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The New Methodology for Assessing of the Applicability of Elastomeric Materials in the Vibration Isolation Systems of Railway Lines

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The technical requirements for the determination of physical parameters of vibration isolating material have not been standardized in Europe and Poland yet, which significantly hinders the ability to compare vibration isolating materials offered on the market. Therefore, there is a need for establishing a norm that could be applied both for the determination of the physico-mechanical properties of elastic vibration isolation elements in rail transport for domestic and foreign producers as well as in their selection for application in a specific vibration isolation system. The paper presents a proposal to standardize the methodology of the estimation of vibration isolation materials physical parameters authorized for use in vibration isolation systems used in rail transport. Methodology for measuring the physico-mechanical parameters of vibration isolating material presented in the paper forms uniform test procedure developed based on a fragmentary norms for flexible materials testing. The use of the proposed research methodology enables the creation of a unified database of elastic materials which parameters will be easy to compare, and choice between them will become easier for designers of vibration isolation systems used in rail transport.

Keywords: vibration isolation systems; elastomeric materials; properties of flexible materials.

1. Introduction

One of the basic issues during projected vibration isolation system is determination of the physico-mechanical properties (Darlow, Zorzi, 1981; Stankiewicz, Targosz, 2015; Targosz, 2007) of one of the basic components of the system which is flexible viroisolating element. These studies include i.e. determination of the static and dynamic module Younge'a, static and dynamic damping factor (in this case the measurement of energy dissipation), aging researches. The studies of these basic mechanical properties were conducted on static and dynamic testing machine Instron 8872 (Fig. 1) which has been classified to class 0.5 of metering devices equipped with climatic chamber working in the temperature range $-100\div350^\circ$C $\pm$ 1°C.

Fig. 1. Static and dynamic testing machine Instron 8872.

The scope of basic research which is to determine the size of selected physical and mechanical properties of materials – the rubber-derived or elastomeric components – for the possibility of their use in vibration isolation systems should include determining the following properties of these materials:

1) volumetric density ρ_0 at room temperature 20±2°C,
2) volumetric porosity p_V,
3) Shore A hardness at room temperature 20±2°C and at temperatures −40, −20, 0, 20, 40, 60°C at speeds of deformation $v = 0.1$ mm/s; 1.0 mm/s; 3.0 mm/s,
4) Young's modulus of material,
5) measurement of the damping coefficient ψ,
6) contractual linear deformation ε_L,
7) contractual quasi-static and dynamic linear elastic modulus E_L for a range of linear deflection $\varepsilon = 0 \div \varepsilon_L$,
8) quasi-static and dynamic stiffness factor k.

In the first stage of the proposed methodology of the study ones should determine the volumetric density of the tested material. Volumetric density ρ_0 of the material should be determined in accordance with applicable standards in this case with Polish norm PN-EN ISO 845:2000 "Rubber and porous plastic material. Determination of volumetric density" from the relationship:

$$\rho_0 = \frac{m_0}{v_0}, \tag{1}$$

where m_0 – sample weight, v_0 – sample volume.

In the second stage of the proposed methodology of the study ones should determine the volumetric porosity of the tested material. Determination of volumetric porosity p_V was carried out in accordance with international standard ISO 4590:1994 "Plastics porous. Determination of the percentage volume of open and closed pores in rigid materials".

The volumetric porosity of the material p_V is a measure of the volume fraction of the pores in the material and is calculated from the relationship:

$$p_V = \frac{V_p}{V_0}, \tag{2}$$

where V_p – pore volume in the sample.

Due to the particle size rubber granules and a small thickness of the boards surveyed the vast majority of the pore is open. In this case, the specific by testing the open porosity virtually equals the porosity volume p_V plate. This observation has been used in this study to determine p_V. The test involves the expulsion of air from the open pores and filling them with water. This is achieved by placing the samples in boiling distilled water and then after cooling to define the change Δm the mass of the sample. In view of the above described properties of the panel material:

$$V_p \approx \frac{\Delta m}{\rho_{\mathrm{H_2O}}}, \tag{3}$$

where Δm – change of mass of sample after soaking in water, $\rho_{\mathrm{H_2O}}$ – H_2O density.

