

A Study of Significant Factors Affecting Viscoelastic Damping Properties of Polymer Materials

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Viscoelastic behaviour of materials is connected with transformation of mechanical energy into heat, which is a measure of a material structural damping. Viscoelastic properties of materials are described by different quantities, e.g. by loss modulus, storage modulus and loss factor. They depend on material type, its structure, excitation frequency, temperature, relative humidity etc. Damping properties were experimentally measured by means of the forced oscillation method. The purpose of the paper was to investigate viscoelastic damping properties of different polymer materials like PE, PP, ABS or rubber. There were studied different factors that have an influence on viscoelastic damping properties of the investigated polymer materials under dynamic loading, mainly the effect of operating temperature, excitation frequency, sample deformation and rubber composition.

Keywords: Viscoelastic Damping, Loss Factor, Excitation Frequency, Deformation, Temperature.

1 Introduction

Viscoelastic behaviour of materials is connected with damping of mechanical vibration, which is undesirable in the majority of cases, e.g. in manufacturing technologies, transport and home appliances [1 - 3]. There are three different material types in terms of viscoelastic damping, i.e. elastic, viscous or viscoelastic materials. They are characterized by stress-strain dependencies during cyclic dynamic loading.

It is assumed that a material sample is subjected to a cyclic loading [4]. Then the cyclic stress $\sigma(t)$ and the cyclic strain $\varepsilon(t)$ depend on the time t and are given by the equations (1) and (2):

$$\sigma(t) = \frac{F(t)}{S} [Pa], \quad (1)$$

$$\varepsilon(t) = \frac{x(t)}{l_0} [-], \quad (2)$$

Where:

F(t)...Time-dependent force [N],

S...Cross-sectional area of the tested material sample [m²],

$$\sigma(t) = \sigma_0 \cdot \cos(\omega \cdot t + \delta) = \sigma_0 \cdot \cos\left(\omega \cdot t + \frac{\pi}{2}\right) = -\sigma_0 \cdot \sin(\omega \cdot t) = -\sigma_0 \cdot \sin(2\pi \cdot f \cdot t) [Pa], \quad (4)$$

$$\varepsilon(t) = \varepsilon_0 \cdot \cos(\omega \cdot t) [-], \quad (5)$$

Where:

σ_0 ...Stress amplitude [Pa],

ω ...Angular frequency [rad·s⁻¹],

f...Excitation frequency [Hz],

ε_0 ...Strain amplitude [-].

It is visible from the Eqs. (4) and (5) that the stress-strain dependence of the perfectly viscous material is nonlinear during a dynamic stress.

$x(t)$...Time-dependent sample displacement [m],

l_0 ...Initial length of the material sample [m].

A perfectly elastic material returns any of the energy stored during loading and exhibits no phase shift [5] between the applied stress and the resultant strain (the phase angle $\delta=0$). For this reason the stress-strain dependence during dynamic stress is expressed by the Hooke's law (3):

$$\sigma(t) = E \cdot \varepsilon(t) [Pa], \quad (3)$$

Where:

E...Young's modulus of elasticity [Pa].

It is evident from the Eq. (3) that the perfectly elastic material is described by linear stress-strain dependence.

On the contrary, a perfectly viscous material is characterized by a complete opposite behaviour in comparison with the perfectly elastic material. In this case, the energy stored during dynamic loading is not returned when the stress is out-of-phase with the strain by the phase angle $\delta=90^\circ$. All the energy is dissipated into heat and this process is characterized as „pure damping“. Then time dependencies of the stress and the strain of the perfectly viscous material are described by the formulas (4) and (5):

Real (i.e. viscoelastic) materials are characterized both elastic and viscous properties [6, 7]. Time dependencies of the stress and the strain of viscoelastic materials are expressed by the equations (6) and (7):

