Self-Heating of Filled Rubber during Cyclic Loading

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Abstract: The self-heating rubber behaviour is studied during a cyclical loading. Cylindrical samples of two types of filled rubber material (70 and 80 Shore A) were submitted to the compressive cyclical strain controlled loading. Temperature change was measured in the centre of samples and the dissipated energy was determined. Loading continued until the equilibrium of temperature was reached. Changes of storage and loss moduli and of loss tangent were determined by means of DMA. All these quantities first diminished in course of loading and then attained steady values.

Keywords: filled rubber; cyclical loading; self-heating; dynamical moduli.

1 Introduction

Filled rubbers have in general low heat conductivity and quite high hysteretic losses in course of cyclic loading. These features lead to considerable self-heating and to the rise of temperature which is the cause of the decrease of modulus and also of the decrease of inner damping of rubber. The fatigue endurance and the strength of rubber decline with the rising temperature as well.

The change of the temperature is the result of the competition between hysteretic self-heating and the heat dissipation to surrounding environment. The quantum of heat released during one cycle is proportional to the dissipated energy of deformation which is irreversibly lost due to the hysteresis. The dissipated energy depends on the test conditions. The heat dissipation to the surrounding depends on the gradient of temperature and on the heat transfer coefficients.

Two types of cyclic test are used in practice: strain controlled with constant strain amplitude ε_0 and stress controlled with constant stress amplitude σ_0. Since the temperature rise leads to the fall of modulus, the strain controlled test results in the decrease of the stress amplitude and, subsequently, in the decrease of hysteresis. In this case the temperature attains steady value quite soon. On the other hand, when the stress control is used, the strain amplitude increases and the dissipation of energy and heat release increase too [1].

2 Experiment

The strain controlled compressive cyclic tests were performed on filled EPDM rubbers Tab. 1 with different hardness: B samples with 70 Shore A and D samples with 80 Shore A. The samples were cylindrical of 20mm diameter and 20 mm height. The compressive preload was 4 mm, the amplitude was 0.5 mm and the frequency was 10 Hz. The sampling frequency was 1 kHz. Temperature was measured by a thermocouple in the centre of specimen and recorded every 1 min till the steady state at 16 min approximately. Every 60 seconds, 20 cycles of force versus displacement were recorded for the purpose of dynamic mechanical analysis [2]. The dynamic mechanical analysis (DMA) is well suited for the identification of the short-time range of rubber response. DMA consists of dynamic tests, in which the force response to a sinusoidal strain controlled loading is measured. DMA tests under sinusoidal tension mode were carried out on an electro-dynamic testing machine Instron ElectroPuls E3000 equipped with an environmental chamber and with WaveMatrix software. Raw test data were recorded and evaluated in the Matlab Signal Processing Toolbox.

Tab. 1: Tested samples.

sample	B	D
number	5	5
Shore A	70	80
dimensions	20/20	20/20

2.1 Cyclical Loading

Cylindrical samples are loaded by a prescribed compressive axial displacement which consists of a harmonic component superposed on a static preload. When a viscoelastic material is subjected to a sinusoidally varying strain after some initial transients the stationary stress-response will be reached in which the resulting stress is also sinusoidal, having the same angular frequency but advanced in phase by an angle δ. Then the strain lags the stress by the phase angle δ. The axial displacement $u(t)$ consists of a static pre-strain u_0 under tension which is superimposed by small sinusoidal oscillations:

$$u(t) = u_0 + \Delta u \sin(2\pi ft). \tag{1}$$

Stresses and strains are calculated with respect to the reference geometry [3] of the pre-deformed specimen

$$\varepsilon_0 = u_0 / (L_0 + u_0), \quad \Delta\varepsilon = \Delta u / (L_0 + u_0), \tag{2}$$

where L_0 is the undeformed length of the specimen. The force response $F(t)$ of the specimen is a harmonic function and can be written as:

$$F(t) = F_0 + \Delta F \sin(2\pi ft + \delta). \tag{3}$$

F_0 is the static force depending only on the pre-deformation u_0. The force amplitude ΔF and the phase angle δ depend, in general, on the pre-deformation, the frequency and the strain amplitude [4].

