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Experimental study of magnetoelastics

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Abstract

The effect of magnetic particles concentration and of a uniform magnetic field on elastic properties and dissipation of mechanical energy of new magnetocontrolled materials (magnetoelastics) was studied. Experimental results for Young's modulus E and shear modulus N are presented. It is revealed that increases of concentration of magnetic particles and magnetic field value give increase of an area of the loops under loading and unloading of magnetoelastics. Experiment for research of magnetoelastic properties by a method of twisting pendulum is advanced. Dependences of decrement of attenuation and the magnetoelastic twisting oscillation period on value of a magnetic field and concentration of magnetic particles are obtained.

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Keywords: Magnetic soft matter; Magnetic polymers and nanocomposites; Magnetoelastics; Magnetic and elastic properties

1. Introduction

In the present work, we consider magnetic soft matter, such as new magnetocontrolled elastic composite materials (magnetoelastics), produced by dispersing magnetic particles in polymer matrix based on either natural or synthetic rubber and liquid organic components.

Structure, magnetic, elastic, magnetodeformational and viscosity properties of these materials, the influence of the magnetic field on the elastic and viscous properties of magnetoelastics were considered in Refs. [1–3]. It was found that application of a magnetic field leads to a considerable rise in Young's modulus and in the viscosity of these materials. In the case of uniaxial extension or a shear, the magnetoelastics behave as typical viscoelastic medium. Under loading or unloading they smoothly pass in a new equilibrium state (see Fig. 1). In the figure, there is change of sample lengths under loading of the sample with $C_V = 16\,\mathrm{vol}\%$ of magnetic particles. Experiment showed that time of transition from first equilibrium state to second equilibrium state is 2–3 s.

Widely known expression uniting Young's modulus E, shear modulus N and Poisson's factor χ for equilibrium state can be written as

$$N = \frac{E}{2(1+\chi)}.$$

When volume does not vary ($\chi = 1/2$) we have more simple ratio: $N = E/3$.

In the case of the torsion deformation of cylinder, a torsion angle α is proportional to the torque P:

$$\alpha = \frac{1}{N}\frac{2L}{\pi r^4}P.$$

Here L is the length of the cylinder and r the radius of cross-section. Formula includes also shear modulus N which means that the torsion deformation is the shear deformation.

In our work, we compared experimental results obtained for equilibrium process of loading–unloading with dynamic characteristics obtained for low frequency in frameworks of classical theory of twisting pendulum [4]. In this theory,

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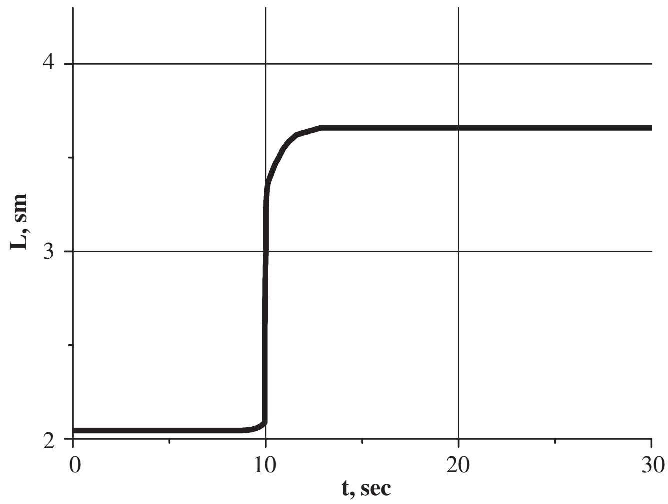

Fig. 1. Change of magnetoelastic length on time under loading ($C_V = 16\%$).

oscillation period

$$T = \frac{2\pi}{\sqrt{(G/M) - \delta^2}}, \tag{1}$$

where M is the moment of inertia of spherical mass m which was suspended on the end of the cylindrical magnetoelastic sample and the twisting modulus

$$G = \frac{N\pi r^4}{2L}, \tag{2}$$

where N is the shear modulus and δ the attenuation coefficient.