$$\sigma(t) = \sigma_0 \cdot \cos(\omega \cdot t + \delta) [Pa], \quad (6)$$

$$\varepsilon(t) = \varepsilon_0 \cdot \cos(\omega \cdot t) [-]. \quad (7)$$

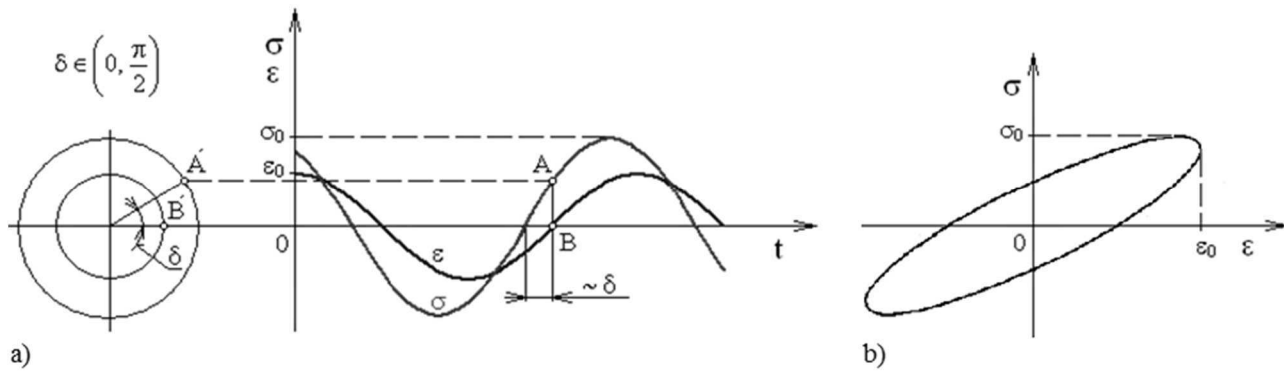


Fig. 1 Time dependencies of the stress and the strain (a) and a typical hysteresis loop (b) of a viscoelastic material

An example of time dependencies of the stress and the strain of a viscoelastic material is shown in Fig. 1. There are also shown the circle diagram with the phase angle δ and the stress-strain dependence of this material in Fig. 1. It is evident that the stress-strain dependence is characterized by a hysteresis loop whose area is equal to the mechanical energy, which is dissipated into heat per cycle of

$$\begin{aligned} \sigma(t) &= \sigma_0 \cdot \cos(\omega \cdot t + \delta) = \sigma_0 \cdot \cos \delta \cdot \cos(\omega \cdot t) - \sigma_0 \cdot \sin \delta \cdot \sin(\omega \cdot t) = \\ &= \sigma_0 \cdot \cos \delta \cdot \cos(\omega \cdot t) + \sigma_0 \cdot \sin \delta \cdot \cos\left(\omega \cdot t + \frac{\pi}{2}\right) = E' \cdot \varepsilon_0 \cdot \cos(\omega \cdot t) + E'' \cdot \varepsilon_0 \cdot \cos\left(\omega \cdot t + \frac{\pi}{2}\right) [Pa], \end{aligned} \quad (8)$$

Where:

E' ... Real component of the complex modulus of elasticity (so-called storage modulus) [Pa],

E'' ... Imaginary component of the complex modulus of elasticity (so-called loss modulus) [Pa].

The storage modulus and the loss modulus [8] are expressed by the equations (9) and (10):

$$E' = \frac{\sigma_0}{\varepsilon_0} \cdot \cos \delta [Pa], \quad (9)$$

$$E'' = \frac{\sigma_0}{\varepsilon_0} \cdot \sin \delta [Pa]. \quad (10)$$

The storage modulus is connected with a material stiffness. The loss modulus is associated with energy dissipation into heat, i.e. with damping properties of materials during dynamic stress. Then the complex modulus of elasticity E^* [9] is described by the equation (11):

$$E^* = E' + i \cdot E'' [Pa]. \quad (11)$$

The material ability to damp mechanical vibration is expressed by the loss factor η [10], which is defined by the formula (12):

$$\eta = \frac{E''}{E'} = \operatorname{tg} \delta [-]. \quad (12)$$

Better damping properties of materials are in general achieved at higher values of the loss factor η , i.e. at the phase angle $\delta \rightarrow \pi/2$. These materials can be applied as base isolators of machinery equipment, vibration isolators in means of transport etc. On the contrary, low damping properties are obtained for the phase angle $\delta \rightarrow 0$ (e.g. metallic materials, concrete and stone). These materials

exhibit a high stiffness and are suitable e.g. in construction and building applications. Viscoelastic properties of materials are influenced by many parameters, e.g. by excitation frequency, temperature, dynamic strain rate, static pre-load, time effects such as creep and relaxation, aging and other irreversible effects [4].

