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COMPARISON OF COMPLEX MODULUS AND ELASTICITY MODULUS OF BITUMEN BONDED MATERIALS

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Abstract: The European standards for asphalt mixture testing are mainly focused on empirical parameters of asphalt mixtures. On the other hand, functional parameters (e.g. fatigue, stiffness) of asphalt mixtures describe real behavior of the material in-situ. These parameters are used for design of road construction according to the Slovak design method where the elasticity modulus is used instead of the complex modulus. The problem is that no standard for elasticity modulus measurement exists in the collection of the European standards. In this study complex modulus measurement was performed according to the European standard, and for comparison elasticity modulus measurement was also done according to the Australian standard.

Keywords: Elasticity modulus, Asphalt mixture, Complex modulus

1. Deformation properties of asphalt mixture

The current bad condition of non-rigid pavements is a problem, which should be examined. The reasons for cracking or collapse of asphalt pavement layers are not really clear. Collapse could be caused by low-class material properties, increasing traffic [1], unstable sub-base, and inaccurate design of road construction or improper building practice. This paper focuses on problems in the area of road construction design in the conditions of Slovakia.

The design method for non- and semi-rigid pavements used in Slovakia [2] is based on calculations of stresses in the pavement and comparison of the calculated stresses with the bearing capacity of materials. This comparison is made for three different temperatures, which describe the seasons of the year (0°C -winter; 11°C -spring and autumn; 27°C -summer). For the calculations material parameters like fatigue parameters [3], the Poisson's ratio, and the coefficient of thermal conduction and also the modulus of elasticity are needed. Almost all of these parameters could be measured in laboratories according to the European standards. The problem is only with the value of the elasticity modulus because there is no valid European standard for measuring this parameter. The technical manual for pavement design contains a table with elasticity modulus values for typical asphalt mixtures. These values are used for calculations but the question is what happens if there is a new type of asphalt mixture?

The closest alternative to the elastic modulus is the complex modulus (also called stiffness modulus). The main difference between these two material properties is that elasticity modulus has static character while complex modulus has dynamic character. In this study the measurement for complex modulus is evaluated according to the European standard and for elasticity modulus according to the Australian standard and they are compared under different temperature conditions. The Australian standard was chosen for the comparison because the samples and conditions for measurement are similar to the European standard. Other known standards use different dimensions of specimens and different loading conditions.

The complex modulus or stiffness modulus describes material's dynamic response to sinusoidal loading. The measurements and the calculations of complex modulus in this paper are performed according to the European standard [4]. According to this standard, the stiffness modulus represents the numerical value of the complex modulus. The complex modulus (E^*) is calculated from two elements, the real element of complex modulus (E_1) and the virtual element of complex modulus (E_2):

$$E_1 = \gamma\left(\frac{F}{z}\cos(\varphi) + \frac{\mu}{10^3}\omega^2\right), \tag{1}$$

$$E_2 = \gamma\left(\frac{F}{z}\sin(\varphi)\right), \tag{2}$$

$$\left|E^*\right| = \sqrt{E_1^2 + E_2^2}, \tag{3}$$

where γ is the factor of sample shape [mm^{-1}]; μ is the mass factor [g]; F is the force [kN]; z is the displacement [mm] ; φ is the phase leg [degrees]; ω is the circular frequency [rad/s].

The equipment used in the study can measure flexural stiffness and the modulus of elasticity according to the Australian standard [5]. For elasticity modulus measurement ordinary test conditions where applied and measurements were done for every studied temperature. Equations of flexural stiffness (S) and modulus of elasticity (E) are set out below,

$$S = \frac{\sigma_t \cdot 10^3}{\varepsilon_t}, \tag{4}$$

$$E = \frac{F\,L_w}{\delta\,w\,h}\left[\frac{3Sw^2 - 4Lw^2}{4h^2} + k(z+\upsilon)\right], \tag{5}$$

where σ_t is the tensile stress [MPa]; ε_t is the tensile strain $[\mu\varepsilon]$; F is the peak force [kN]; δ is the peak deflection at center of beam [mm]; w is the width of a sample [mm]; h is the height of a sample [mm]; S_w is the support span width [mm]; L_w is the loading span width [mm]; k is the actual shear stress divided by average shear stress; υ is the Poisson's ratio.

