Effects of Pre-strain, Strain Amplitude and Frequency on Dynamic Compressive Properties of Magnetorheological Elastomeric Composite

T.H. Nam[1,*], I. Petríková[1], B. Marvalová[1]

[1] *Faculty of Mechanical Engineering, Technical University of Liberec, Studentská 1402/2, 461 17 Liberec 1, Czech Republic*

[*] *nam.tran.huu@tul.cz*

Abstract: Dynamic compressive properties of isotropic magnetorheological elastomeric composite (MEC) under cyclic compression loading have been studied in this paper. Effects of pre-strains from 5 to 20%, strain amplitudes from 0.01 to 0.04, and excitation frequencies from 10 to 50 Hz on the dynamic properties of isotropic MEC under harmonic cyclic compression loading were examined. Results showed that the storage and loss moduli of the isotropic MEC decreased with increasing the strain amplitude, but they enhanced with the rise of the pre-strain and frequency. Although the storage modulus of the MEC changed slightly over time, the loss modulus reduced somewhat with increasing time. The reduction in the loss modulus of the MEC under cyclic compression loading is attributed to increasing material temperature during the testing. Besides, despite the loss angle tended to reduce over time, it changed irregularly with raising the pre-strain, strain amplitude, and frequency as well. In general, the dynamic compressive properties of the MEC strongly depended on the pre-strain, strain amplitude, and frequency of cyclic loading.

Keywords: magnetorheological elastomer; composite materials; dynamic properties; cyclic compression test.

1 Introduction

Magnetorheological elastomeric composites (MECs) have been produced by introducing ferromagnetic particles into a non-magnetic elastomeric matrix. The MECs belong to a group of smart materials, because their rheological and mechanical properties can be controlled by applying an external magnetic field [1]. MECs exhibit a change in their stiffness and damping properties under the magnetic field. With their changing and controllable properties, MECs have been used in a broad range of engineering field applications [2]. MECs are considered to be viscoelastic rubber-like materials, thus they inherit predominant properties of the rubber matrix such as large deformations, stress softening effect, amplitude and frequency dependency, and time-dependent features. Therefore, studies of the dynamic mechanical properties of MECs under various loading conditions are essential for engineering applications.

The viscoelastic mechanical properties of MECs have been extensively studied during the past decade. The measurement of viscoelastic mechanical properties of MECs has been carried out by using either transient or dynamic mode [3–5]. The dynamic mechanical properties of MECs depend on constituent material properties and loading conditions such as preloads, frequency, and amplitude. Besides, the dynamic mechanical properties of MECs can be studied by the equations typically for viscoelastic materials. In this paper, the isotropic MEC was produced from a silicone matrix and micro-sized carbonyl iron powders (CIPs). The main objective of this paper is to study the dynamic properties of the isotropic MEC cylindrical samples subjected to cyclic compression loading. Effects of the pre-strain, strain amplitude, and excitation frequency on the dynamic properties of the isotropic MEC under harmonic cyclic compression loading were examined.

2 Experimental

2.1 Materials

Micro-sized CIPs, silicone rubber ZA13 and its catalyst were used to fabricate the isotropic MEC. The micro-sized CIPs (type: 44890) were supplied by Sigma-Aldrich (USA). The micro-sized CIPs have overall spherical shapes with 2–5 μm ($\geq$ 99.5%) in diameter. The silicone rubber ZA13 and its catalyst were created by Zhermack S.P.A (Italy) and were provided by Havel Composites Ltd. (Czech Republic).

2.2 Processing of isotropic MEC

The isotropic MEC samples were produced as follows. To begin with, the silicone rubber ZA13 mixed with its catalyst in the weight ratio of 1:1. Subsequently, the CIPs with a volume fraction of 27% were added to the mixture. The mixture was then throughout stirred in a glass cup and was put in a vacuum chamber for about 15 min to eliminate air bubbles trapped during the mixing process. Next, the mixture was poured into a plastic mold and was placed in the vacuum chamber for about 10 min to remove thoroughly air bubbles trapped inside the mixture. Lastly, the mixture in the mold was cured for 24 h at room temperature (RT) to create isotropic MEC samples. Microstructural morphology of the MEC can be found in our earlier reports [3–5].

