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Dedicated to Academician Professor Dr. Emil Burzo on His 80th Anniversary

MAGNETORHEOLOGICAL ELASTOMER ELASTICITY - BASED CAPACITOR

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ABSTRACT. In the present paper, a magnetorheological elastomer (MRE) based on silicone rubber, magnetorheological suspension and catalyst, in a magnetic field, is obtained. Using the plane capacitor method, it is shown that the elastic properties of the magnetorheological elastomer are influenced by the intensity and direction of the applied magnetic field. The obtained experimental results are presented and discussed.

Keywords*: silicone rubber, magnetorheological elastomer, plane capacitor, carbonyl iron, magnetic Young modulus.*

INTRODUCTION

Magnetorheological elastomers (MREs) are part of the magnetically active materials category. They consist of an elastic matrix into which magnetizable nano- or microparticles are dispersed or aligned [1-4]. Like in the case of the magnetorheological suspensions [5-9], some physical the physical properties like of the MREs drastically change under the action of the magnetic field. This particular feature is used in mechanical shocks absorbers and dampers [10], (bat the damping mechanism differs from the classical magnetomechanical damping magnetostrictive ferromagnets [11-14]).

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One property of interest is related to the change of the electric conductivity of MREs in a magnetic field [15, 16], property used in obtaining active or passive electric circuit elements [17-22]. Such devices can be used in the manufacturing of deformations and mechanical tensions sensors and/or transducers. The physical properties of the MREs [1-4, 10, 15-23] strongly depend on the method of preparation. In this context, the obtaining procedure at an anisotropic MRE and the study of its elastic properties by means of the plane capacitor method is presented in the paper.

EXPERIMENT

Plane capacitor with MRE

The components used in obtaining the plane capacitor with MRE-based dielectric material are: silicone rubber, RTV-3325 (Bluestar – Silicones), silicone oil (Merck), catalyst, 60R (Merck) and carbonyl iron (Sigma) as microparticles with diameter between 4.5μm and 5.4μm and iron content of min 97%. A liquid mixture, consisting in 2.4cm^3 carbonyl iron and 0.2cm^3 silicone oil, is brought to the temperature of 573±5% [20] and maintained at this temperature for ≈5 minutes. At the end of the 5 minutes time the mixture is allowed to reach room temperature. Following the thermal decomposition of carbonyl iron, iron nanoparticles with average diameter of 61.2nm are formed inside the liquid matrix [20]. The obtained product is mixed and homogenized with silicone rubber (1.2cm^3±10%) and catalyst (0.2cm^3±10%). The formed mixture is injected between two parallel copper plates (diameter 30mm), provided on the outline with a spacer so as to maintain the distance between the plates at 3.5mm±10%.The as-formed set was placed between the poles of a type Phylatex (Germany)-Weiss electromagnet. The magnetic field has a normal direction to the surface of the plane capacitor plates and intensity of H=840kA/m±10%. After 24 hours, a plane capacitor with MRE dielectric material based on silicone rubber and iron nanoparticles (60% vol.) is obtained.

Measurements

The electric capacity of the plane capacitor at the temperature of the environment (296 K ± 10%) and in the absence of the magnetic field is measured with the capacimeter CM-7115A (Fujian). The capacitor with MRE is introduced in a transverse magnetic field (normal to the plates) and then in a longitudinal magnetic field (in plane). Three sets of measurements are performed with the CM-7115A (Fujian) capacimeter precision.

RESULTS AND DISCUSSION

The average values of the capacity *C* as a function of the magnetic field intensity *H* are presented in Fig.1a. At *H*=0, the capacity of the plane capacitor is fixed to the value C_0=96pF. We note with C_T the capacity of *C* in a transverse magnetic field and with C_L the capacity of the same *C* in a longitudinal magnetic field. When applying a transverse magnetic field ($0<H(kA/m)\leq 400$), the value of *C* jumps from C_0=96pF to C_T=124 pF, for *H*= 15kA/m. For $15<H(kA/m)\leq 400$, C_T has a quasi-linear growth with *H*. At *H*=400 kA/m one obtains $C_T=157pF$. In a longitudinal magnetic field, the values $C_L(H)<C_T(H)$. Here, as Figure 1 shows, two regions of $C_L=C_L(H)$, namely: $96\leq C_L(pF)\leq 97.5$, for: $0\leq H(kA/m)\leq 100$; $97.5<C_L(pF)\leq 131$, and for: $100<H(kA/m)\leq 400$, can be observed. Neglecting the edge effects [27], the capacitance of the plane capacitor with MRE based dielectric may be approximated to:

$$C_0=\varepsilon_0\varepsilon_r\frac{\pi d^2}{4h_0},\ \text{for } H=0 \quad \text{and} \quad C=\varepsilon_0\varepsilon_r\frac{\pi d^2}{4h},\ \text{for } H\neq 0 \tag{1}$$

Here ε_0 =8.85 pF/m, ε_r is the relative permittivity of the MRE; *d*, h_0 and *h* are the diameter and thicknesses of the MRE.

The linear magnetic strain is:

$$e=(h-h_0)/h_0=[(C_0/C)-1] \tag{2}$$

where h_0 and *h* can be obtained from Eqs.(1) .

For C_0 si *C=C(H),* from Fig.1, introduced in (2), on obtained in Fig.2, (e_T) transversal magnetic linear strain and (e_L) magnetic longitudinal linear strain.

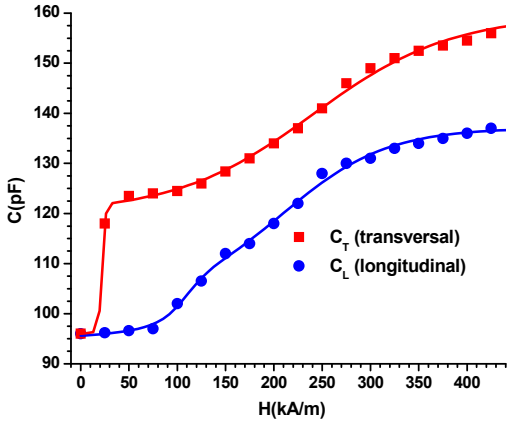

Fig. 1. Capacitance C of the plane capacitor as a function of the strength magnetic field H.

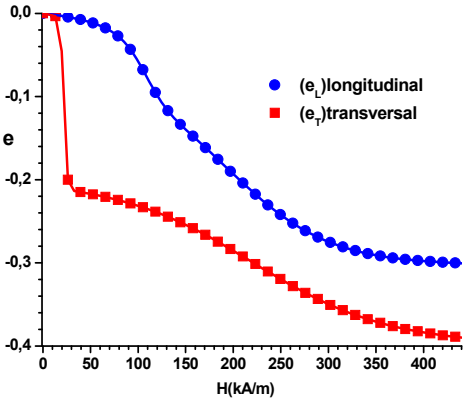

Fig. 2. The linear magnetic strain e as a function of the strength magnetic field H.

We see from Fig. 2 like MRE is compressed. MRE compression value depends on the strong magnetic field intensity vector direction. From Fig.2, it is observed that for H ≥ 20kA/m, compressing due to the transverse magnetic field is far enlarging compared to that due to the longitudinal magnetic field. In a magnetic field, the nanoparticles from the inside of the elastic matrix are magnetized. We consider that the nanoparticles are of diameter $d \approx d_m$. Then, their magnetic moment is [25]:

$$m = \frac{\pi}{6} d_m^3 \chi H \cos\alpha \tag{3}$$

where d_m is the diameter of the magnetizable particles, H is the magnetic field strength and α is the angle between the $\vec{H}$ and direction of chains magnetic dipoles $\vec{m}$.