The four-point bending method with a prismatic beam specimen can be used for measurement according to both of these standards. The specimen size was 380x50x50 mm and the loading scheme of the equipment is given in *Fig. 1*.

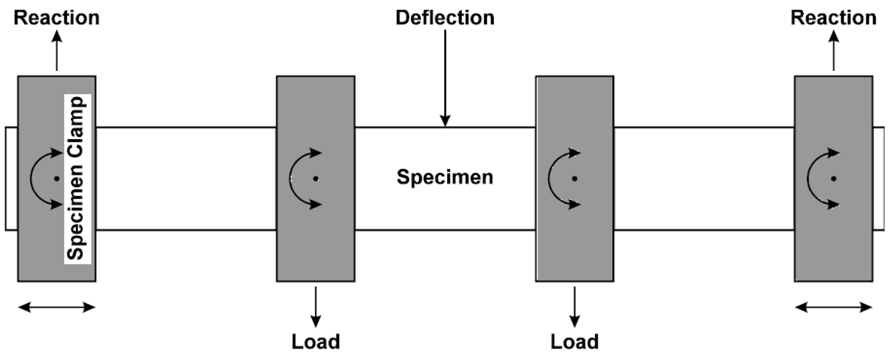

Fig. 1. Side view of loading scheme using 4-PB apparatus [6]

The beam is loaded at two inner points and it is fixed at two outer points in a vertical direction. Load is applied with sinusoidal shape using the inner clamps. The value of the complex modulus is the stiffness of beam in the 100^{th} loading cycle and the control strain should be no more than 50 $\mu\varepsilon$.

2. Examined asphalt mixture

The material chosen for the study was an asphalt mixture, which is one of the most used road construction materials for surface and binder courses of roads in Slovakia. Asphalt concrete (AC 11 O) with continuous gradation curve had maximum grain size of 11 mm and the chosen binder was road bitumen with penetration grade 50/70 with adhesive additives. The mixture was also tested for empirical properties of asphalt mixtures according to the type of the testing standards. The results of the measurements can be seen in *Table I*.

Table I

Results of basic asphalt mixture measurements

Mixture	AC 11	Limits
Binder content (%)	5.4	5.4 >
Air void content (%)	3.0	2.5 - 4
Void content filled by bitumen (%)	81.1	70 >
Indirect tensile strength ratio (%)	85	80 >
Wheel tracking slope (mm/10^3 cycles)	0.06	< 0.07
Proportional rut depth (%)	4.45	< 5.0

The measurement results show that this mixture is good enough for use in pavement construction and in heavy-loaded road sections as well. Negative influence of moisture on this asphalt mixture was also observed, because it caused structural damage of mixture [7], which was measured in this study using the indirect tensile strength ratio. Differences between the results and the limit values are minimal. These results support the assumption that the stiffness of the mixture should reach appropriate values.

3. Results of the measurements

Even though the complex modulus and elasticity modulus are different properties, the measurement methods are quite similar. For both properties a four-point bending test with 100 loading cycles of sinusoidal shape was applied. The phase angle and the dissipated energy were also observed during these measurements, because they are necessary elements in both complex and elasticity modulus calculations. Although the conditions for measurements were similar, phase angle and dissipated energy had different values during these measurements. Temperature dependence of the asphalt mixture was also observed in the study, because it is one of the causes of road deformation [8].

3.1. Phase angle

When a visco-elastic material is subjected to sinusoidal varying stress, the steady state will eventually be reached in which the resulting strain is also sinusoidal, having the same angular frequency but retarded in phase by an angle φ as it can be seen in *Fig. 2*. This is analogous to the delayed strain observed in creep experiments [9] and it means that the material is linear. The figure below also describes the bending oscillations during the test on the beams, where the amplitude of load is time dependent [10].