If the incompressibility of the rubber is assumed $A_0L_0 = A(L_0+u_0)$, where A_0 is the cross-sectional area of the undeformed specimen, we can relate the force to the cross-sectional area A of the pre-deformed specimen:

$$\sigma(t) = \frac{F(t)}{A} = \sigma_0 + \Delta\sigma\left[\cos\delta \sin(2\pi ft) + \sin\delta \cos(2\pi ft)\right]. \tag{4}$$

The dynamic stress-response $\sigma(t)$ normalized by the deformation amplitude $\Delta\varepsilon$ can be written:

$$\sigma(t) = \sigma_0 + \Delta\varepsilon\left[E'(\varepsilon_0, f, \Delta\varepsilon)\sin(2\pi f t) + E''(\varepsilon_0, f, \Delta\varepsilon)\cos(2\pi f t)\right], \tag{5}$$

where

$$E'(\varepsilon_0, f, \Delta\varepsilon) = \frac{\Delta\sigma}{\Delta\varepsilon}\cos(\delta), \tag{6}$$

and

$$E''(\varepsilon_0, f, \Delta\varepsilon) = \frac{\Delta\sigma}{\Delta\varepsilon}\sin(\delta) \tag{7}$$

are the storage and dissipation moduli respectively and δ is the phase angle. The phase angle was determined using linear viscoelastic theory by discrete Fourier transform in Matlab. In the course of loading an increase of temperature was observed due to a part of the dissipated work. The temperatures of samples increase in the course of tests and reach their steady state after 10^4 cycles approximately see Fig. 1. Area of hysteresis loop which characterises the dissipated energy decreases during the test and its inclination diminished see Fig.2. This means that the stress amplitudes and dynamic moduli decrease due to the increase of temperature. The storage modulus, the loss modulus in Fig.3 and loss angle in Fig. 4 have similar decreasing trend.

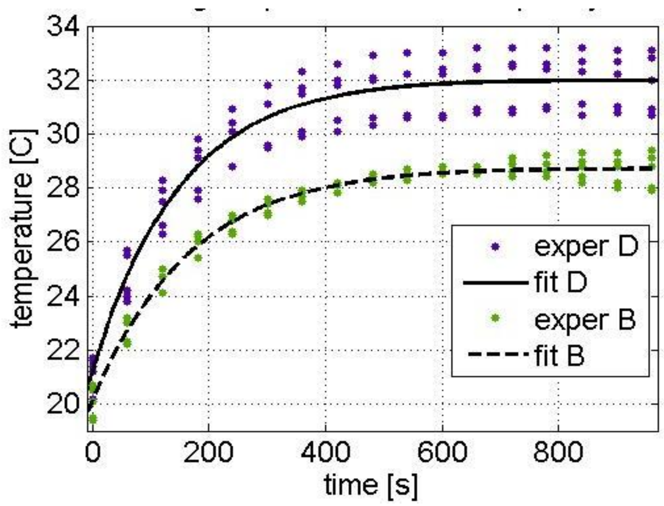


Fig. 1: Rise of temperatures during the cyclic loading at 10Hz - rubber B /70 Sh A and rubber D/80 Sh A

