Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Rheological properties of materials used in bridge asphalt pavement structures

Piotr Radziszewski [a], Piotr Pokorski [a], Michał Sarnowski [a]*

[a]*Warsaw University of Technology, Al. Armii Ludowej 16, 00-637 Warsaw, Poland*

Abstract

One of the elements that determine the durability of bridge structures is the bridge pavement. The durability of bridge pavements depends on two main factors: traffic load and climatic conditions. Bridge deck surfaces might exceptionally become exposed to extreme low and high temperature conditions. Stresses and strains in this type of construction are different from those of the road surfaces located on the soil. Bituminous binders and asphalt mixtures are thermoplastic components of waterproofing layers and surfacing. Their properties vary depending on the temperature. This paper presents the laboratory test results of rheological properties of asphalt mixtures for bridge pavements. The research plan included typically used asphalt mixtures - asphalt concrete (AC), stone mastic asphalt (SMA) and mastic asphalt (MA). A new type of mixtures, stone mastic asphalt with high grit content SMA-MA, were also tested. Paper presents test procedure for determining the stiffness of asphalt mixtures on cylindrical samples. Samples preparation and test method of direct tension–compression on cylindrical specimens (DTC-CY) were discussed. The selected results of dynamic modulus and phase angle at different temperatures and varied frequencies were presented. These parameters describe the visco-elastic properties which determine the durability of bridge pavements. The results were presented as a leading curves, black curves and Cole-Cole graphs. A comparison of the results of asphalt mixtures with the results of binder in dynamic shear rheometer DSR was performed. The functional evaluation of the asphalt mixtures was extended for fatigue life test and rutting resistance. The results of conducted research proved that the types of asphalt mixture affect the viscoelastic properties and durability of bridge pavements.

Keywords: bridge pavement, dynamic modulus, asphalt mixture, rheological properties.

* Corresponding author. Tel.: +48 22 234 64 61.
E-mail address: p.pokorski@il.pw.edu.pl

1. Introduction

The bridge deck pavement determines to a significant extent the durability of the entire bridge structure. Bridge pavement works in a very specific load conditions. It is subjected to loads of traffic vehicles and climatic factors. On the pavement act horizontal and vertical forces, low and high temperatures, water and de-icing salts. Aggressiveness load in the case of bridge pavement is much higher than the pavement on soil. The pavement on bridge decks operates in different conditions than the one on earth foundation. Stresses and deformations reach higher values, therefore there is greater risk of damages. Courses layout, thickness and features are different. Wheel loading vehicle causes, as in outside pavement of the object, stress and strain compressive and tensile loads. They can cause permanent deformation, and fatigue cracking of asphalt layers. Stress and strain in the bridge pavement depend on the type of the deck. Other values are the maximum strain in the surface on the object with a concrete and orthotropic steel decks. Bridge pavement is exposed to large and rapid temperature changes. In addition to basic features that the pavement should meet (load distribution on the bridge deck, ensuring the adhesion to the base course, evenness, roughness, resistance to abrasion and rutting), it should protect the bridge deck from the destructive effect of water and de-icing agents used during the winter periods. In Europe, bridge pavements are built using asphalt technology. A decisive impact on the durability of this kind of pavement have rheological properties of asphalt mixtures.
In Europe bridge asphalt pavements are paved on the insulations (waterproofing). Asphalt pavement on the bridges consists of a protective layer and wearing course. These layers are usually made of mastic asphalt MA, asphalt concrete AC and stone mastic asphalt SMA. Due to the specific conditions of the load on a bridge decks, asphalt mixes with a high content of mastic and closed structure are preferred. There are a mixtures of mastic asphalt MA and SMA for the protective layer and asphalt concrete AC and SMA for wearing course. Fig. 1 shows the typical layouts pavement layers on the bridge decks.