The next step of researches is the calculation of Shore A hardness of the tested material. Determination of Shore A hardness was performed according to standard PN-EN ISO 868: 2005 "Plastics and hard rubber. Determination of hardness by pressing method using a durometer (Shore hardness)". Hardness $\overline{Sh_A}$ Shore A has been determined by carrying out at least 30 measurements of hardness for each sample with a durometer Shore Sauter HBA 100–0 scale A. The tests were performed at 20±2°C. On the basis of the individual results the size of the arithmetic average hardness $\overline{Sh_A}$ and its standard deviation σ_{Sh} were calculated by the following formulas:

$$\overline{Sh_A} = \frac{\sum\limits_{i=1}^{n} Sh_{Ai}}{n}, \tag{4}$$

$$\sigma_{Sh} = \sqrt{\frac{\sum\limits_{i=1}^{n} \left(Sh_{Ai} - \overline{Sh_A}\right)^2}{n}}, \tag{5}$$

where Sh_{Ai} – individual result of measurement of hardness Shore A, n – number of measurements ($n \geq 30$).

Because of the large surface roughness, the porosity of the slabs and large pore size of the indenter relative to the measurements do not reflect the hardness of the plate on a macroscopic scale but only the hardness of webs of the glued rubber granules used to perform a specific disc. Hardness for rubber available on the market and elastomeric materials allow for spot measurements and do not provide authoritative study feasibility of porous materials. On the basis of the average $\overline{Sh_A}$ bridges of rubber and porosity volume p_V board, the weighted average hardness $\overline{Sh_{A\ \mathrm{plate}}}$. It is described as following dependency and a reliable indicator of the hardness of the porous plate in terms of macroscopic:

$$\overline{Sh_{A\ \mathrm{plate}}} = \overline{Sh_A} \times (1 - p_V), \tag{6}$$

where p_V – porosity by volume of the plate material vibration isolating.

In the next stage of the proposed methodology of the study the modulus of elasticity of the tested material should be determined. The modulus of elasticity (Young's modulus) is calculated from secant of stabilized hysteresis loop mechanical work based on relation $E = \partial\sigma/\partial\varepsilon$. In practice Young's modulus can be calculated from equation $E = \tan\alpha$ where α is the angle of inclination secant with respect to the horizontal axis of deformation ε coordinate system stress σ and strain ε. The above definition refers to the case of linear-elastic materials, the course of which resembles the hysteresis loop "spindle", as illustrated in Fig. 2, and are successfully used for materials with low loss, and so a small span between the curves load and relief. In the case

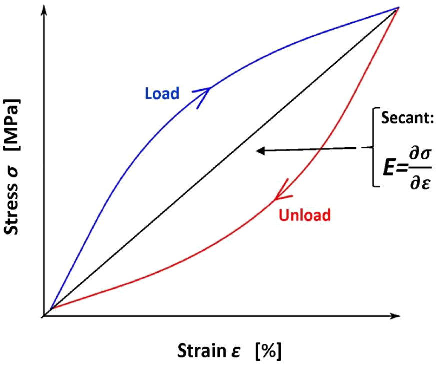

Fig. 2. The hysteresis loop of linear-elastic materials.

of rubber, the spread is large, so the averaged size of the E individually relative to the curve progression or digression would be burdened with large errors.

The rubbers and other elastomeric materials exceeding a certain magnitude of deformation are the phenomenon of a non-linear elasticity. The hysteresis loop changes shape to guide individual sellers within the loop becomes impossible, therefore, cannot be set as modulus based on the above cited rule. The load curve of the hysteresis loop reflects the vibro-isolator response to external mechanical force the curve to relieve it reflects the relaxation of the material. For engineering applications of vibration isolating materials more important is knowledge of the load curve. Given the need to define the contractual elastic modulus E it is therefore reasonable to base it on course load curve.

In the next stage of the proposed methodology of the study ones should determine the damping coefficient ψ which is important for evaluating the vibration isolating properties of the materials (Osiński, 1998; Jones 2001). Damping coefficient ψ can be defined as (Fig. 3):

$$\Psi = \frac{W_{\mathrm{loop}}}{W_{\mathrm{load}}}, \tag{7}$$

where W_{loop} – the amount of work losses contributed by vibroisolator due to internal friction and dispersed into the environment as heat. W_{loop} is the difference between work, W_{load} is made in step progression in accordance with the load curve of the hysteresis loop, and the operation of the vibro-isolator dedicated phase in accordance with the decrease of the unloading curve, W_{load} – work done by the external force F to deform the vibroisolator by an setpoint deflection Δl.