2. Results and discussion

We investigated magnetoelastics with volume concentration of magnetic particles C_V from 0 to 30 vol% and mass concentration of plasticizer about 75%. The size of iron particles was 2 μm. Measurements were done in magnetic field and without it.

In our experiments, we measured elongation after 30–40 s from the moment of loading. In Fig. 2, there are dependences of elastic stress σ on elongation Δx for magnetoelastics with $C_V = 0\%$ (a), 11% (b), 16% (c) and 30% (d) of volume concentration of magnetic particles; curves 1 for $H = 0$ and curves 2 for $H = 1000$ Oe.

From Fig. 2 one can see that with increase of magnetic particle concentration the area of loading–unloading hysteresis becomes larger and additional dissipation of energy takes place. And for all samples the hysteresis area in magnetic field is larger than without the field. Dependences of Young's modulus E on magnetic particle concentration in magnetic field and without it are given in Fig. 3.

Shear modulus was measured for two orientations of magnetic field: external magnetic field was perpendicular and parallel to plane of shear stress. Fig. 4 gives

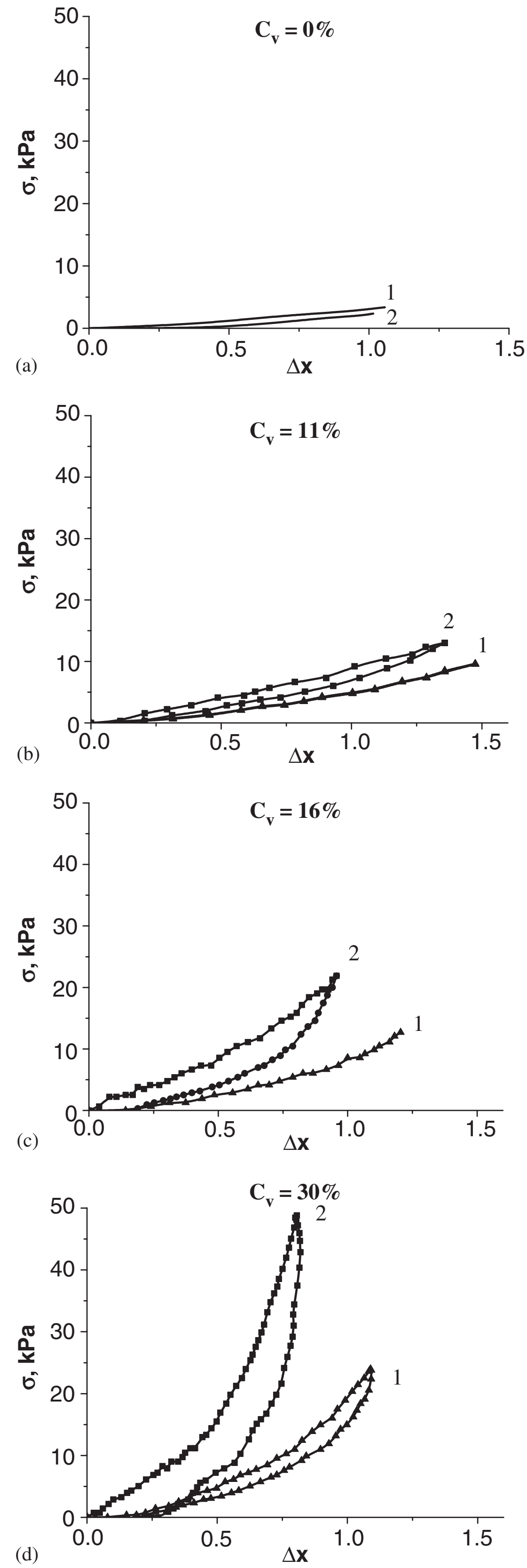

Fig. 2. Dependences of stress σ on related elongation Δx for magnetoelastic samples with for different concentrations.