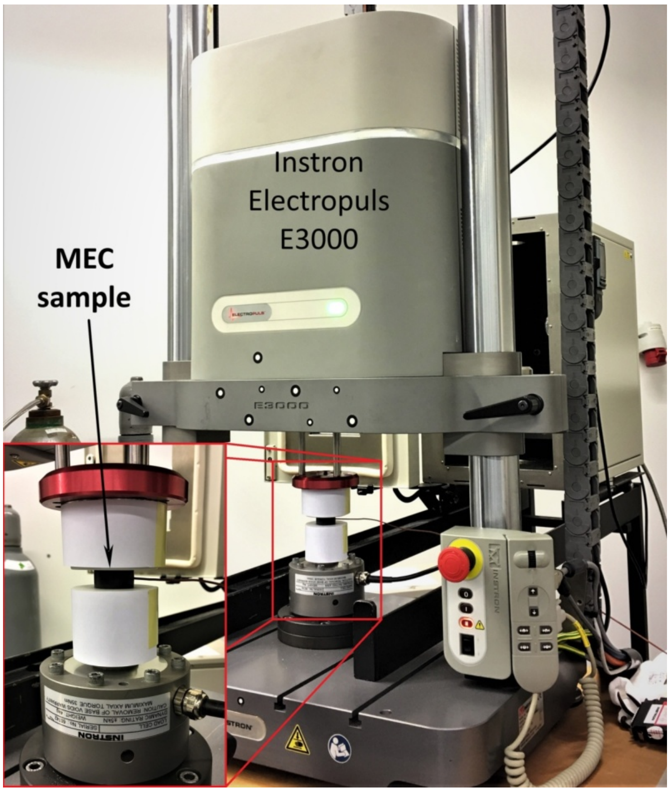

Fig. 1: The experimental setup of cyclic compression test for the MEC samples.

2.3 Cyclic compression test

The cyclic compression test for the MEC samples was performed under harmonic sinusoidal loading in the displacement control mode using Instron Electropuls E3000 testing system (Instron Corp., MA, US). The experimental setup of the cyclic compression test for the MEC samples is depicted in Fig. 1. The dynamic properties of the MEC were measured through cyclic compression tests for 120 min with various pre-strains from 5 to 20%, and strain amplitudes from 0.01 to 0.04, and frequencies from 10 to 50 Hz. Twenty cycles of force and displacement were recorded every 120 sec for dynamic mechanical analysis of the MEC.

2.4 Characterization of the MEC dynamic properties

The cyclic compression test under harmonic sinusoidal loading is conducted to characterize the dynamic properties of the isotropic MEC specimens. Therefore, the compressive stress and strain of the isotropic MEC samples will vary sinusoidally with the same angular frequency ω in the steady condition after initially several cycles. However, the compressive stress and strain will lag by a phase angle δ (loss angle).

The isotropic MEC specimens were loaded in the cyclic compression with a sinusoidal displacement-controlled process $u(t)$ of the following form:

$$u\left(t\right) = u_0 + \Delta u \, \sin\left(2\pi f t\right), \tag{1}$$

where u_0 is the static pre-displacement, Δu is the displacement amplitude, and f is the excitation frequency.

To calculate stresses and strains the pre-deformed specimen was chosen as the reference geometry. The sinusoidal strain in the reference geometry was described as follows [6,7]:

$$\varepsilon\left(t\right) = \frac{u(t)}{L_0} = \varepsilon_0 + \Delta\varepsilon \, \sin\left(2\pi f t\right), \tag{2}$$

where $L_0 = L_u - u_0$ is the pre-deformed sample length, L_u is the un-deformed length, $\varepsilon_0 = u_0/L_0$ is the pre-strain, and $\Delta\varepsilon = \Delta u/L_0$is the dynamic strain amplitude.