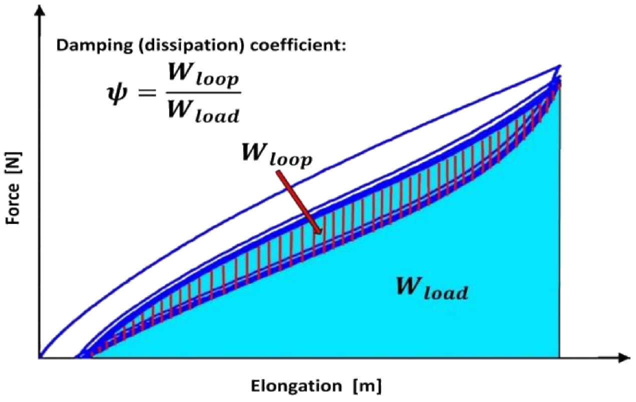

Fig. 3. A measure of vibroisolator damping.

The definition of the physical work is expressed by the relation:

$$W = \oint_{l_0}^{l} F(l)\,\mathrm{d}l. \tag{8}$$

The coordinate system *force* F – deflection l, W_{load} corresponds to the size of the area under the load curve of the hysteresis loop and W_{loop} is the difference between the size of the area under the curve of the load and the size of the area under the curve relief as illustrated in Fig. 3.

The next step is determination of contractual linear deformation ε_L. Contractual linear deformation ε_L is the maximum relative deformation ε rubber load curve in a compression test area corresponding to the linear elasticity of rubber in the scope of applicability of Hooke's law. Contractual linear deformation ε_L size can be calculated from the equation:

$$\varepsilon_L = \frac{\Delta l_L}{l_0}, \tag{9}$$

where Δl_L – change of the height of the sample during the compression test in area of linear elasticity stable hysteresis loop, l_0 – initial thickness of the sample.

In the next stage of the proposed methodology of the study ones should determine the contractual quasi-static and dynamic linear elastic modulus E_L for a range of linear deflection $\varepsilon = 0 \div \varepsilon_L$. Contractual modulus of elasticity of rubber E_L for a range of linear deflection is determined based on the size of the straight section of the load curve stable hysteresis loop compression mechanical work, corresponding to the area studied linear elasticity of rubber in the scope of applicability of Hooke's law. E_L value can be determined based on the data from the chart stabilized hysteresis loop based on the following equation:

$$E_L = \frac{\Delta\sigma_L}{\Delta\varepsilon_L} = \frac{\Delta\frac{F_L}{S_0}}{\frac{\Delta l_L}{l_0}}, \tag{10}$$

where F_L – change of the value of force F on the load curve hysteresis loop during compression corresponding to the region of linear elasticity, S_0 – output cross-section of the sample.

The next step is determination of quasi-static and dynamic stiffness factor k. Volume stiffness coefficient k is defined as a derivative of the force inducing strain relative to deformation. In practice it is a measure of the force increment ΔF acting on the elastic body under the influence of the individual absolute strain Δl:

$$k = \frac{\partial F}{\partial l} \approx \frac{\Delta F}{\Delta l} = E \times \frac{S_0}{l_0}. \tag{11}$$

Dynamic stiffness factor k is determined, directly from the graph of the hysteresis loop in the coordinate system of the force F and the absolute deformation Δl, while the modulus of elasticity E is determined from the same graph of hysteresis, but in a coordinate system stress σ and the strain ε. The coefficient k depends on the geometrical dimensions of the test object and whenever they change requires the calculation of new values of k. Thus, in contrast to the Young's modulus E stiffness ratio k is not a material constant.

2. Experimental results

Studies examining properties of the physical parameters based on the above-described methodology were conducted on a material sample which is flexible part of a vibration isolating system of subgrades used in the construction of tram tracks in Poland. The sample was cut from the mat made of rubber granules linked by polyurethane adhesive proposed by one of the Polish companies (Fig. 4).

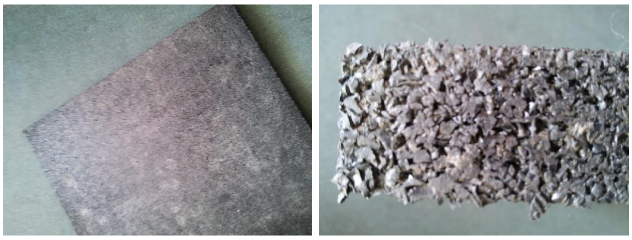

Fig. 4. Vibration isolation plate.

Linear dimensions of samples should be determined according to the applicable standards, in this case the Polish norm PN-EN ISO 1923:1999 "Plastics, porous and rubber materials. Determination of linear dimensions". Transverse dimensions of the test samples of $120 \pm 0.5 \times 120 \pm 0.5$ mm were chosen in order to maintain the same size of the sample with an accuracy of ± 0.1 mm. Such a large cross-section area S_0 guarantees the validity of the estimation of physico-mechanical properties of elastic element. To eliminate edge effects resulting from perform technology of elastic plates the test samples were cut at a distance of at least 20 mm from the edge of the plate by water jet and abrasive at high pressure by means of a "water-jet" technology which guarantees the absence of thermal effects of cutting, high quality cutting surface and high repeatability shape and dimensions.

