The study of mechanical properties of magnetorheological elastomers under compressive stress

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Abstract. The study of magnetorheological elastomers is one of the major areas of searching for construction materials with unique properties. These are smart composite materials which constantly find new areas of use because they combine the advantages of elastomers and ferromagnetic materials. This article presents the results of study of the mechanical properties of magnetorheological elastomers under compressive stress. As part of the study, a series of compression cycles was performed at different magnetic induction values, strain amplitude and input frequency. The influence of each parameter on the material characteristics was determined utilizing a rheological model of a viscoelastic material. The presented results were supplemented with methodology of measurement and sample preparation as well as information related to the construction of the testing station.

1. Introduction
Polyurethane polymer materials are widely used in mechanical engineering [1, 2]. Also, their composites with various types of additives are widely used in industrial applications [3, 4]. Magnetorheological elastomers can be considered as a particular example of such composite materials. They combine the advantages of polymers and ferromagnetic materials. They are characterized by the possibility to alter certain mechanical properties which are controllable through the use of magnetic field. For this reason, their areas of use are continually expanding. Their main area of application is vibration absorption equipment [5–8], but also other specialized equipment such as: force sensors (detection component) [9] or electromechanical micromodules for measuring magnetic field (detection component) [10]. Magnetorheological elastomers may also be used to build more advanced structures of smart materials, utilizing for example auxetics [11]. Effective use or magnetorheological elastomers is not possible without accurate determination of their mechanical characteristics. Works are currently underway to study the discussed composites under conditions of compressive stress [7, 12], shearing [13–16], as well as tensile strength [17]. Taking into account the number and diversity of potential applications of magnetorheological elastomers, further study into their properties is therefore justified.

2. Methodology of study
The study entailed an examination of a cycle of compression. The samples used in the experiment were magnetorheological elastomers. The matrix material was made of polyurethane being a mixture of polyols VORALUX® HF 505 and 14922 and isocyanate HB 6013. The utilized ferromagnetic material was powdered iron carbonyl with particle diameter in the range from 6 to 9 μm, manufactured by Fluka. The constituent materials were mixed mechanically, degassed and placed in a special mold. The cross-
linking of samples took part in the presence of a magnetic field with induction \( B = 300 \text{ mT} \). The finished samples were cylinders with diameter \( d = 20 \text{ mm} \) and height \( h = 20 \text{ mm} \). Selected microscope image of one of such samples is provided in figure 1.

The view of the mold used to prepare the samples is provided in figure 2. The aluminum mold 4 is placed between two steel covers 1. Inside, there are channels 3 which form the desired geometric properties of the magnetorheological elastomer. The mold is fastened to the cover with bolts 5. Hermetic closure of the cover 1 is ensured by aluminum alloy bolts 2 with proper tensioning. During the cross-linking of samples, the mold is subject to a magnetic field along their axes. Correct selection of materials causes the electromagnetic field flux is closed off by the prepared samples. This is the result from the used aluminum alloy and air having significantly lower coefficients of magnetic permeability than the mold covers and the magnetorheological component itself. Such mold construction enables re-use. Another advantage is that in allows to prepare samples of varying geometric properties, which can be altered by adjusting the shape of the channels in which the composite material is being cross-linked. Such a solution is advantageous because different testing calls for different sample geometry.