The Eq. (6) can be modified as follows:

Viscoelastic materials are characterized by various states over broad temperature and frequency ranges [4]. Temperature dependencies of viscoelastic parameters for a typical viscoelastic material are shown in Fig. 2a. There are referred four different regions characterizing the behaviour of viscoelastic materials, i.e. glassy (I), transition (II), rubbery (III) and flow (IV) regions. The glassy region is characterized by the highest material stiffness and low material damping properties. The glassy region is changed into the transient region at the glass transition temperature t_g , which is defined by the peak of the loss modulus E'' . There are reached the highest material damping properties in the transition region. The temperature t_0 is used to define the peak of the loss factor in the transition region. It is also evident in this region, that the material stiffness (i.e. the storage modulus E') is in general rapidly decreasing with increasing the operating temperature. In the rubbery region, the material is characterized by a lower plateau in the stiffness and reasonable damping properties (see Fig. 2a). Flow behaviour of viscoelastic materials is obtained at higher temperatures in the flow region. Frequency dependencies (see Fig. 2b) of viscoelastic parameters are different compared to the temperature dependencies. It is evident that the storage modulus E' is in general increasing with increasing the excitation frequency. The loss modulus E'' and the loss factor η have a similar behaviour depending on the excitation

frequency. Firstly, these viscoelastic parameters are increasing with increasing the excitation frequency. From a certain frequency, these quantities are decreasing with increasing excitation frequency. Subsequently in the area of

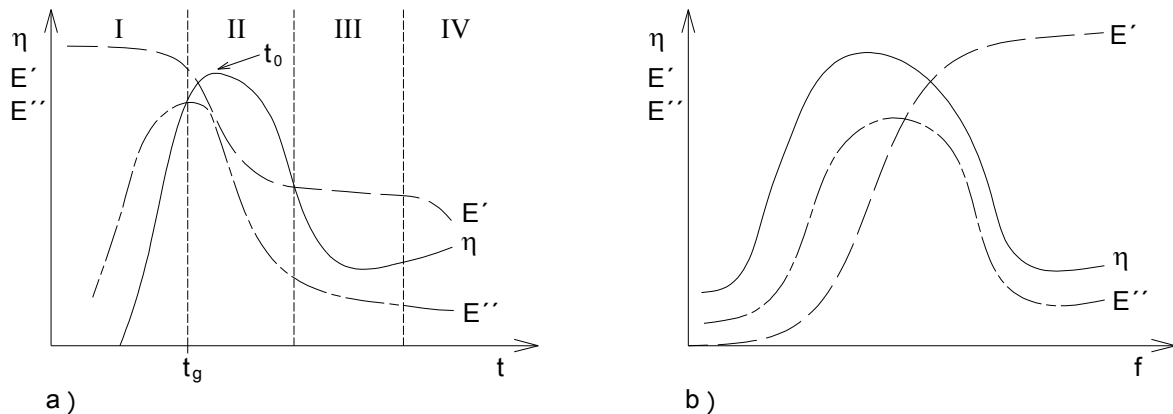


Fig. 2 Temperature (a) and frequency (b) dependencies of viscoelastic parameters for a typical viscoelastic material

The aim of this paper is to investigate viscoelastic damping properties of selected polymers. The influence of excitation frequency, sample deformation, operating temperature and rubber composition on viscoelastic damping properties of the polymer materials was investigated in this paper. The tested materials were compared to each other in terms of their ability to damp mechanical vibration too.

2 Experimental

a. Measurement methodology of viscoelastic parameters

Experimental measurements of frequency and deformation dependencies of the viscoelastic parameters (i.e. η , E' and E'') were performed by the forced oscillation method using Mettler Toledo DMA1 measuring equipment. Schematic representation of the forced oscillation method and time dependencies of the cyclic force F acting on a material sample and the sample deformation x

high excitation frequencies, the loss modulus and the loss factor achieve low values and their changes are negligible (see Fig. 2b).

are shown in Fig. 3. Material samples are clamped between fixed and sliding jaws. Hereat, a cyclic loading is carried out by the sliding jaws. It is evident that the time dependencies of the force F and the deformation x are periodic with maximum values F_0 and x_0 . The force F is in general out-of-phase with the deformation x by the phase angle δ (see Fig. 3). The measurements were realized for the maximum force $F_0 = 10$ N and aren't suitable for materials with low viscoelastic damping properties (e.g. for hard and metallic materials). For this reason the measurements were performed on different types of polymer materials.