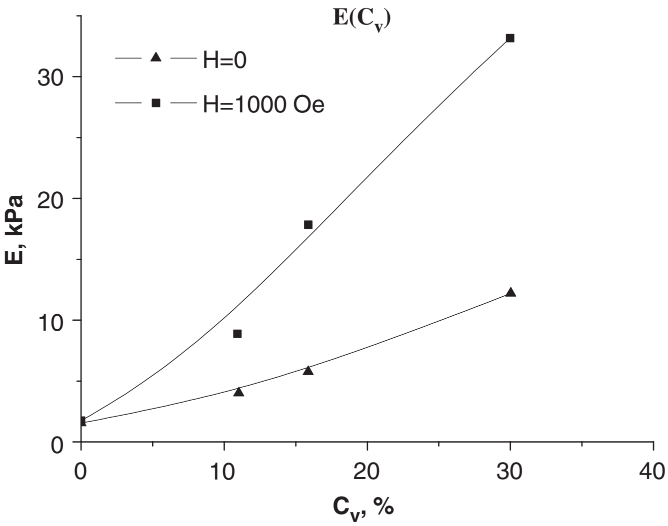

Fig. 3. Dependences of Young's modulus E on volume concentration C_V.

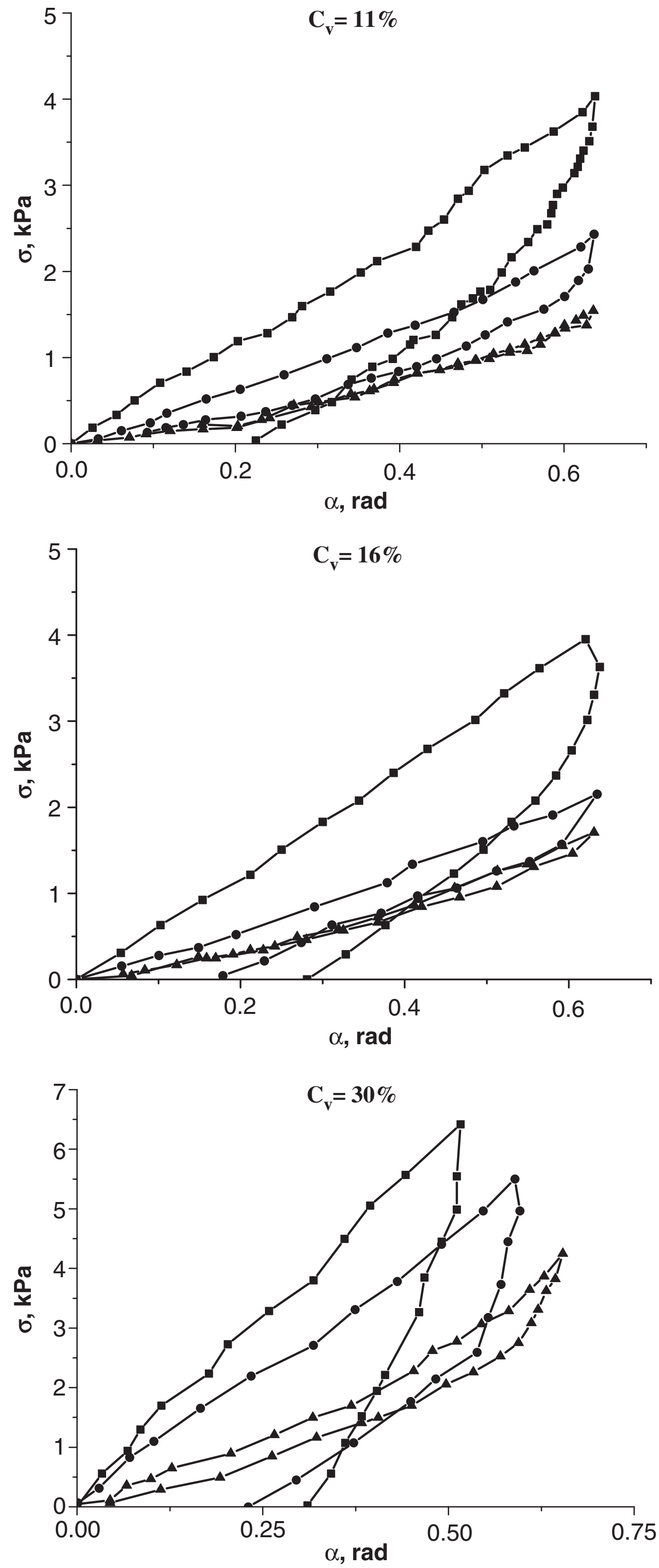

Fig. 4. Dependences of stress σ on shear angle α for magnetoelastic samples with different volume concentrations $C_V H = 0$ (■) and $H = 1000\,\mathrm{Oe}$ for perpendicular (♦) and parallel (▲) direction to S.

experimental dependences of shear stress σ on shear angle α for magnetoelastics with volume concentration of magnetic particles $C_V = 11\%$, 16% and 30%. One can see that these dependences are similar to dependences of stress on elongation for uniaxial stretch. With increase of the magnetic particle concentration, the area of loading–unloading hysteresis also becomes larger. For shear case we have large differences in area of hysteresis for parallel and perpendicular orientations of magnetic field. The area of hysteresis for perpendicular orientation of magnetic field is larger than for parallel orientation. Dependence of shear modulus for two orientations of magnetic field and without it on magnetic particle concentration is shown in Fig. 5.

Experimental results for Young's modulus E and shear moduli N_1 and N_2 are presented in Table 1. Here N_1 is for perpendicular orientation and N_2 is for parallel orientation of the magnetic field.