The force response $F(t)$ can be written as a harmonic sinusoidal function in Eq. 3.

$$F\left(t\right) = F_0 + \Delta F \, \sin\left(2\pi f t + \delta\right), \tag{3}$$

where F_0 is the static force depending only on the pre-strain. The force amplitude ΔF and the phase angle δ depend on the pre-strain, frequency, and strain amplitude [6].

The isotropic MEC is assumed to be an incompressible material, i.e. $A_u L_u = A_0 L_0$ in which A_u and A_0 are cross-sectional areas of un-deformed and pre-deformed specimens. The dynamic stress response $\sigma(t)$ can calculate by dividing the force by the cross-sectional area of the pre-deformed specimen:

$$\sigma\left(t\right) = \frac{F\left(t\right)}{A_0} = \sigma_0 + \Delta\sigma\left[\cos\delta \sin\left(2\pi f t\right) + \sin\delta\cos\left(2\pi f t\right)\right], \tag{4}$$

where σ_0 is the static stress and $\Delta\sigma$ is the stress amplitude.

The dynamic stress response $\sigma(t)$ normalized by the strain amplitude $\Delta\varepsilon$ can be written as [6,7]:

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

where E' is the storage modulus and E'' is the loss modulus.

Storage and loss moduli are determined according to the standard ISO-4664 as:

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

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

The loss tangent ($\tan\delta$) is the ratio of the loss modulus E'' to the storage modulus E'. The loss angle δ was determined using the discrete Fourier transform (DFT) at the main excitation frequency [3,4]. The amplitudes of the compressive stress and strain were determined from experimentally recorded signals.

The storage modulus shows the MEC capability to store the strain energy, which contributes to the MEC stiffness. The loss modulus indicates the ability of the MEC to dissipate the strain energy. Therefore, the loss modulus can be estimated from the dissipated energy [3,4]. The dissipated energy D in a loading cycle is expressed as:

$$D = \int_0^T \sigma\left(t\right)\dot{\varepsilon}\left(t\right)dt = \pi\Delta\varepsilon^2 E^* \sin\delta = \pi\Delta\varepsilon^2 E''. \tag{8}$$

3 Results and discussion

3.1 Effects of pre-strains on the MEC dynamic compressive properties

The dynamic compressive properties of the MEC specimen under the cyclic loading at the frequency of 50 Hz, the strain amplitude of 0.03, and different pre-strains from 5 to 20% were measured for 120 min corresponding to 360,000 cycles. Typical stress-strain hysteresis loops of the isotropic MEC sample at various pre-strains were presented in Fig. 2a. The storage and loss moduli and the loss angle versus time at various pre-strains were described in Figs. 2b-2d. As Fig. 2a shows, the area and slope of the MEC hysteresis loops increase with increasing the pre-strain. It is clearly observed the beak of hysteresis loop for 5% pre-strain. The beak is a sign to indicate a gap between the grip and the MEC specimen when the grip is moved upwards, thus the compressing force is equal to zero at the end of the unloading cycle. This shows that the sample does not instantaneously return to its original position during unloading.