The frequency dependencies of the tested materials were measured for the sample deformation $x_0 \cong 10$ μm (see Fig. 3). The deformation dependencies were determined at an excitation frequency of 1 Hz. The viscoelastic parameters of investigated material samples were experimentally measured in the excitation frequency range of 1-251 Hz, in the deformation range of 1-201 μm and in the temperature range from -80 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$.

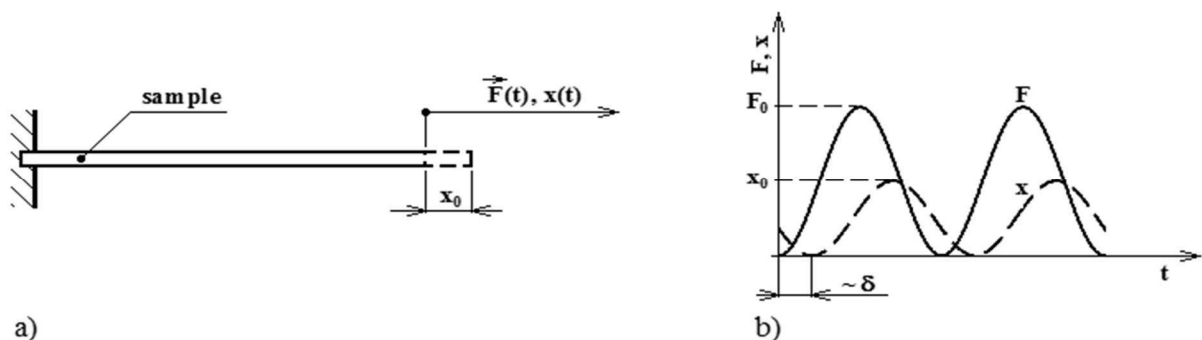


Fig. 3 Schematic representation of forced oscillation method (a) and time dependencies of the acting force F and the sample deformation x during the sample testing (b)

b. Investigated materials

The experimental measurements of the real and imaginary components of the complex modulus of elasticity and the loss factor were performed for different material

types. The designation, characterization and density of the investigated materials are shown in Tab. 1. The detailed compositions of the rubber mixtures are shown in Tab. 2. The rubber components are expressed in phr units

(i.e. parts per hundred rubber), meaning parts of any non-rubbery material per hundred parts of raw gum elastomer

(rubbery material) [11]. The dimensions of the tested materials were (10 × 5 × 1) mm (height × width × thickness).

Tab. 1 Specification of investigated materials

| Material designation | Material characterization | Density ρ [kg·m ⁻³] |
|----------------------|---|--------------------------------------|
| 0 phr | Rubber mixture without silica Perkasil KS-408 concentration | 982 |
| 15 phr | Rubber mixture with low silica Perkasil KS-408 concentration | 1059 |
| 30 phr | Rubber mixture with middle silica Perkasil KS-408 concentration | 1129 |
| 60 phr | Rubber mixture with high silica Perkasil KS-408 concentration | 1252 |
| ABS | Akrylonitrilbutadienstyren | 1180 |
| EVA | Ethylen vinyl acetate | 1042 |
| LDPE | Low-density polyethylene | 919 |
| PP | Polypropylene | 910 |
| PS | Tough polystyrene | 1050 |
| POM | Polyoxymethylene | 1421 |
| PVC | Unsoftened polyvinyl chloride | 1357 |

Tab. 2 Composition of rubber mixtures (in phr)

| Component | Rubber mixture type | | | |
|------------------------|---------------------|--------|--------|--------|
| | 0 phr | 15 phr | 30 phr | 60 phr |
| SBR 1500 | 100 | 100 | 100 | 100 |
| Silica Perkasil KS-408 | 0 | 15 | 30 | 60 |
| Nyflex 228 | 5 | 5 | 5 | 5 |
| ZnO | 5 | 5 | 5 | 5 |
| Rhenogran TMTD 80 | 2 | 2 | 2 | 2 |
| Rhenogran MBTS 80 | 0.5 | 0.5 | 0.5 | 0.5 |
| Sulphur | 2.5 | 2.5 | 2.5 | 2.5 |