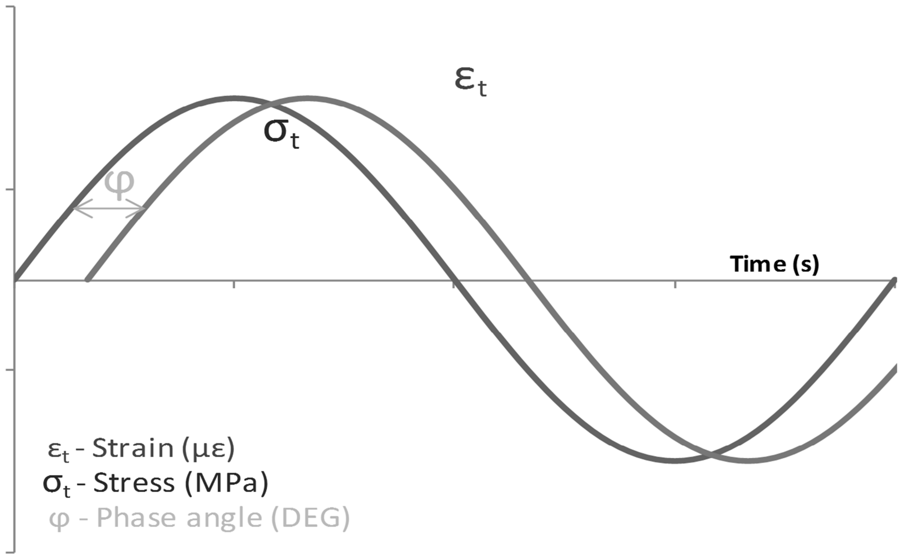

Fig. 2. Illustration of phase lags between the amplitude of applied stress and the amplitude of corresponding strain, which is the main characteristic of visco-elastic behavior

The results show that during the measurement according to the European Standard (ES), the phase angle had higher values than the measured values according to the Australian Standard (AS). Temperature dependence of the phase angle can be seen in *Fig. 3*. The mathematical function between the temperature and the phase angle can be described with an exponential curve. The equations of both curves can also be seen in *Fig. 3*. The slope of the phase angle in AS is steeper than the slope of the phase angle in ES. These results also show that the differences are greater when the temperature is close to 0°C.

3.2. Dissipated energy

Asphalt is a visco-elastic material. The parameters, which describe its behavior, can also be observed during complex modulus measurement [11], [12]. Asphalt mixture dissipates energy under mechanical work (loading and relaxation). Usually, in an elastic material the energy is stored in the system when the load is applied. All the energy is recovered when the load is removed; in this case the unloading and the loading curves coincide. Visco-elastic materials are characterized by a hysteresis loop because the unloaded material traces a different path to that when it is loaded (phase lag is recorded between the applied stress and the measured strain); in this case the energy is dissipated in the form of mechanical work, heat generation, or damage. The area of the hysteresis loop represents the dissipated energy in the load cycle, and the following equation can be used to calculate its value in linear visco-elastic material [13],

$$W_i = \pi \sigma_i \varepsilon_i \sin(\varphi_i), \tag{6}$$

where: W_i is the dissipated energy for i-th cycle [kJ/m^3]; π is the mathematical constant; σ_i is the applied stress [MPa]; ε_i is the strain level [με]; φ is the phase leg [degrees].

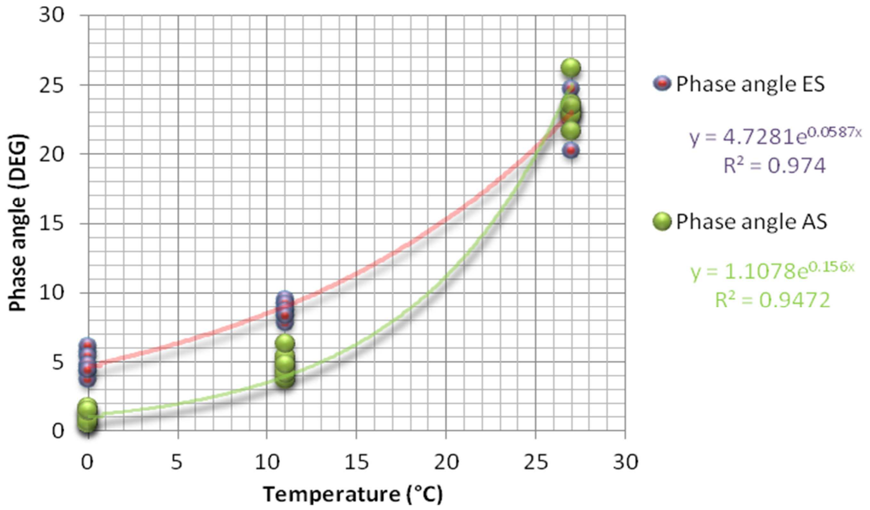

Fig. 3. Temperature dependence of phase angle during measurements according to the European standard (ES) and Australian standard (AS)