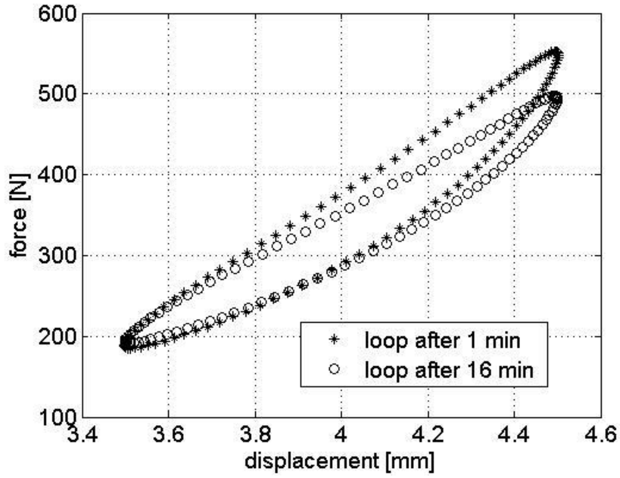


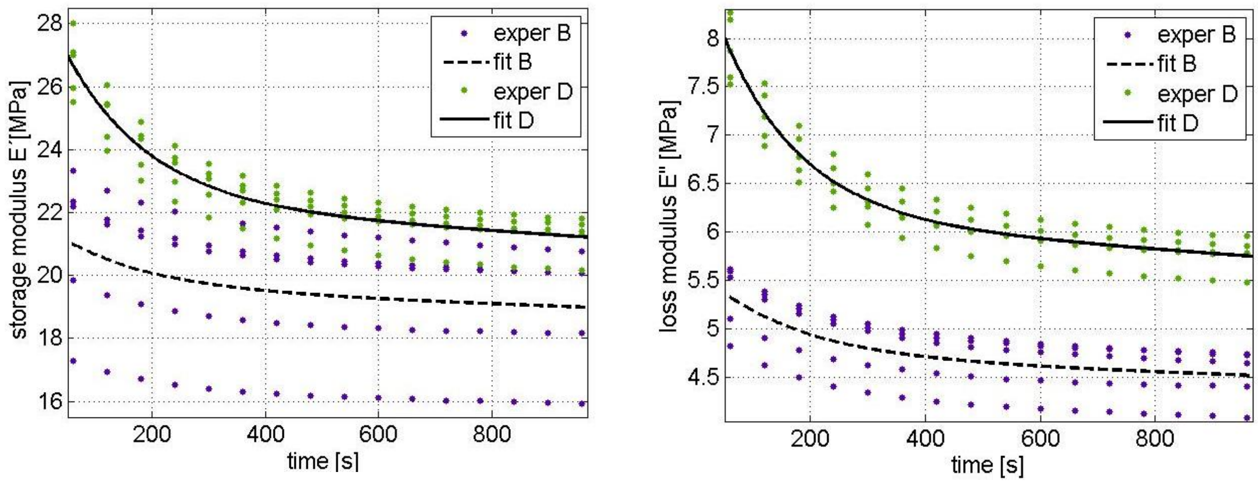
Fig. 2: Evolution of hysteresis loop during a test at 10 Hz - sample of rubber B.

2.2 Hysteretic Heating

The area of hysteresis loop corresponds to the energy dissipated in the cycle which is transformed partially into heat. The area of loop was determined in every loading cycle from the stored data. The values of dissipated energy per cycle decrease almost exponentially and reach the steady state after 10^4 cycles see Fig. 5. The steady state results from the balance in the heat generated by the dissipation of work and the heat drain to the surroundings. Studies of self-heating of polymers and rubbers [5-7] showed that only a certain part - around 55% of the dissipated work is converted to heat. The evolution of the temperature θ is governed by the heat equation

$$\rho c \frac{\partial \theta}{\partial t} - \kappa \Delta \theta = \dot{\mathrm{Q}}, \qquad (8)$$

where ρ is density, c is specific heat, κ is thermal conductivity and $\dot{Q}$ is dissipated power per unit volume.



a) storage modulus

b) loss modulus

Fig. 3: Dynamical moduli decreasing due to temperature rise during cyclic compressive tests at 10 Hz.