3 Measured results and discussion

The measured frequency and deformation dependencies of the viscoelastic parameters (i.e. E' , E'' and η) are influenced by different factors that are evaluated in this

chapter. Examples of these measured dependencies are shown in Fig. 4. The frequency dependence (see Fig. 4a) was measured at the sample deformation amplitude $x_0 \cong 10 \mu\text{m}$. The deformation dependence (see Fig. 4b) was obtained for the excitation frequency $f = 1 \text{ Hz}$.

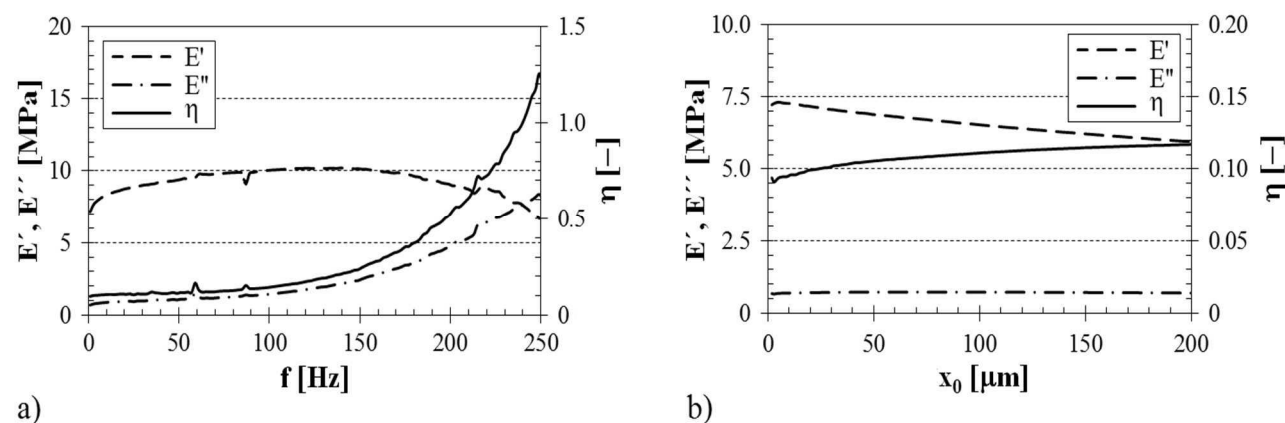


Fig. 4 Frequency (a) and deformation (b) dependencies of viscoelastic parameters for the 30 phr rubber mixture at the temperature $t = 25 \text{ }^\circ\text{C}$.

The effects of the material type on its damping properties at the operating temperature $t = 25 \text{ }^\circ\text{C}$ are shown in Fig. 5. It is evident that the lowest damping properties during dynamic stress are obtained in the case of ABS, PS and POM materials. Low damping properties are also achieved at PVC and PP materials (see Fig. 5a). On the contrary, better damping properties were observed for the

remaining materials, especially for the rubber mixture 0 phr (see Fig. 5b). These facts are related to the macromolecular structure of the studied materials, where better structural damping (see Fig. 5b) is achieved by the mutual movement of adjacent macromolecules during the dynamic stress [12].