During these measurements only 100 loading cycles were applied, so no evolution of dissipated energy could be seen, however in this study comparison of the dissipated energy after the 100th loading cycle were performed for both tests. In *Fig. 4* the temperature dependence of the dissipated energy after the 100th loading cycle can be seen. According to the results in the figure below, the dissipated energy does not depend on the temperature during the measurement according to ES. On the other hand, during the measurement according to AS, the dissipated energy significantly depends on the temperature. The temperature dependence of the dissipated energy can be described with a mathematical function where the coefficient of correlation is about 0.99.

3.3. Complex modulus, elasticity modulus, flexural stiffness

The main purpose of this study is the comparison of static and dynamic deformation characteristics. The complex modulus as mentioned in studies [14], [15] is a dynamic deformation property, and load is applied with specific frequency. The elasticity modulus is a static deformation property and does not depend on frequency or angular velocity. Despite of these differences there should be relationship between these characteristics. For complex modulus measurement six different frequencies were applied. The aim was to find out, which of these frequencies should be set for complex modulus measurement to reach the closest value to that of the elasticity modulus.

Comparison was made for each of the chosen temperatures, and the comparison for 11° C can be seen in *Fig. 5*. According to this comparison, similar values of complex modulus and elasticity modulus could be observed when the test frequency for complex modulus measurement was set to 10 Hz.

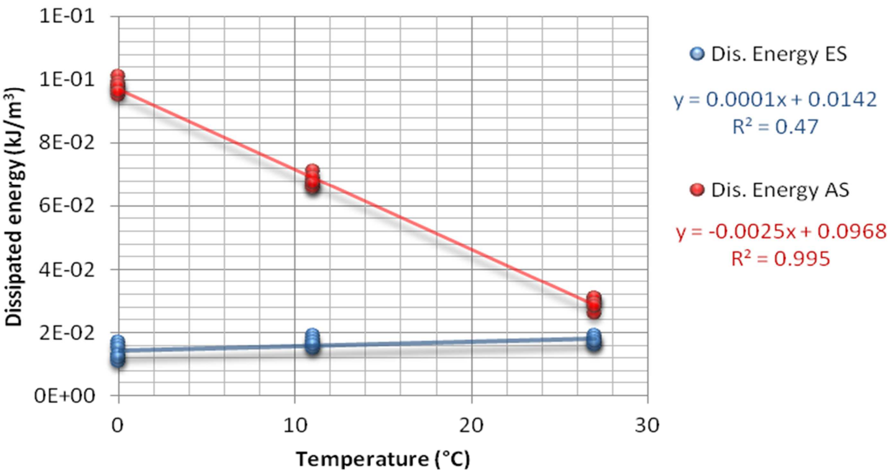

Fig. 4. Temperature dependence of dissipated energy during measurements according to the European Standard (ES) and the Australian Standard (AS)

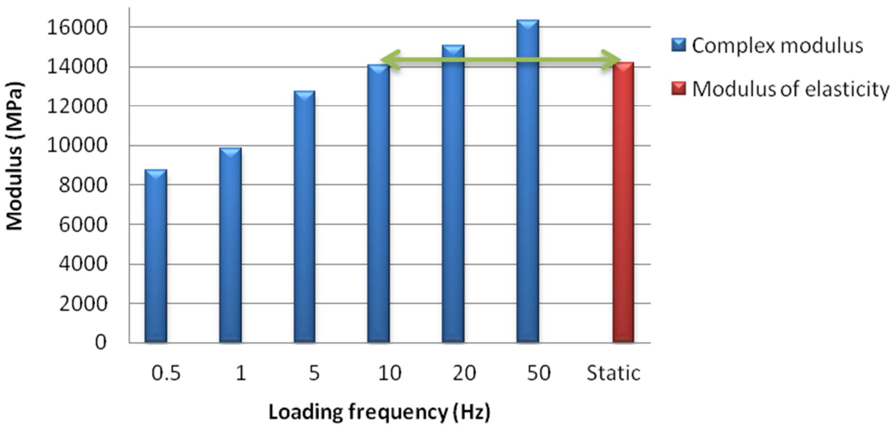

Fig. 5. Comparison of complex modulus at different frequencies with elasticity modulus (11° C)