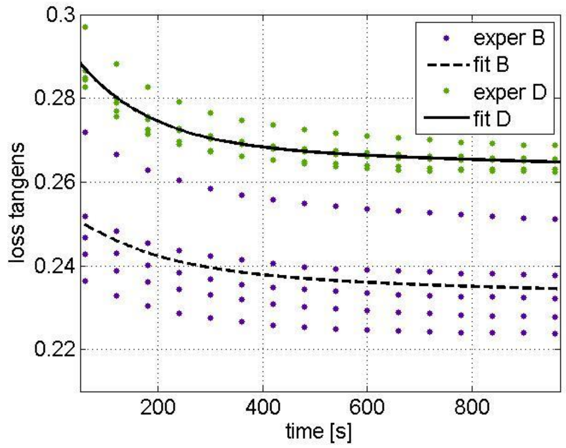


Fig. 4: The loss tangent decreasing slowly due to self-heating of rubber samples at 10 Hz .

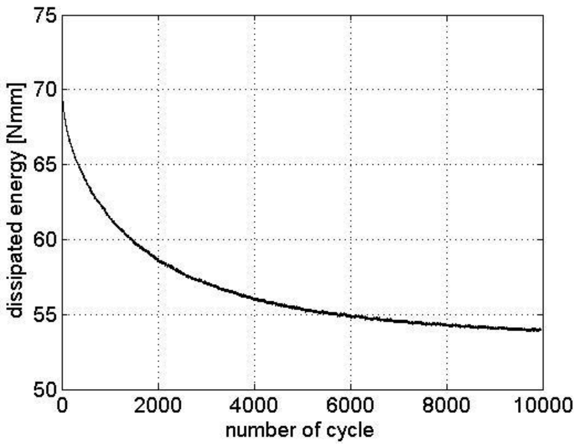


Fig. 5: Area of hysteresis loop in every cycle at 10 Hz - the steady state after 10^4 cycles.

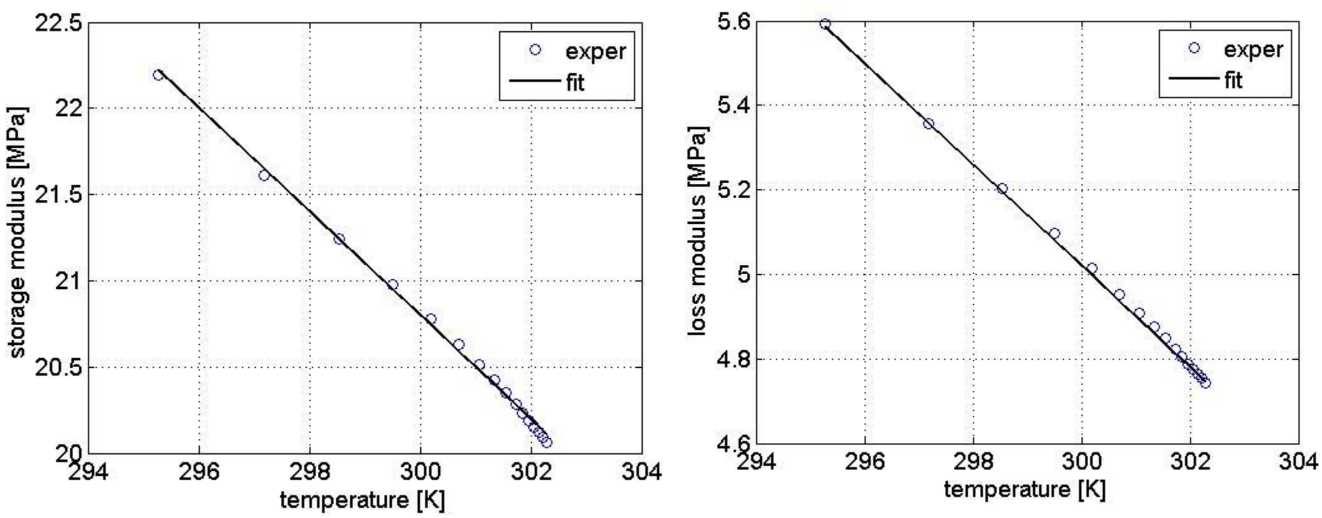
The thermal boundary conditions are of two types. The loading grips are coated by Teflon to reduce friction and the thermal state here can be considered as adiabatic. The heat convection should be considered at the cylindrical surface:

$$\kappa \frac{\partial \theta}{\partial r} + \lambda\left(\theta - \theta_0\right) = 0 \quad \text{at} \;\; r = R. \tag{9}$$

The evaluation of the nonlinear transient heat transfer problem will be the subject of finite element analysis. The thermo-mechanical coupling will be also considered.