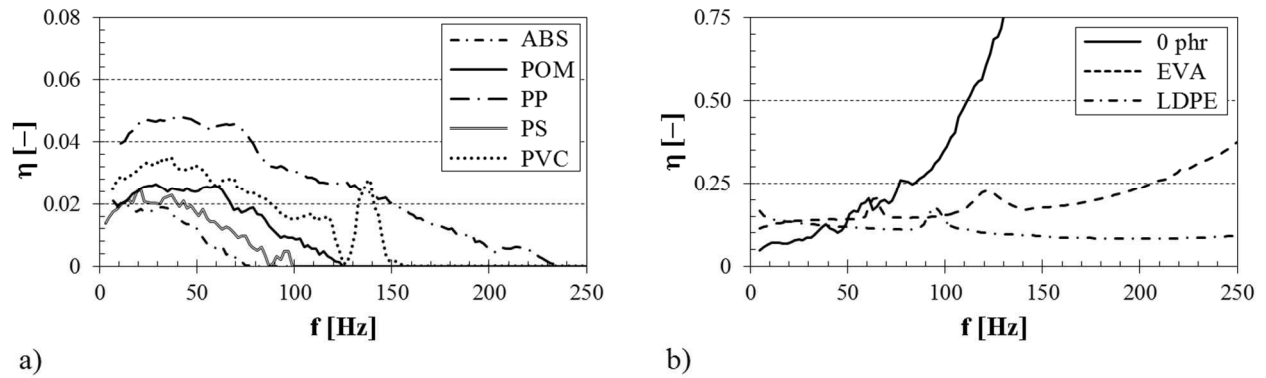


Fig. 5 Frequency dependencies of the loss factor at the temperature $t = 25\text{ }^\circ\text{C}$ and the sample deformation amplitude $x_0 \cong 10\text{ }\mu\text{m}$ for materials with low (a) and higher (b) damping properties

As mentioned above, viscoelastic properties of materials are significantly influenced by the operating temperature. The temperature effect of the excitation frequency on the loss factor for selected materials is shown in Fig. 6. As shown in the case for the rubber mixture of 30 phr, viscoelastic damping of this material decreases in general with increasing the operating temperature. Similar conclusions were obtained for other investigated rubber mixtures and polystyrene. It is caused by the so-called Brownian effect [13], which is manifested by an increased movement of macromolecules with increasing the operating temperature [7]. Contrariwise, the loss factor is in general increasing with increasing the operating temperature, e.g. for LDPE (see Fig. 6), ABS and PVC materials.

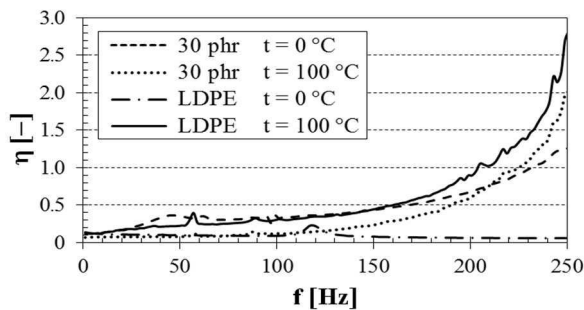


Fig. 6 Effect of operating temperature on loss factor at the sample deformation amplitude $x_0 \cong 10\text{ }\mu\text{m}$

The temperature effect on the viscoelastic parameters of some polymer materials at the sample deformation amplitude $x_0 \cong 10\text{ }\mu\text{m}$ and the excitation frequency $f = 20\text{ Hz}$ is shown in Fig. 7. It is evident from Fig. 7a, that better damping properties are again obtained at silica-filled rubbers, mainly in the temperature range between -40 and $0\text{ }^\circ\text{C}$. In the transition region, the long molecular chains of the polymer are in a semirigid and semi-flow state and are able to rub against adjacent chains [4]. Materials with a better viscoelastic damping are featured by lower temperatures t_g and t_0 (see Fig. 2), which is given by the material structure. Below the glass temperature t_g (generally in the range between -40 and $10\text{ }^\circ\text{C}$ depending on the material type – see Fig. 7b), the material is hard, brittle and the Brownian micro-movement ceases. It is manifested by a high material stiffness. The flow region was observed at the operating temperature $t > 100\text{ }^\circ\text{C}$ in the case of the non-cross-linked polymers, i.e. the tested thermoplastics (mainly PS and LDPE materials). The flow region wasn't found for the tested rubber materials, because these materials belong to cross-linked polymer materials, which is given by sulphur bridges. Therefore viscoelastic behaviour of the rubber materials is characterized only by the rubber region at higher operating temperatures.