The parameter χ is the initial magnetic susceptibility of the MRE. For $\mu_p >> \mu_e$ (μ_p and μ_e are the relative magnetic permeability of the iron nanoparticles and silicone rubber) this may approximated to [25]:

$$\chi = 3\frac{\mu_p - \mu_e}{\mu_p + 2\mu_e} \approx 3 \tag{4}$$

Introducing the expression (4) into Eq. (3) yields:

$$m = 0.5\pi d_m^3 H \cos\alpha \tag{5}$$

We consider $\vec{H}$ constant. Then, between two neighboring and identical magnetic dipoles, an attractive magnetic force occurs [20, 25]:

$$F_m = -\frac{3\mu_0\mu_e m^2}{\pi\, r^4} \tag{6}$$

where μ_0 = 12.56 x 10^{-7} H/m and *r* is the distance between the centers of the two dipoles.

The mechanical stress induced in to the MRE by F_m [26]:

$$\sigma = N_C \, F_m \big/ S = \frac{3}{2}\varphi \frac{F_m}{\pi\, d_m^2} \tag{7}$$

where N_c/S is the number of columns per transverse cross-section unit of MRE [26] and φ is the volume fraction of the iron nanoparticles.

From Eqs. (5), (6) and (7), which for $r=d_m$ results mechanical stress induced in to MRE by longitudinal magnetic field, i.e.:

$$\sigma_L = -4.5\varphi\mu_0 H^2 \cos^2\alpha \tag{8}$$

Here α is the angle between vector intensity of magnetic field and the direction of the dipoles columns.

For α=0, the stress is maximum and has the expression:

$$\sigma_T = -4.5\,\varphi\mu_0 H^2 \tag{9}$$

where σ_T is the stress component corresponding to vector intensity magnetic field normal to the plates.

For the magnetic tension, Eqs. (8) and (9), the elastic matrix reacts with the longitudinal elastic tension σ_{eL} and the transverse elastic tension $\sigma_{eT,}$ respectively.

At equilibrium are available equalities $\sigma_{eL} = \sigma_L$ and $\sigma e_T = \sigma_T$ or:

$$4.5\varphi\mu_0 H^2 = k_L\, d_0/S\, [(h/h_0)\text{-}1]_L \cos^2\alpha = k_L\, h_0/S\, [(C/C_0)\text{-}1]_L \cos^2\alpha = E_L\, e_L \tag{10}$$

$$4.5\varphi\mu_0 H^2 = k_T\, d_0/S\, [(h/h_0)\text{-}1]_T = k_T\, h_0/S\, [(C/C_0)\text{-}1]_T = E_T\, e_T \tag{11}$$

where k_L and k_T are MRE elastic constant, $e_L=[(C/C_0)\text{-}1]_L$ and $e_T=[(C/C_0)\text{-}1]_T$ are the longitudinal and the transversal linear strain, *S* is surface aria and:

$$\boldsymbol{E_T} = k_T\, d_0/S \text{ and } E_L = k_L\, d_0/S \cos^2\alpha \tag{12}$$

is the magnetic elasticity module (E_T) for transversal magnetic field and (E_L) is the magnetic elasticity module for longitudinal magnetic field. From Eqs. (10) and (11) results:

$$E_L = 4.5\varphi\mu_0 H^2/[(C/C_0)\text{-}1]_L \text{ and } E_T = 4.5\varphi\mu_0 H^2/[(C/C_0)\text{-}1]_T \quad (13)$$

The angle of α is obtained from the Eqs. (12) and (13), namely:

$$\alpha = \arccos[(E_T/E_L)^{0.5}] \quad (14)$$

For $\varphi = 0.60$, $\mu_0 = 12.56 \times 10^{-7}$ H/m and $(C/C_0)_{L,T}$, from Fig. 1, and the Eqs. (13) can be obtained $E_{L,T} = E_{L,T}(H)$, plotted in Fig. 3.

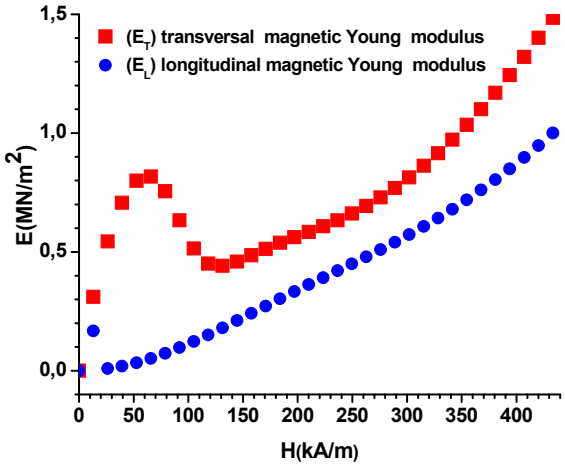

Fig. 3. Magnetic module E_T and E_L function of the magnetic strength field H.