2.3 Changes in Material Properties

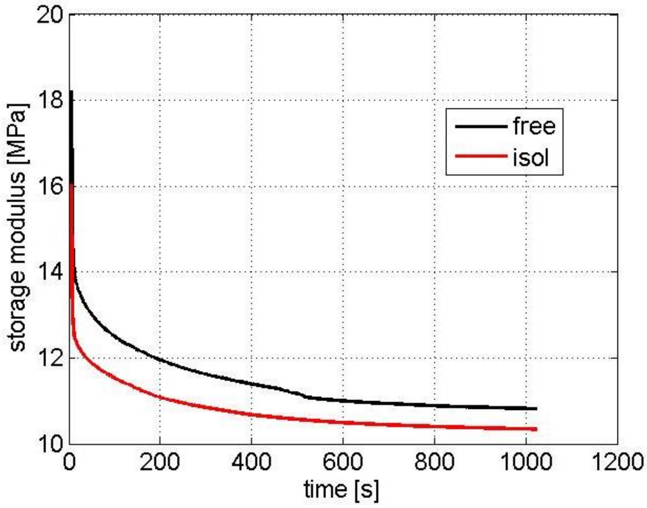
The dynamical moduli and the loss angle as well as the area of hysteretic loops depend inversely on the rising temperature caused by self-heating see Figs.3-5. This dependency can be approximated by a linear function as can be seen in Fig. 6.



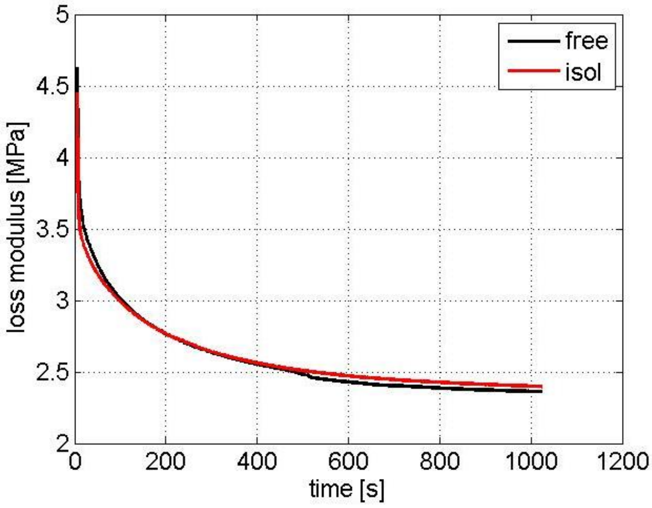
a) storage modulus

b) loss modulus

Fig. 6: Decrease in dynamical moduli of rubber B as the function of rising temperature during cyclical loading at 10 Hz.



a) decreasing storage modulus - rubber B, storage modulus is slightly higher for free convection



b) decreasing loss modulus - rubber B, no apparent difference in loss modulus

Fig. 7: Dynamical moduli in cyclic compressive test of rubber B at 20 Hz. Convection of heat was either free at cylindrical surface or the surface was insulated thermally.

The influence of the loading frequency was studied on the same type of cylindrical rubber samples of diameter and height 20 mm. The loading frequency was 20 Hz, the compressive prestrain u_0 was 4mm and the amplitude Δu was 0.5 mm. To determine the effect of heat transfer to the surrounding, the lateral surface of some samples was thermally isolated. The values of dynamical moduli and loss angle fall very steeply in the beginning of loading and are lower in comparison with those for the 10 Hz frequency see Fig. 7 and 8. The biggest difference is in the dissipated energy for the frequencies 10 Hz and 20 Hz but the thermal insulation did not have any significant impact on the area of hysteresis loops see Fig. 9. The temperature raised by 12 K in the free sample and by 16 K in the insulated sample.

