wang, M. Yu, J. Fu, and S. Qi, "Investigation on the effects of doped dendritic Co particles on rheological property of magnetorheological gel," *Smart Materials and Structures*, vol. 27, no. 10, article 105041, 2018.

- [9] I. Bica, E. M. Anitas, and L. Chirigiu, "Magnetic field intensity effect on plane capacitors based on hybrid magnetorheological elastomers with graphene nanoparticles," *Journal of Industrial and Engineering Chemistry*, vol. 56, pp. 407–412, 2017.
- [10] I. Bica and E. M. Anitas, "Magnetic field intensity and graphene concentration effects on electrical and rheological properties of MREs-based membranes," *Smart Materials and Structures*, vol. 26, no. 10, article 105038, 2017.
- [11] I. Bica, E. M. Anitas, Q. Lu, and H. J. Choi, "Effect of magnetic field intensity and  $\text{-Fe O}$  nanoparticle additive on electrical conductivity and viscosity of magnetorheological carbonyl iron suspension-based membranes," *Smart Materials and Structures*, vol. 27, no. 9, Article ID 095021, 2018.
- [12] Y. Li, J. Li, W. Li, and H. Du, "A state-of-the-art review on magnetorheological elastomer devices," *Smart Materials and Structures*, vol. 23, no. 12, Article ID 123001, 2014.
- [13] M. Rahman, Z. C. Ong, and S. Julai, "A review of advances in magnetorheological dampers: their design optimization and applications," *Journal of Zhejiang University-Science A*, vol. 18, no. 12, pp. 991–1010, 2017.
- [14] M. Schümann, J. Morich, T. Kaufhold, V. Böhm, K. Zimmermann, and S. Odenbach, "A mechanical characterisation on multiple timescales of electroconductive magnetorheological elastomers," *Journal of Magnetism and Magnetic Materials*, vol. 453, pp. 198–205, 2018.
- [15] M. Sedlacik, M. Mrlik, V. Babayan, and V. Pavlinek, "Magnetorheological elastomers with efficient electromagnetic shielding," *Composite Structures*, vol. 135, pp. 199–204, 2016.
- [16] P. Domínguez-García, S. Melle, J. M. Pastor, and M. A. Rubio, "Scaling in the aggregation dynamics of a magnetorheological fluid," *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics*, vol. 76, no. 5, Article ID 051403, 2007.
- [17] M. S. Kandelousi, L. Chirigiu, and I. Bica, "Studies of Electroconductive Magnetorheological Elastomers," in *Electric Field*, InTech, 2018, chapter 3.
- [18] I. Bica, E. M. Anitas, M. Bunoiu, B. Vatzulik, and I. Juganaru, "Hybrid magnetorheological elastomer: Influence of magnetic field and compression pressure on its electrical conductivity," *Journal of Industrial and Engineering Chemistry*, vol. 20, no. 6, pp. 3994–3999, 2014.
- [19] D. Senkal, H. Gurocak, and E. I. Konukseven, "Passive haptic interface with MR-brakes for dental implant surgery," *Presence: Teleoperators and Virtual Environments*, vol. 20, no. 3, pp. 207–222, 2011.
- [20] S. C. Isler, F. Soysal, T. Ceyhanlı, B. Bakırarar, and B. Unsal, "Regenerative surgical treatment of peri-implantitis using either a collagen membrane or concentrated growth factor: A 12-month randomized clinical trial," *Clinical Implant Dentistry and Related Research*, vol. 20, no. 5, pp. 703–712, 2018.
- [21] M. Trobos, A. Juhlin, F. A. Shah, M. Hoffman, H. Sahlin, and C. Dahlin, "In vitro evaluation of barrier function against oral bacteria of dense and expanded polytetrafluoroethylene (PTFE) membranes for guided bone regeneration," *Clinical Implant Dentistry and Related Research*, vol. 20, no. 5, pp. 738–748, 2018.
- [22] M. Ravis, P. Marius, T. Serban et al., "Influence of the bone cements processing on the mechanical properties in cranioplasty clinical applications of biomaterials in surgery view project dental biomaterials and tissue engineering view project," *Revista de Chimie*, vol. 90, no. 4, p. 990, 2018.
- [23] A. Makowiecki, U. Botzenhart, J. Seeliger, F. Heinemann, P. Biocev, and M. Dominiak, "A comparative study of the effectiveness of early and delayed loading of short tissue-level dental implants with hydrophilic surfaces placed in the posterior section of the mandible—A preliminary study," *Annals of Anatomy*, vol. 212, pp. 61–68, 2017.
- [24] A. I. Leal, S. G. Caridade, J. Ma et al., "Asymmetric PDLA membranes containing Bioglass® for guided tissue regeneration: Characterization and in vitro biological behavior," *Dental Materials*, vol. 29, no. 4, pp. 427–436, 2013.



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