For the purpose of a comprehensive determination of characteristics of the examined magnetorheological samples, a suitable testing program was devised. Four MRE samples were compressed until maximum strain, equal to, sequentially, \( \varepsilon = 10 \% \), \( 20 \% \), \( 30 \% \) (the strain amplitude) was achieved. The examinations were carried out by controlling the set strain profile. Both in the stabilization period and the experiment in question, its course was triangular. The input frequency was, sequentially: \( f = 0.04 \text{ Hz}, 0.1 \text{ Hz}, 0.25 \text{ Hz}, 0.5 \text{ Hz} \). During the first stage, sample stabilization was achieved for \( m = 50 \) cycles at velocity \( v_{\text{stab}} = 5 \text{ mm min}^{-1} \). For the purpose of measurement, the samples were loaded with initial stress, followed by carrying out and measuring five load and unload cycles with velocity dependent on the assumed input frequency, with average value being determined afterwards. Measurements were carried out for different magnetic field induction values, sequentially: \( B = 0 \text{ mT}, 32 \text{ mT}, 64 \text{ mT}, 95 \text{ mT}, 127 \text{ mT} \). Further experimentation was performed strictly in sequence, to ensure that every sample has an identical load history. In total, 1200 hysteresis loops were recorded. The diagram of the testing program is provided in figure 3. It provides a detailed account of a single test for the following parameter values: \( f = 0.04 \text{ Hz}, \varepsilon = 10 \% , B = 0 \text{ mT} \) (no applied magnetic field).
In order to carry out the planned testing, a specialized testing station was designed and built, the diagram is provided in figure 4. The enclosure 2 together with covers was made of a special iron alloy with good magnetic properties. After mechanical processing, the components of the enclosure were annealed in order to obtain uniform characteristics along its entire cross-section. Inside the enclosure, there is an induction coil 4 with a magnetorheological elastomer sample 3. The entire unit is affixed to the base 5 made of non-magnetic, austenitic steel. This enables the magnetic field flux to be closed off by the examined sample. The view of the built testing station is provided in figure 5.

**Figure 3.** Diagram of the testing program.

**Figure 4.** Diagram of the testing station; 1 – compressive force transmitter, 2 – enclosure, 3 – coil, 4 – tested sample, 5 – base.

**Figure 5.** Built view of the testing station; 1 – force sensor, 2 – compressive force transmitter, 3 – enclosure, 4 – power supply, 5 – temperature sensor, 6 – base, 7 – displacement sensor.

### 3. Testing results

Example measurement results are provided in figure 6, whereas the selected set of determined hysteresis loops is provided in figure 7. The juxtaposition of hysteresis loops for the entire strain range is provided in figure 8.

From the analysis of the graph provided in figure 6 it is concluded that the compressive stress value $\sigma$ and strain value $\varepsilon$ are functions of time. One can observe that peak values for both curves occur at different time values. Therefore, they are not in perfectly in-phase. What follows is the tested material exhibits the viscoelastic characteristics. The scale of changes occurring in the magnetorheological elastomer caused by the influence of the magnetic field are provided in figure 7. A clear increase is visible in the value if inclination angle of the diagonals and areas of the obtained hysteresis loops as a function of magnetic field induction. An analysis of the characteristics presented in figure 8 allows to
conclude that the change of maximum strain of the tested sample results in a change of shape of the hysteresis loop. The higher the maximum strain, the more the resulting graph deviates from a perfect elliptical shape. Individual sections of the hysteresis loop are characterized by increasing progression, and the increase of stress becomes more non-linear in relation to strain. This is a result of higher strain causing a less uniform distribution of stress. This is related to high susceptibility of the matrix material, and what follows, material changes in the sample cross section as a result of affected load.

**Figure 6.** Example measurement results for sample no. 3, $\varepsilon = 30\%$, $f = 0.1$ Hz, $B = 32$ mT, $m = 2$.

**Figure 7.** Set of determined hysteresis loops; $\varepsilon = 10\%$, $f = 0.25$ Hz.

**Figure 8.** Juxtaposition of hysteresis loops for the entire strain range; $f = 0.5$ Hz, $B = 127$ mT.
4. Test result analysis
For the purpose of a detailed result analysis, a Kelvin-Voigt rheological model was employed. The reason for its selection was its transparent structure, which makes it easy to interpret. It is one of the most commonly used models for the description of magnetorheological elastomers. However, one needs to emphasize that its usefulness is limited to a certain degree [12]. For this reason, many research teams devote their attention to formulate new mathematic models for composite materials of this type. This article focuses in particular on the determination of what physical characteristics and to what degree affect the mechanical properties of magnetorheological elastomers. For such an application, the performance of the Kelvin-Voigt model is deemed satisfactory.