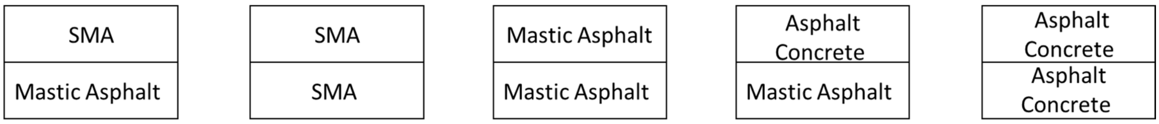

Fig. 1. Typical types of asphalt layer system on bridge deck

At Warsaw University of Technology the tests of rheological properties of typically used asphalt mixtures and new type of bridge asphalt mixture were carried out.
The main purpose of the laboratory tests and analyzes described in the article was to compare rheological properties of materials used in bridge asphalt pavement structures

2. Research Methodology

To characterize asphalt mixtures behaviour used in bridge pavements a number of parameters are used that allow for complex and detailed description of the material properties. Such parameters include the ones that describe the rheological properties of the binder as well as the properties of asphalt mixtures. The parameters that well describe the rheological properties of asphalt mixtures are complex modulus and phase angle. At Warsaw University of Technology conducted a research on complex modulus and phase angle asphalt mixtures for bridge pavement by direct tensile compression method (DTC-CY) according to polish standard PN-EN 12697-26. In the direct compression tensile method, samples of asphalt mixtures are subjected to cyclic alternating tension and compression. During the laboratory tests deformation at low values of load (deformation of less than 25 x 10^{-6}) are induced. A sinusoidal load with constant amplitude and a specified frequency is applied to the sample material. It causes sine wave stress of the same frequency but different amplitude. On this basis a complex modulus and phase angle are established. Due to the viscoelastic properties of asphalt composites strain in relation to stress is offset by an angle δ - the phase angle. Fig. 2 shows the relationship between stress and strain.

Stress (σ) is defined by formula:

$$\sigma = \sigma_0 * \sin(\omega t) \tag{1}$$

where:

σ_0- initial stress, ω - angular frequency, t - time.

Strain (ε) is defined as:

$$\varepsilon = \varepsilon_0 * \sin(\omega t - \delta) \quad (2)$$

where:

ε_0- initial strain, δ - phase angle.

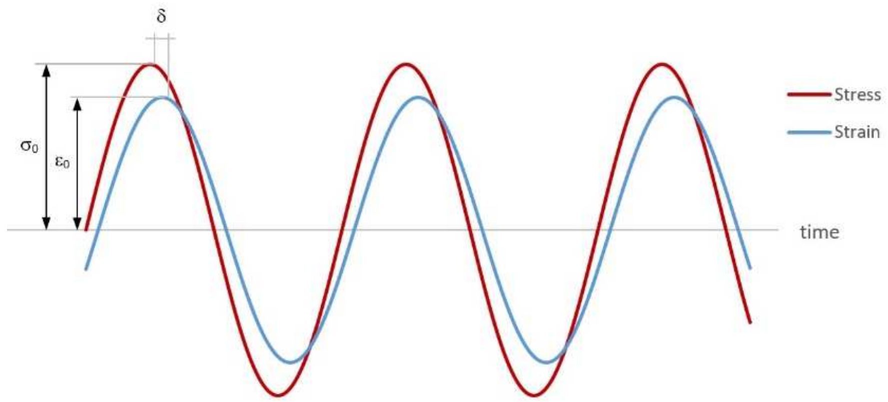

Fig 2. The relationship between stress and strain

Complex modulus is defined as:

$$E^*_{(i\omega)} = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0{}^*} * e^{i\delta} = E_1 + E_2 * i \quad (3)$$

where:
E_1 - real part of the complex modulus (storage modulus),
E_2 - imaginary part of the complex modulus (loss modulus),
i - imaginary unit,
δ - phase angle.
Dynamic complex modulus is defined as the absolute value of the complex modulus:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (4)$$