3 Conclusion

The mechanical properties of hard rubbers (70 and 80 Shore A) and the self-heating were studied in the cyclic compressive tests with the strain control. Rubber D of higher hardness exhibits higher energy dissipation under cyclic loading. It leads to the heat generation, to the temperature rise and to decrease in the dynamic modulus and loss angle. All monitored quantities reached steady state after approximately 10^4 cycles in the strain controlled loading.

The heat generation depends on the energy dissipation due to nonlinear viscoelastic properties of rubber. The energy dissipation is proportional to the area of hysteresis loops – Lissajous curves. The area depends on the loss modulus of rubber and on temperature. The results of strain-controlled experiments show the dependence of the energy dissipation on the temperature, on frequency, on preload and on the amplitude of cyclic loading. The mechanical properties are temperature dependent.

The self-heating depends on the dissipated energy and on the heat transfer to surrounding environment. The thermal insulation leads to higher self-heating of rubber elements.

In practical engineering applications the rubber dampers are subjected to dynamic loading superimposed on a preload such as weight of engine or vehicle. Such cyclic loading is rather force controlled. In such case the heat generation and the temperature rise can attain quite high level which can significantly affect the properties of rubber damping elements and lead to a catastrophic failure.

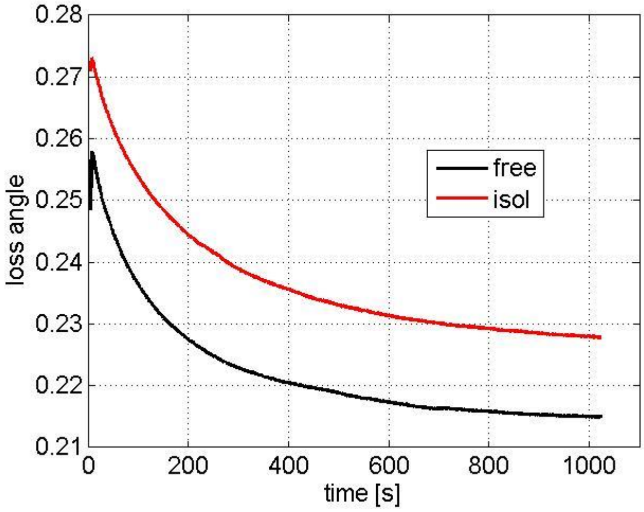


Fig. 8: Loss angle in cyclic compressive test of rubber B at 20 Hz – difference for free and prevented heat convection.

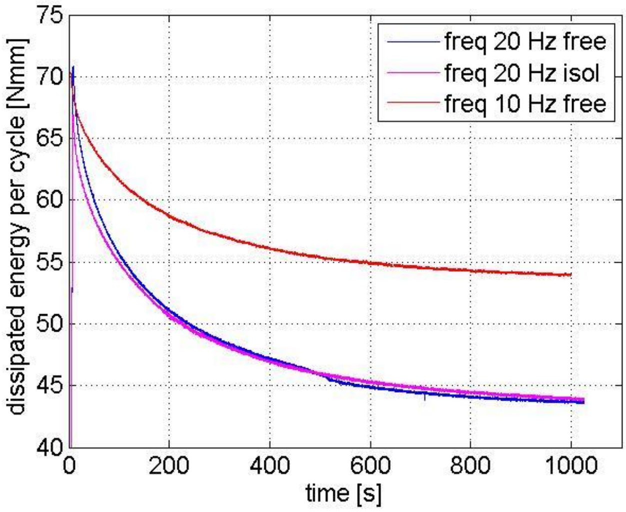


Fig. 9: Comparison of the evolution of the area of hysteresis loop in cyclic tests – rubber B.

Acknowledgement

This work was supported by national financial resources of Ministry of Education Youth and Sports of Czech Republic for specific university research (SGS 21120).

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