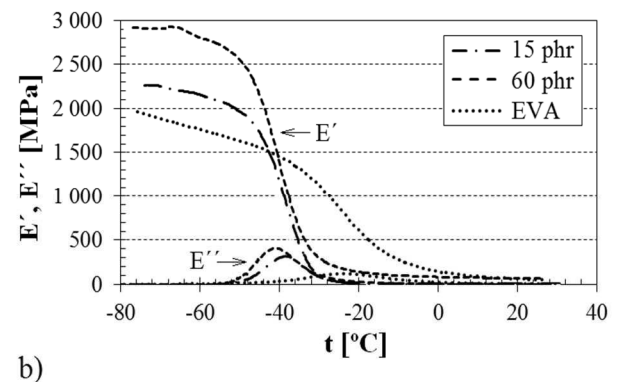
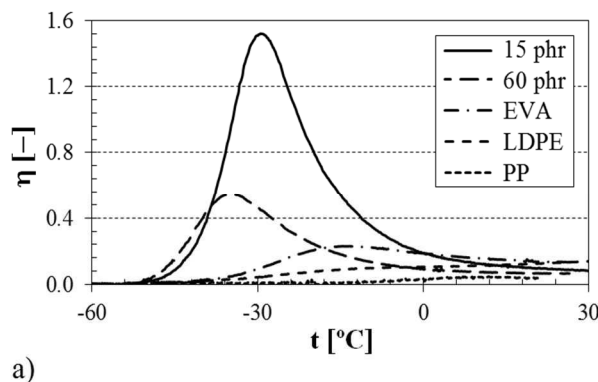


Fig. 7 Effect of operating temperature on loss factor (a) and components of complex modulus of elasticity (b) at the sample deformation amplitude $x_0 \cong 10\text{ }\mu\text{m}$ and the excitation frequency $f = 20\text{ Hz}$

A rubber composition has in general a significant influence on viscoelastic damping too. Fig. 8 shows the deformation dependence of the rubber composition on the loss factor at the temperature $t = 25\text{ }^{\circ}\text{C}$ and at the excitation frequency $f = 1\text{ Hz}$. It is evident that the loss factor increases with increasing sample amplitude for higher filler concentrations of the silica type Perkasil KS-408 in the rubber mixtures. It is caused by filling of a free volume of filler particles between macromolecules. For this reason the applied filler material has a positive influence on damping of mechanical vibration. Similarly, the effect of the rubber composition on the loss factor at the temperature $t = 100\text{ }^{\circ}\text{C}$ and the sample deformation $x_0 = 10\text{ }\mu\text{m}$ is shown in Fig. 9. It is evident that the applied filler in rubber mixture has the opposite effect on viscoelastic damping compared to the previous case. It is visible that the loss factor is in general increasing with decreasing filler concentrations. It is caused by the fact that interaction between macromolecules and the filler is increasing with the increasing filler concentration. For this reason, the internal friction of adjacent macromolecules is decreasing during dynamic stress.

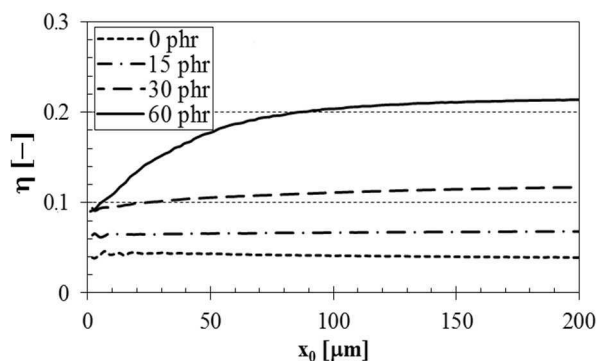


Fig. 8 Deformation dependencies of the loss factor for rubber mixtures at the temperature $t = 25\text{ }^{\circ}\text{C}$ and the excitation frequency $f = 1\text{ Hz}$

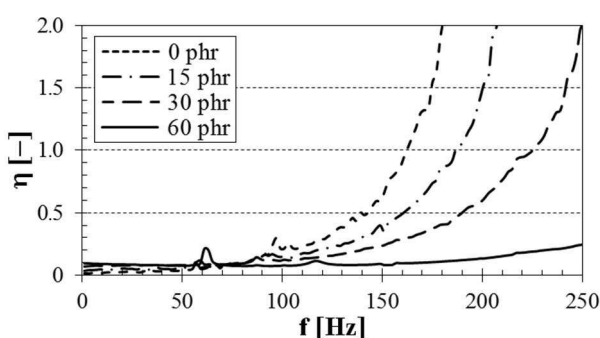


Fig. 9 Frequency dependencies of the loss factor for rubber mixtures at the temperature $t = 100\text{ }^{\circ}\text{C}$ and the sample deformation $x_0 = 10\text{ }\mu\text{m}$