Analysis of experimental data shows that without magnetic field we have almost classical relation $E = 3N$. However, in magnetic field, this relation is broken. Such behavior can be explained by internal structurization of magnetic particles and by appearing non-uniform magnetic field.

Damped oscillations of twisting pendulum were also investigated. For this we measured weight of ball m, length and diameter of cylindrical magnetoelastic and dependence of twisting angle α on time. Knowing experimental value of shear modulus we calculated oscillation period for twisting pendulum by formulas (1) and (2).

As example Fig. 6 gives the dependences of twisting angle α on time t for cylindrical samples with concentration $C_V = 17.5\%$ without magnetic field and in magnetic field $H = 580\,\mathrm{Oe}$.

It was found that increase of magnetic particle concentration or increase of magnetic field results in decrease of oscillation period. The analysis of experimental results has

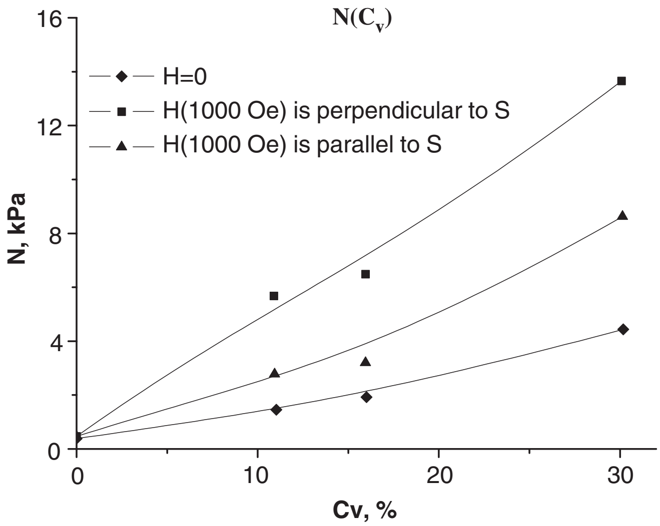

Fig. 5. Dependences of shear modulus N on volume concentration C_V for two directions of magnetic field and without field.