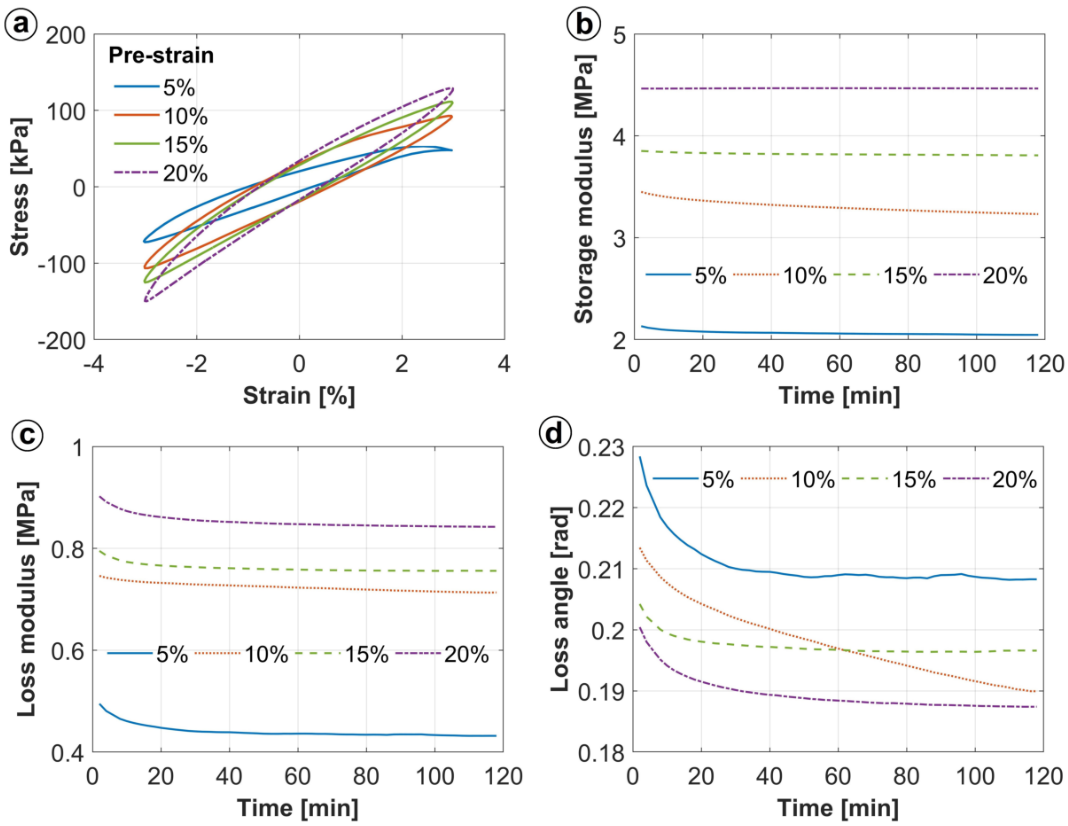

Fig. 2: Typical stress-strain hysteresis loops; (b-d) storage and loss moduli, and loss angle of isotropic MEC under cyclic loading with the frequency of 50 Hz, the strain amplitude of 3%, and various pre-strains.

As seen in Fig. 2, the storage and loss moduli of the MEC enhance with increasing the pre-strain, but the loss angle tends to decrease. Besides, although the storage modulus reduces slightly over time at the pre-strains of 5 and 10%, it almost does not change at the pre-strains of 15 and 20%. The stability of storage modulus appears as a long plateau during 120 min cyclic testing, especially at high pre-strains. The loss modulus declines slightly over time, especially at the beginning period. The loss angle decreases with increasing time, but the change of the loss angle at 10% pre-strain is different from the others. A comparison of loss moduli determined from recorded signals according to Eq. 7 and from the dissipated energy by Eq. 8 was shown in Fig. 3. The values of loss modulus calculated from the energy dissipation are in very good agreement with those determined from recorded signals. The maximal relative error between such loss moduli is less than 0.2%.

3.2 Effects of strain amplitudes on the MEC dynamic compressive properties

The dynamic properties of the isotropic MEC sample under cyclic compression loading at the frequency of 50 Hz, the pre-strain of 20%, and strain amplitudes from 0.01 to 0.04 were measured for 120 min. Typical stress-strain hysteresis loops, storage and loss moduli, and loss angle of the isotropic MEC specimen under

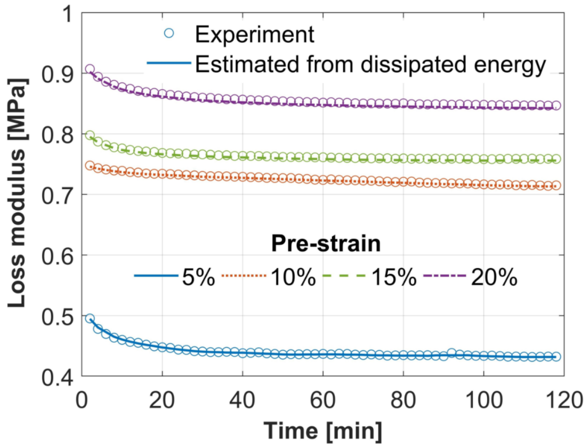

Fig. 3: Loss moduli of the MEC determined from recorded signals according to Eq. 7 and estimated from the dissipated energy by Eq. 8 as functions of time and pre-strain.