If the excitation frequency at the sample deformation $x_0 = 10\text{ }\mu\text{m}$ increases, it can have positive (see Fig. 9) or negative (see Fig. 5a) influences on viscoelastic damping. There was also investigated the effect of the excitation frequency on viscoelastic damping for different sample deformations in this paper. Fig. 10 shows the effect of two different excitation frequencies (i.e. 1 Hz and 15 Hz) for

the rubber sample 60 phr at the operating temperature of $100\text{ }^{\circ}\text{C}$ on the loss factor. It is evident that better viscoelastic damping was in general found at the higher excitation frequency (i.e. at $f = 15\text{ Hz}$). At higher excitation frequencies, macromolecules are not able to respond to changes in the loading direction. It is accompanied by a higher internal friction and better material damping properties during dynamic stress.

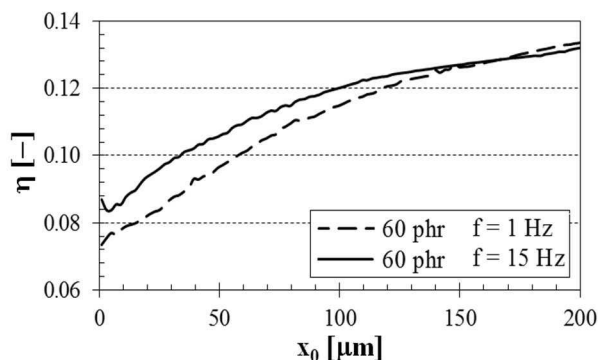


Fig. 10 Effect of the excitation frequency on the loss factor at the temperature $t = 100\text{ }^{\circ}\text{C}$ for the sample 60 phr

The sample deformation at the excitation frequency $f = 1\text{ Hz}$ has influence on viscoelastic damping too. It was found that the deformation effect on viscoelastic material damping is less pronounced (see Fig. 8 and Fig. 10) compared to the excitation frequency effect (see Fig. 9). More pronounced changes of the loss factor were only observed at low deformations during dynamic loading of the investigated materials.

4 Conclusion

This work was focused on viscoelastic material damping that is connected with transformation of mechanical energy into heat during dynamic loading of a material. Viscoelastic damping is characterized by the loss factor, which is considered as a measure of a material structural damping during the dynamic loading. Experimental measurements of viscoelastic damping of different materials were performed by the forced oscillation method using Mettler Toledo DMA1 measuring equipment. It was found in this study that the material ability to damp mechanical vibration is influenced by excitation frequency, sample deformation, operating temperature and material composition. It was also observed in terms of the excitation frequency, that the loss factor of harder materials (as is ABS, PVC, POM etc.) is relatively small. A maximum value of the loss factor is in general achieved at low excitation frequencies ($f_{max} \rightarrow 50\text{ Hz}$). Subsequently, the loss factor of these materials is decreasing with increasing the excitation frequency. But in the case of more elastic materials (as is EVA and rubber), the loss factor increases significantly with increasing the excitation frequency. It was found that the studied rubber materials are characterized by rubber behaviour compared to the tested thermoplastics. For this reason the rubber materials embody better damping properties above the glass temperature and belong to more suitable materials in terms of viscoelastic damping in comparison with the thermoplastics.

The viscoelastic behaviour of the rubber materials is also significantly influenced by their material composition. There was investigated the effect of the silica Perkasil KS-408 concentration on the viscoelastic damping in this work. It can be concluded that the loss factor was decreasing with the increasing silica filler concentration at the constant sample deformation of 10 μm and the increasing excitation frequency. The opposite trend was observed at the constant excitation frequency of 1 Hz and the increasing sample deformation. Low density, resistance to corrosion, form adaptation and lower prices of filled rubber belong to further advantages of the studied filled rubber materials.

Acknowledgements

This work was supported by the European Regional Development Fund in the Research Centre of Advanced Mechatronic Systems project, project number CZ.02.1.01/0.0/0.0/16_019/000867 within the Operational Programme Research, Development and Education and by a grant IGA/FT/2017/007.

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10.21062/ujep/132.2018/a/1213-2489/MT/18/3/523

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