According to the information derived from *Fig. 5,* the correspondence of complex modulus and elastic modulus occurred at load frequency 10 Hz for three selected temperatures. Flexural stiffness, a static material property was also compared with the complex modulus and elasticity modulus, and it was calculated according to the

Australian Standard. Comparisons of these properties for three different temperatures can be seen in *Fig. 6*. This graph clearly shows that the complex modulus at load frequency 10 Hz has similar values to the elasticity modulus or flexural stiffness for each of the selected temperatures.

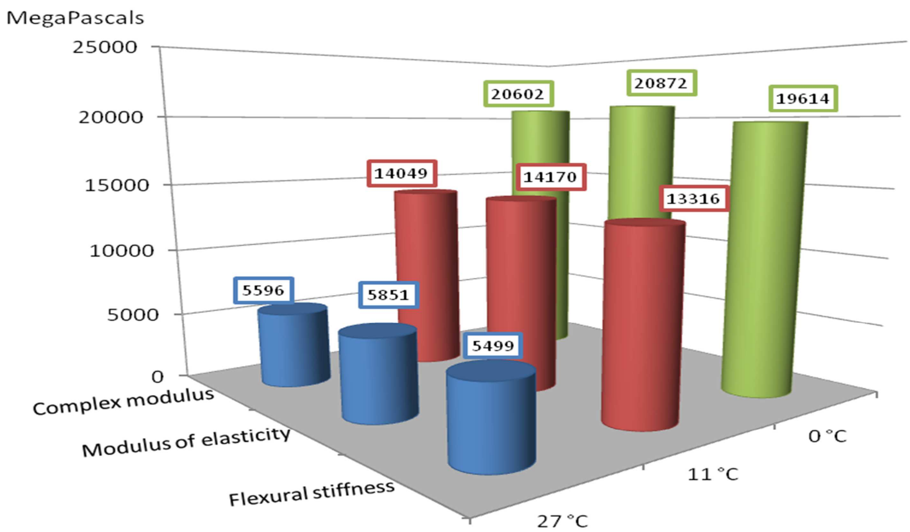

Fig. 6. Comparison of complex modulus, elasticity modulus and flexural stiffness at three different temperatures

4. Conclusion

Two different standards of measurement were used in this study because each of them describes visco-elastic material behavior based on different characteristics (ES - complex modulus; AS - modulus of elasticity).

The measurements were made at three temperatures because temperature change affects the basic properties of asphalt mixture. Temperature dependence was observed in the study of phase angle, dissipated energy and complex modulus. Investigation of phase angle and dissipated energy indicated differences between measurements according to the European Standard and the Australian Standard. Phase lag and dissipated energy represent the visco-elastic behavior of material. Additional study of phase lag and dissipated energy could lead to better understanding of the visco-elastic behavior of asphalt mixtures, which could then be applied to the mathematical model of the pavement construction.

The results of this study clearly show that the complex modulus could be used in road design calculations as a replacement for elasticity modulus. Specific frequency conditions during complex modulus measurement need to be set to reach similar values as for the elasticity modulus. This fact means that elastic modulus measurement can be replaced with complex modulus measurement at loading frequency 10 Hz. According to these results the 10 Hz frequency is suitable, but for greater accuracy there is the need of more measurements at frequencies close to 10 Hz.

One of the first assumptions was that with changing temperature there should be greater differences between the complex modulus and the elasticity modulus. This assumption has been clearly disproved according to the presented results. No differences greater than 4.5% between the values can be seen in results, which may also be considered as standard error of the measurements. The conclusions of this paper are valid only for measurements using the method of four-point bending, so if other methods are used, additional measurements should be done.

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