cyclic compression loading at strain amplitudes were depicted in Fig. 4. As observed in Fig. 4a, the stress-strain hysteresis loop at low strain amplitudes is nearly elliptic, but it transforms to a non-elliptical shape at high strain amplitudes. This result indicates that the MEC behaves as a nonlinear viscoelastic material at high strain amplitudes. The increase in the strain amplitude results in larger and wider hysteresis loops of the MEC. Besides, the slope of the MEC hysteresis loops slightly decreases with the rise of the strain amplitude, leading to the reduction of the loss modulus (Fig. 4c).

As observed in Figs. 4b-4c, the storage and loss moduli of the MEC reduce with increasing the strain amplitude. The decrease in the storage and loss moduli of the MEC with the rise of the strain amplitude is attributed to increasing the energy of dissipation under cyclic loading, as presented by Tong et al. [8]. Interestingly, the reduction in storage and loss moduli declines with raising the strain amplitude. The loss angle varies irregularly with increasing the strain amplitude (Fig. 4d). Besides, although the storage modulus of the MEC changes slightly during 120 min testing, the loss modulus reduces somewhat over time, especially at the initial period. The change of the loss angle over time is similar to that of the loss modulus. Moreover, the loss moduli calculated from recorded signals are in very good agreement with those determined from the energy dissipation (Fig. 5). The maximal relative error between such loss moduli is less than 0.4%.

3.3 Effects of frequencies on the MEC dynamic compressive properties

The dynamic properties of the isotropic MEC subjected to cyclic compression loading with the pre-strain of 20%, the strain amplitude of 0.03, and different frequencies were measured for 120 min. The stress-strain hysteresis loops, storage and loss moduli, and loss angle of the MEC sample at various frequencies were presented in Fig. 6. Results showed that the increase in the loading frequency results in smaller hysteresis loops. The slope of hysteresis loops enhances slightly with the rise of the frequency. Although storage and loss moduli increase with increasing frequency, the loss angle decreases slightly. Storage and loss moduli grow rapidly with raising the frequency to 30 Hz, and then gain moderately at higher frequencies.

The variation of storage and loss moduli and loss angle of the MEC specimen over time were presented in Fig. 6. Despite the storage modulus changed slightly over time, the loss modulus reduced strongly with increasing the time at the beginning of the test and followed by a slight reduction. The loss moduli determined from recorded signals are in good agreement with those calculated from the energy dissipation (Fig. 7). The maximal relative error between such loss moduli is less than 0.7%. The variation of loss angle over time is similar to that of loss modulus. In general, the dynamic proper-ties of the MEC varied markedly with raising the pre-strain, strain amplitude, and frequency of cyclic loading. Although the storage modulus changed slightly over time, the loss modulus and loss angle decreased with increasing time.