Sequentially, an analysis was performed of the influence of selected parameter values on the set of obtained results. To this end, percentage increments were calculated as noted for the loss angle $\varphi$ in individual cases. Figure 9 provides the loss angle values as a function of magnetic induction $B$ for the carried out tests. The juxtaposition of the determination coefficient $R^2$ and the maximum percentage scale of loss angle variation $\Delta \varphi_{max}(B)$ as a function of magnetic induction $B$ is shown in table 1.

| $f$ (Hz) | $R^2$ | $\Delta \varphi_{max}(B)$ (%) | $R^2$ | $\Delta \varphi_{max}(B)$ (%) | $R^2$ | $\Delta \varphi_{max}(B)$ (%) |
|---------|-------|-------------------------------|-------|-------------------------------|-------|-------------------------------|
| 0.04    | 0.872 | 18.17                         | 0.843 | 12.53                         | 0.990 | 14.92                         |
| 0.1     | 0.958 | 7.58                          | 0.937 | 14.91                         | 0.996 | 21.45                         |
| 0.25    | 0.887 | 7.53                          | 0.918 | 10.04                         | 0.998 | 21.95                         |
| 0.5     | 0.899 | 11.92                         | 0.911 | 17.45                         | 0.951 | 27.63                         |

Figure 9. Set of obtained values of loss angle $\varphi$ as a function of magnetic induction $B$, $\varepsilon = 30\%$.

Based on the presented graphs, one can state that it is possible to determine that the value of the loss angle $\varphi$ changes together with the increase of the magnetic induction $B$ affecting the examined samples. The observed phenomenon results from ferromagnetic material particles interacting within the composite. These result from the influence of the magnetic field and depend on its intensity. The observed change is linear. The representation quality of obtained results is described by the value of the determination coefficient $R^2$. Since the value of the $R^2$ coefficient is close to one, a very good linear representation is observed. The largest observed scale of loss angle variation as a function of magnetic induction $\Delta \varphi_{max}(B)$ is equal to 27.63 %.

Figure 10 demonstrates selected results of the performed analysis. Table 2 presents a juxtaposition of the determination coefficient values $R^2$ and maximum percentage scale of loss angle variation $\Delta \varphi_{max}(\varepsilon)$ as a function of strain amplitude $\varepsilon$. 

Table 1. Juxtaposition of determination coefficient values $R^2$ and maximum range of loss angle variation $\Delta \varphi_{max}(B)$ as a function of magnetic induction $B$.

| $\varepsilon = 30\%$ | $\varepsilon = 20\%$ | $\varepsilon = 10\%$ |
|-----------------------|-----------------------|-----------------------|
| $f$ (Hz) | $R^2$ | $\Delta \varphi_{max}(B)$ (%) | $R^2$ | $\Delta \varphi_{max}(B)$ (%) | $R^2$ | $\Delta \varphi_{max}(B)$ (%) |
| 0.04    | 0.872 | 18.17                         | 0.843 | 12.53                         | 0.990 | 14.92                         |
| 0.1     | 0.958 | 7.58                          | 0.937 | 14.91                         | 0.996 | 21.45                         |
| 0.25    | 0.887 | 7.53                          | 0.918 | 10.04                         | 0.998 | 21.95                         |
| 0.5     | 0.899 | 11.92                         | 0.911 | 17.45                         | 0.951 | 27.63                         |
Figure 10. Set of determined loss angle values $\varphi$ as a function of strain $\varepsilon$, $B = 64$ mT.

Table 2. Juxtaposition of determination coefficient values $R^2$ and maximum range of loss angle variation $\Delta\varphi_{\text{max}}(\varepsilon)$ as a function of strain $\varepsilon$.

| $f$  | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) |
|------|-------|-----------------------------------------------|-------|-----------------------------------------------|-------|-----------------------------------------------|-------|-----------------------------------------------|
| $B$ (mT) | 0 | 0.996 | 0.998 | 0.998 | 0.982 | 0.984 | 0.973 | 0.973 |
| 32   | 0.997 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
| 64   | 0.999 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
| 95   | 0.999 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
| 127  | 0.999 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |

As follows from the resulting data, for the used maximum strain range, the observed change is linear. The highest noted loss angle variation, as a function of strain amplitude $\Delta\varphi_{\text{max}}(\varepsilon)$ is 53.43 %.