According to the research methodology proposed by author in the first step the volumetric density ρ_0, volumetric porosity p_V and Shore'a A hardness of the flexible plate at room temperature 20°C were determined. The test results are shown in Table 1.

Table 1. Result of determination of the volumetric density ρ_0, volumetric porosity p_V and Shore'a A hardness of the elastic plate.

ρ_0 [kg/m^3]	p_V [%]	Shore A hardness	
		$\overline{Sh_A} \pm \sigma_{Sh}$ [^{o}Sh]	$\overline{Sh_{A\ \text{plate}}}$ [^{o}Sh]
547	47.7	22 ± 2	11.3

In the next stage of the study the contractual linear deformation ε_L and dynamic linear elastic modulus E_L were calculated for various speed of deformation of the sample in the temperature range from −40 to +60°C. Obtaining reduced and increased temperatures was carried out on the basis of standard PN-EN ISO 3383:1994. The test results are shown in Table 2.

Table 2. Results of investigations of contractual linear deformation ε_L and dynamic linear elastic modulus E_L.

t [°C]	ε_L [%]			E_L [MPa]		
	$v = 0.1$ [mm/s]	$v = 1.0$ [mm/s]	$v = 3.0$ [mm/s]	$v = 0.1$ [mm/s]	$v = 1.0$ [mm/s]	$v = 3.0$ [mm/s]
−40	11.6	9.84	9.95	1.66	2.46	2.45
−20	12.4	11.1	10.8	1.06	1.24	1.41
0	12.8	11.9	12.8	0.79	0.94	0.99
20	13.5	12.8	12.2	0.75	0.79	1.00
40	13.2	11.9	12.4	0.73	0.77	0.82
60	11.1	9.8	10.6	0.78	0.77	0.82

Results of the approximation of test results of the dynamic elastic modulus E_L and the contractual linear deformation ε_L as a function of temperature and strain rate of material from the rubber granules linked polyurethane adhesive are shown in Figs. 5 and 6.

In the next stage of the study the dynamic elastic modulus $E_{L \div 20\%}$ and damping coefficient ψ were calculated for various speed of deformation of the sample

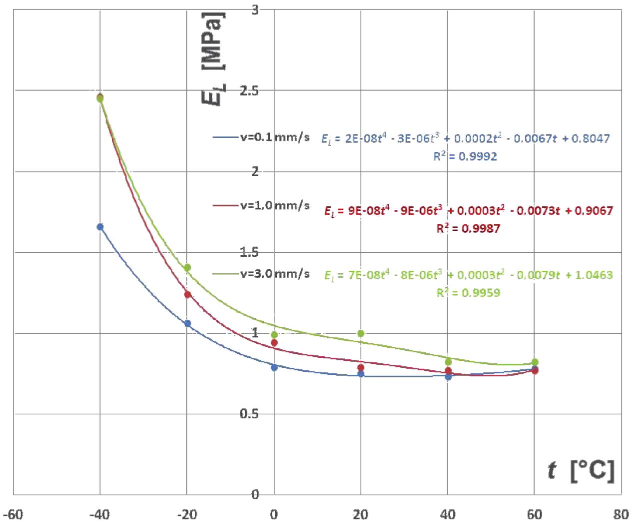

Fig. 5. Contractual elastic modulus E_L vs. temperature t and velocity deforming rubber-derived material v.

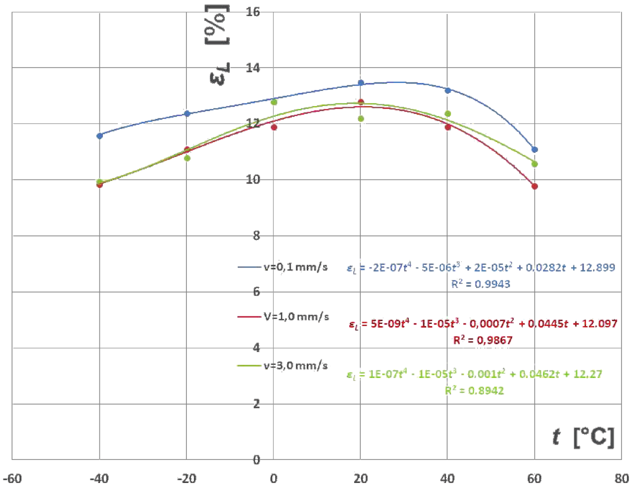

Fig. 6. Contractual linear deformation ε_L vs. temperature t and velocity deforming rubber-derived material v.

in the temperature range from -40 to $+60$°C. The test results are shown in Table 3.