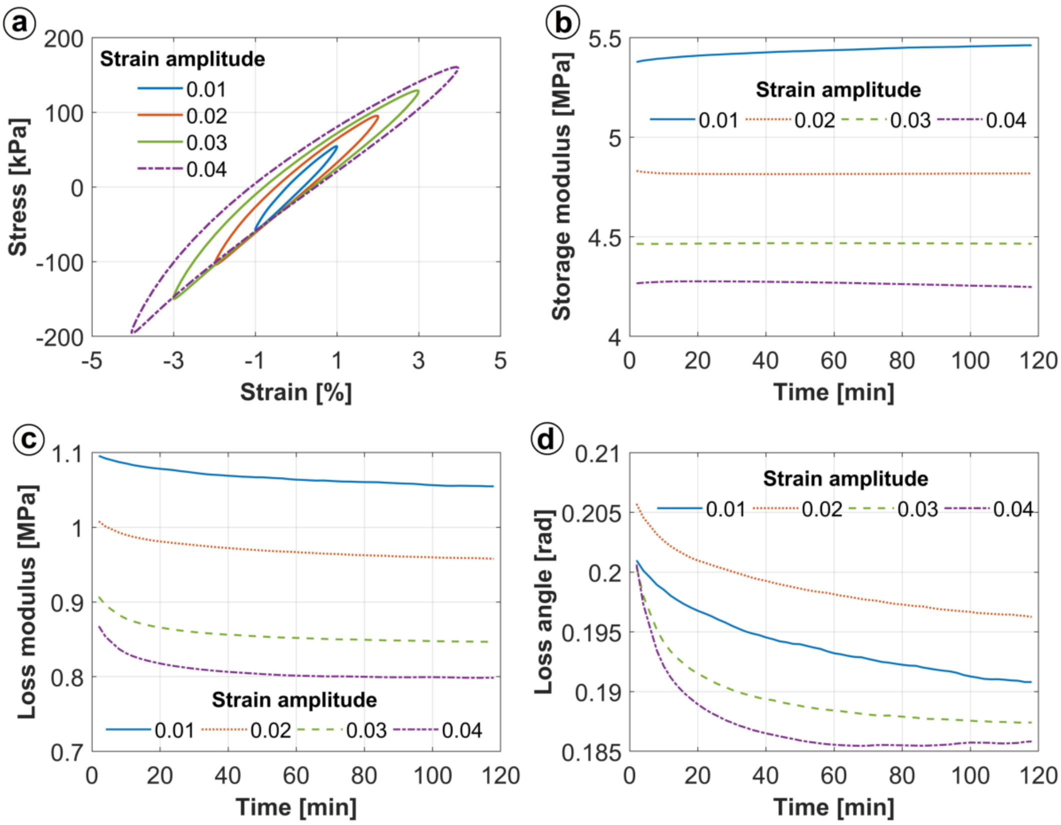

Fig. 4: (a) Typical stress-strain hysteresis loops; (b-d) storage and loss moduli, and loss angle of isotropic MEC under cyclic compression loading with the frequency of 50 Hz, 20% pre-strain, and different strain amplitudes.

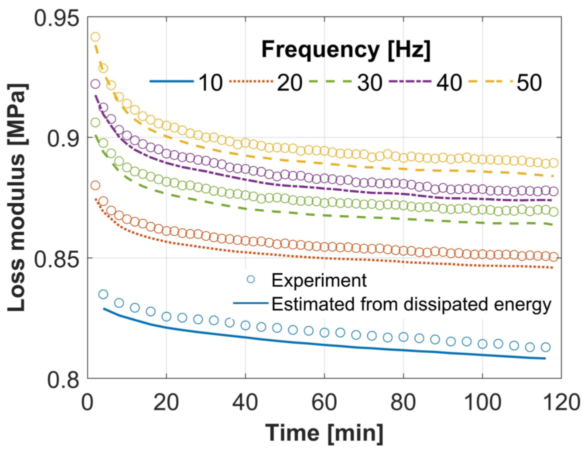

Fig. 5: Loss moduli of the MEC determined from recorded signals according to Eq. 7 and estimated from the dissipated energy by Eq. 8 as functions of time and strain amplitude.

4 Conclusion

The experimental research on the dynamical properties of the isotropic MEC made of the silicone matrix filled with the CIPs under cyclic compression loading has been conducted in this paper. Effects of different pre-strains, strain amplitudes, and loading frequencies on the dynamic properties of the isotropic MEC were investigated. The storage and loss moduli of the isotropic MEC decrease with the rise of the strain amplitude, but they enhance with increasing the pre-strain and frequency as well. Although the storage modulus of the isotropic MEC varies slightly over time, the loss modulus reduces with raising the time. The decrease in the loss modulus of the isotropic MEC under cyclic compression loading is ascribed to increasing material temperature during the testing. In short, the dynamic properties of the MEC under cyclic compression loading strongly depended on the pre-strain, strain amplitude, and excitation frequency.