Figure 11 demonstrates the graph of selected loss angle variation $\varphi$ as a function of input value $f$ during testing. On the basis of available subject literature, it is predicted that the dynamic modulus will vary together with the change of frequency. The rigidity of cross-linked elastomer materials indicates a growing trend together with the increase of input frequency [18, 19]. Based on the obtained results, it is not possible to unequivocally define the characteristics of the change. An analysis of the published data allows to identify that the loss angle variation $\varphi$ as a function of frequency value $f$ is alternating and oscillates around a certain average. Such behavior of the composite material may be caused by low value of used input frequency ($f \leq 0.5$ Hz). Figure 11 demonstrates the position of determined loss angle values $\varphi$ as a function of input frequency, $\varepsilon = 10 \%$. 

Figure 11. Set of determined loss angle values $\varphi$ as a function of input frequency, $\varepsilon = 10 \%$. 

As follows from the resulting data, for the used maximum strain range, the observed change is linear. The highest noted loss angle variation, as a function of strain amplitude $\Delta\varphi_{\text{max}}(\varepsilon)$ is 53.43 %. 

Table 2. Juxtaposition of determination coefficient values $R^2$ and maximum range of loss angle variation $\Delta\varphi_{\text{max}}(\varepsilon)$ as a function of strain $\varepsilon$.

| $f$  | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) | $R^2$ | $\Delta\varphi_{\text{max}}(\varepsilon)$ (%) |
|------|-------|-----------------------------------------------|-------|-----------------------------------------------|-------|-----------------------------------------------|-------|-----------------------------------------------|
| $B$ (mT) | 0 | 0.996 | 0.998 | 0.998 | 0.982 | 0.984 | 0.973 | 0.973 |
| 32   | 0.997 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
| 64   | 0.999 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
| 95   | 0.999 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
| 127  | 0.999 | 0.997 | 0.996 | 0.978 | 0.980 | 0.980 | 0.973 | 0.973 |
values in relation to the calculated averages $\varphi_{av_1}, \varphi_{av_2}, \varphi_{av_3}$. Table 3 presents a juxtaposition of the average value $\varphi_{av}(f)$ and the maximum range of loss angle variation $\Delta \varphi_{\text{max}}(f)$ as a function of input frequency. The highest deviation from the average loss angle value as a function of frequency $\Delta \varphi_{av}(f)$ is 8.92%.

| $B$ (mT) | $\varphi_{av}(f)$ | $\Delta \varphi_{av}(f)$ (%) | $\varphi_{av}(f)$ | $\Delta \varphi_{av}(f)$ (%) | $\varphi_{av}(f)$ | $\Delta \varphi_{av}(f)$ (%) |
|----------|-------------------|-------------------------------|-------------------|-------------------------------|-------------------|-------------------------------|
| 0        | 0.244             | 5.91                          | 0.286             | 1.29                          | 0.322             | 8.80                          |
| 32       | 0.253             | 8.31                          | 0.302             | 2.10                          | 0.338             | 5.85                          |
| 64       | 0.258             | 8.92                          | 0.314             | 3.50                          | 0.358             | 4.81                          |
| 95       | 0.264             | 6.69                          | 0.319             | 1.81                          | 0.371             | 5.08                          |
| 127      | 0.272             | 6.51                          | 0.325             | 4.58                          | 0.390             | 3.22                          |

5. Conclusion
As part of the performed study, a series of examinations of mechanical characteristics of magnetorheological elastomers were carried out. The examination focused on the influence of induction of the magnetic field $B$, strain amplitude $\varepsilon$ and input frequency $f$ on the value of magnetic loss angle $\varphi$. It is an important material characteristic which allows to evaluate a series of characteristics, including viscous and flexible parameters. It was demonstrated that changes observed in the values of loss angle variation $\varphi$ for the considered range of strain and magnetic field induction are highly linear. Moreover, one needs to emphasize that the strain amplitude $\varepsilon$ has had a much larger influence on the determined values than magnetic induction $B$. In most of their applications, magnetorheological elastomers are shaped to receive shear stress load. In this mode of operation, the strain amplitude does not affect composite rigidity to such a significant extent. The described characteristics should be considered when designing systems utilizing materials of this group. Within the scope of works carried out, it was not possible to unequivocally determine the influence of frequency on the loss angle value. However, it was demonstrated that in the considered range, its average value introduces an error value not exceeding 9%.

6. References
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