Table 3. Dynamic elastic modulus $E_{L\div 20\%}$ and damping coefficient ψ values.

t [°C]	$E_{L\div 20\%}$ [MPa]			$\psi_{\varepsilon=20\%}$ [–]		
	$v = 0.1$ [mm/s]	$v = 1.0$ [mm/s]	$v = 3.0$ [mm/s]	$v = 0.1$ [mm/s]	$v = 1.0$ [mm/s]	$v = 3.0$ [mm/s]
-40	2.5	2.91	3.84	0.44	0.54	0.71
-20	1.45	1.59	1.72	0.33	0.44	0.54
0	1.16	1.23	1.25	0.36	0.38	0.43
20	1.09	1.19	1.25	0.34	0.39	0.41
40	1.10	1.19	1.23	0.32	0.39	0.38
60	1.26	1.23	1.34	0.30	0.33	0.39

Results of the approximation of test results of the dynamic elastic modulus $E_{L\div 20\%}$ and damping coefficient ψ as a function of temperature and strain rate of material from the rubber granules linked polyurethane adhesive are shown in Figs. 7 and 8.

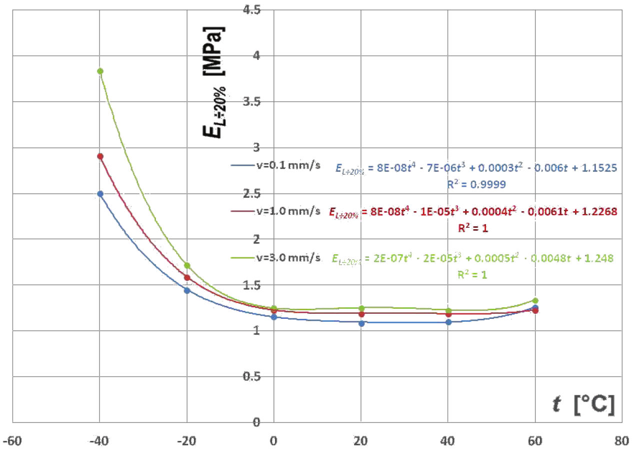

Fig. 7. Dynamic elastic modulus $E_{L\div 20\%}$ vs. temperature t and velocity deforming rubber-derived material v.

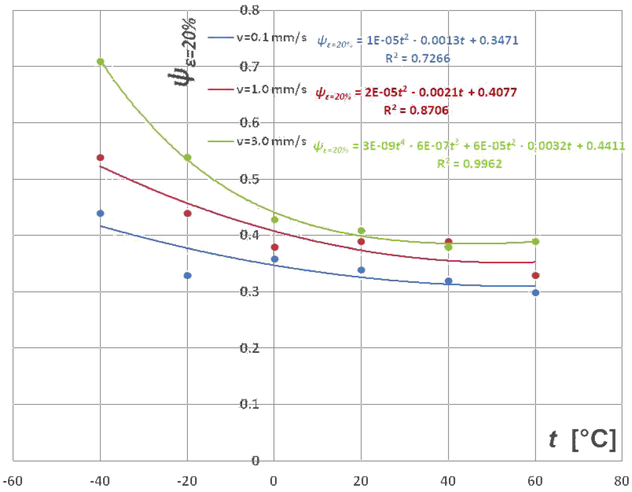

Fig. 8. Damping coefficient ψ vs. temperature t and velocity deforming rubber-derived material v for relative deformation $\varepsilon = 20\%$.

3. Conclusion

Technical requirements for the determination of the characteristics of vibration isolating material have not been standardized in Europe and Poland yet. Comprehensively and unequivocally studies of mechanical properties of elastic materials based on the graph of the hysteresis loop of mechanical work have not been normalized also. Manufacturers of rubber-derived materials, research laboratories and certification institutes make the researches of elastic materials according to their own needs and the convenience using different sets of PN and PN-EN ISO, DIN, ASTM and others standards, which hinder the ability to compare each other vibration isolating materials offered. Described in the paper methodology for determination of physical and mechanical properties of vibration isolating materials based on the chart stabilized hysteresis loops based on mechanical work is therefore not based on fragmented standards, but on knowledge in the field of mechanics of non-linear elastic materials.

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