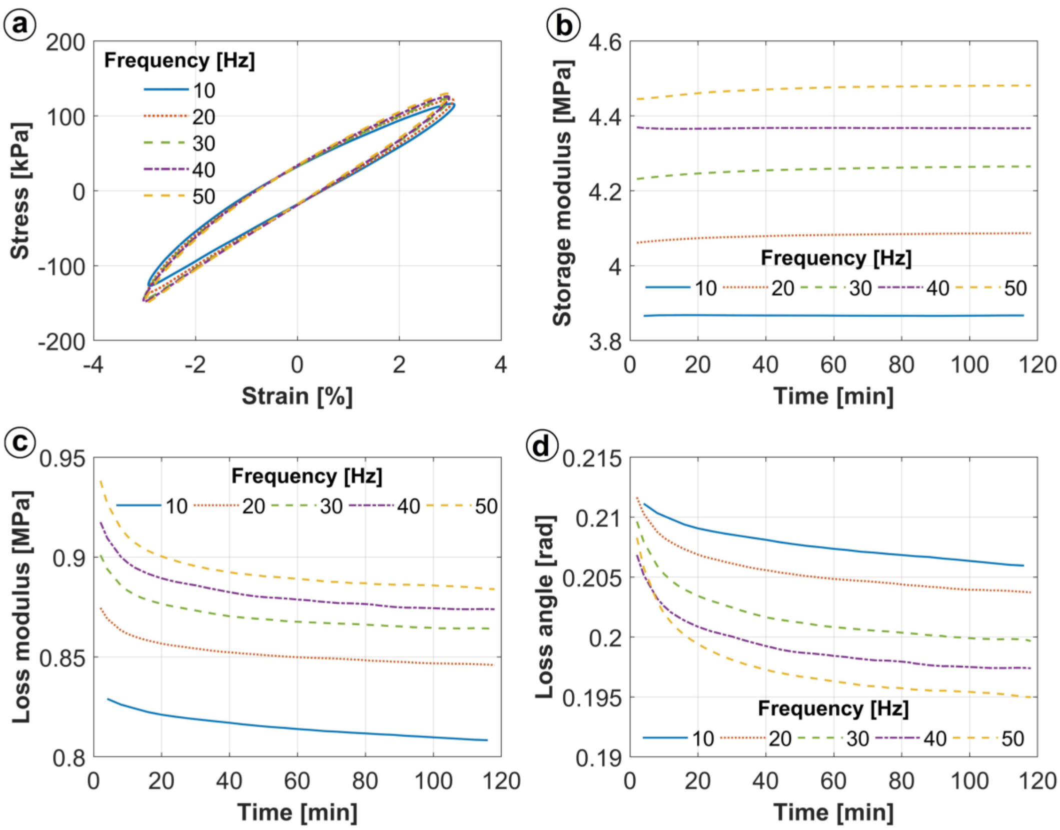

Fig. 6: (a) Typical stress-strain hysteresis loops; (b-d) storage and loss moduli, and loss angle of isotropic MEC under cyclic loading with the pre-strain of 20%, the strain amplitude of 0.03, and different frequencies.

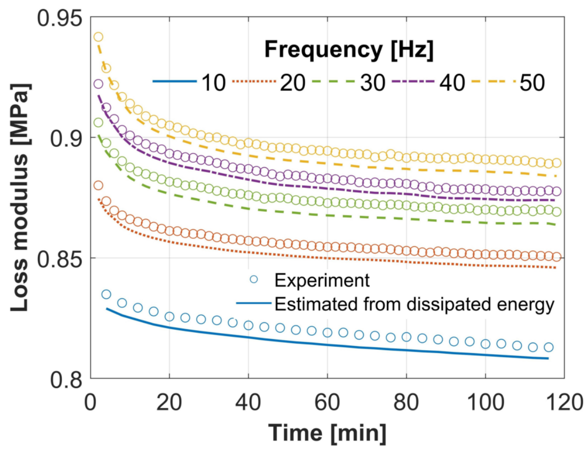

Fig. 7: Loss moduli of the MEC determined from recorded signals according to Eq. 7 and estimated from the dissipated energy by Eq. 8 as functions of time and frequency.

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