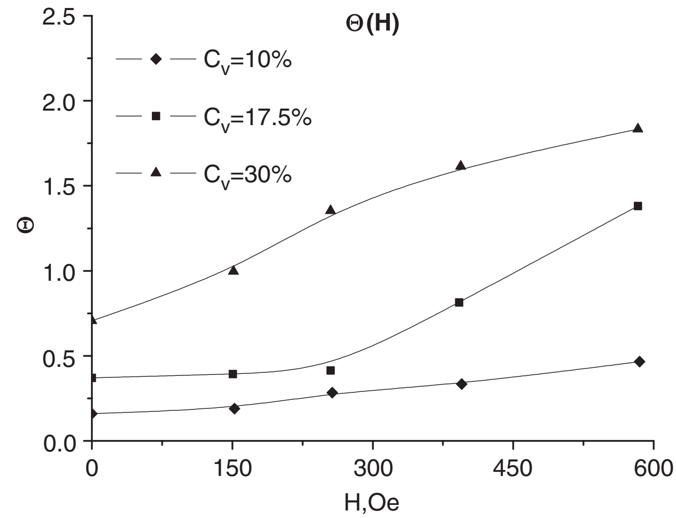

Fig. 7. Dependences of decrement of attenuation on magnetic field for different volume concentrations of magnetic particles.

Table 1
Young's and shear moduli for different volume concentrations of magnetic particles

C_V (%)	$H=0$		$H=1000\,\mathrm{Oe}$		
	E (kPa)	N (kPa)	E (kPa)	N_1 (kPa)	N_2 (kPa)
0	2.0	0.7	2.0	0.7	0.7
11	4.2	1.6	8.8	5.6	2.9
16	6.1	2.0	17.8	6.4	3.4
30	12.1	4.4	32.5	13.5	8.9

Table 2
Decrement of attenuation and period of oscillations for magnetoelastic samples with different volume concentrations

C_V (%)	$H=0$		
	θ	T_1 (s)	T_2 (s)
11	0.16	2.78	2.67
16	0.37	1.44	1.57
30	0.73	0.93	1.03

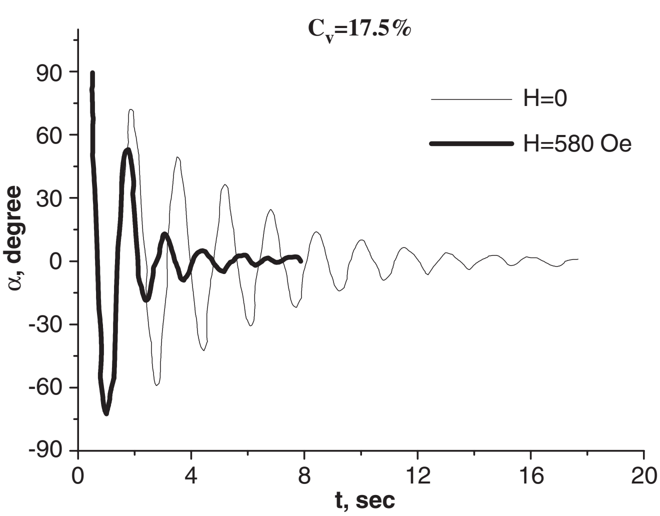

Fig. 6. Dependences of twisting angle α on time t in magnetic field and without field.

shown that magnetic field influences the decrement of attenuation.

The dependences of decrement of attenuation on magnetic field H for different magnetic particle concentrations are shown in Fig. 7. These results are in good agreement with results for area of loop of equilibrium shear stress.

Results for comparison of experimental data with results obtained by calculation are in Table 2, where θ is the decrement of attenuation, T_1 the experimental oscillation period, T_2 the oscillation period, by classical formulas (1) and (2).

3. Conclusion

We investigated mechanical properties of magnetoelastics by three independent methods and showed that without magnetic field the results are in good agreement with classical theory. It is found that increase of magnetic particles concentration and value of magnetic field increases dissipation of mechanical energy in magnetoelastics. The property of dissipation of mechanical energy can be tested by determining the areas of loading–unloading loop.

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