Introducing $E_{L,T} = E_{L,T}(H)$ from Fig. 3 in Eqs. (14), and obtained $\alpha = \alpha(H)$, plotted in Fig. 4.

Shall see from Fig.4, as the angle α are shrinking as the H increase, corresponding with the modification of E_L, from Fig. 3. Introducing $C=C(H)$ values (Fig. 1a) and C_0=96pF into Eq. (10) and the dependence $e=e(H)$ is obtained as shown in Fig. 2. It can be noticed the linear strain e increases with the magnetic field $\vec{H}$ and it is sensibly dependent its direction. For $\alpha=0$ (transverse magnetic field) expression (11) can be rewritten as $\sigma_T = E e_T$. Then, using Eq. (7) for φ=0.60, $0 \le H(kA/m) \le 440$ and $e_T = e_T(H)$ from Fig. 2 one obtains $E=E(H)$ as plotted in Fig. 3. It can be noticed from Fig. 3 that the magnetic Young modulus E sensibly increases with H, in accord with the model proposed in Refs. [28, 29]. The columns formed by the iron nanoparticles have the same direction as $\vec{H}$. At the moment of a longitudinal magnetic field application ($\vec{H}$ *in plane)* the chains formed by the iron nanoparticles

tend to orient towards $\vec{H}$. An angle α will occur between the direction of $\vec{H}$ and that of the chains. We intend to determine α with the growth of $\vec{H}$. For this, we use the expression (6), *E=E(H)* from Fig. 3 and $e_L = e_L(H)$ from Fig. 2. Then, for φ=0.60 and *0 ≤ H (kA/m) ≤ 440*,the dependence $\alpha = \alpha(H)$ will be obtained as plotted in Fig.4. It can be seen from Fig. 4 that the angle α decreases with the increase of *H*. According to Refs. [28, 29] the value of α depends on $F_m \sim H^n$ (where $n \leq 2$).

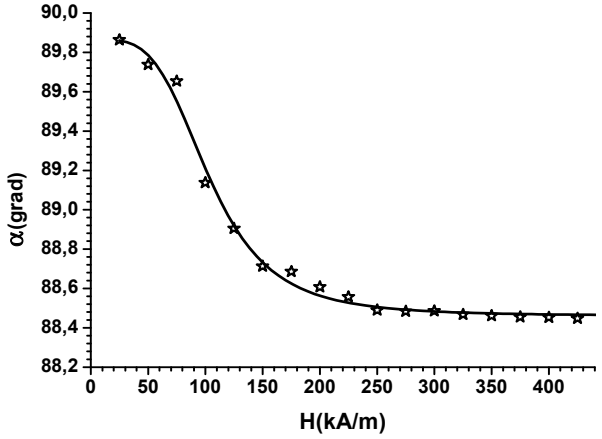

Fig. 4. The angle α between $\vec{H}$ and the direction of the dipoles columns $\vec{m}$ as a function of the longitudinal strength magnetic field H.

CONCLUSIONS

- Anisotropic MRE was obtained by magnetic field polymerization of the mixture formed by silicone rubber with catalyst and magnetorheological suspension based on silicone oil and Fe nanoparticles;
- The electric capacitance *C* of the plane capacitor with the MRE, the magnetic field – induced linear strain *e* and the stress σ depend on the strength and direction of $\vec{H}$;
- The magnetic Young modulus *E* of the MRE is strongly influenced by $\vec{H}$;
- The angle α between by $\vec{H}$ and the direction of the chains formed by iron particles decreases rapidly within the field range *20 ≤H(kA/m) ≤240* and becomes constant for higher field values.

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