Real and imaginary parts of the complex modulus are calculated from the following formulas:

$$E_1 = |E^*| * \cos\delta \quad (5)$$

$$E_2 = |E^*| * \sin\delta \quad (6)$$

In the case of the viscoelastic materials (e.g. asphalt mixture) the value of an δ phase angle is in between 0 to 90 degree. With the increase of phase angle material shows increased participation of viscous properties and reduced elastic properties. The sinusoidal load changes in the test do not correspond to the actual nature of the traffic load conditions, however allow for the determination of the rheological properties of the viscoelastic material.
Measurements of the dynamic complex modulus (called: dynamic modulus) and phase angle were conducted in accordance with standard PN-EN 12697-26 with load frequencies ranging: 20, 10, 3, 1, 0.3 and 0.1 Hz. Adopted test temperatures were as follows: 0°C and 10°C, 20C and 30°C (in accordance to the standard) and extended measurement range was added of -10°C and 40°C The results of dynamic modulus obtained in the DTC-CY method are not identical to the results obtained from the measurements using 4-point bending beams method or calculation methods. Comparison of research methodology and specific conversion factors between these methods have been developed by the Research Institute of Roads and Bridges.

3. Characteristics of mixtures covered by the test plan

On the basis of research experience on new material and technological solutions regarding bridge pavements, four asphalt mixtures were selected for the tests:

- asphalt concrete AC 11 for protective layer,
- stone mastic asphalt SMA 8 for wearing curse,
- mastic asphalt MA 8 for protective and wearing course,

- stone mastic asphalt with high grit content SMA-MA 8 for protective layer.

The same polymer modified bitumen PmB 45/80-55 was used in all mixtures. Selecting these mixtures in the study is a continuation of research in the field of bridge pavements conducted for several years at the Warsaw University of Technology. AC, SMA and MA mixtures are typical asphalt mixtures used on the bridge decks for both protective and wearing course. Additionally a mastic asphalt with high grit content (SMA-MA 8). SMA-MA is a new type of asphalt mixture designed for use in insulation and protective layers. This mixture is a creative combination of three technologies: conventional insulating mastic (binder+mineral filler+sand), mastic asphalt (MA) and stone mastic asphalt (SMA) with a high percentage of grit fraction which forms the mineral base. As a result, mastic asphalt with high grit content (SMA-MA) is characterised by an extensive grit base (similar to that of stone mastic asphalt SMA), greater content of sand fraction (similar to that of mastic asphalt) and high percentage of binder – about 8.5-9% m/m (similar to that of insulating mastic). This composition of the mixture provides good sealing properties (percentage of air voids: about 0.5-0.8% m/m) and resistance to permanent deformations.

Table 1 compares the composition of mastic asphalt with high grit content (SMA-MA) and standard asphalt mixtures for bridge deck insulation and pavement systems.

Table 1 Examples of asphalt mixtures for bridge deck pavement

Material	SMA-MA 8	SMA 8	MA 8	AC 11
	% m/m			
Binder content	9.0	7.0	8.0	5.4
Mineral filler	12.7	11.2	27.6	8.5
Natural broken sand	-	-	11.0	-
Sand broken	12.7	12.1	11.1	28.4
Gabbro grit 2/5	14.6	17.7	18.4	9.5
Gabbro grit 5/8	51.0	52.0	23.9	17.0
Gabbro grit 8/11	-	-	-	31.2

In order to comparison of the asphalt mixtures properties with the binder properties a results of binder in dynamic shear rheometer (DSR) was also performed. The functional evaluation of the asphalt mixtures was extended for fatigue life test and rutting resistance.

4. Analysis of the results

4.1. Binder rheological properties

In all mixtures covered by the test plan the same polymer modified bitumen PmB 45/80-55 was used. For comparison, the results of road bitumen 50/70 were also presented. The basic properties of this binders were shown in Table 2.

Table 2 Binders basic properties

	Penetration in 25°C [· 0,1mm]	Softening Point [°C]	Fraass breaking point [°C]	Elastic Recovery after RTFOT aging [%]
PmB 45/80-55	60	67,4	-17	86
50/70	60	49	-16	-

Fig. 3 shows the rheological properties of binder in different temperatures. Fig. 4 shows Black curve of binder an the full temperature range function. Cole-Cole plot of binder was shown on Fig. 5.

The Fig.3,4,5 show the test results done in the DSR rheometer of polymer modify bitumen PmB 45/80-55 and comparison of road bitumen 50/70.

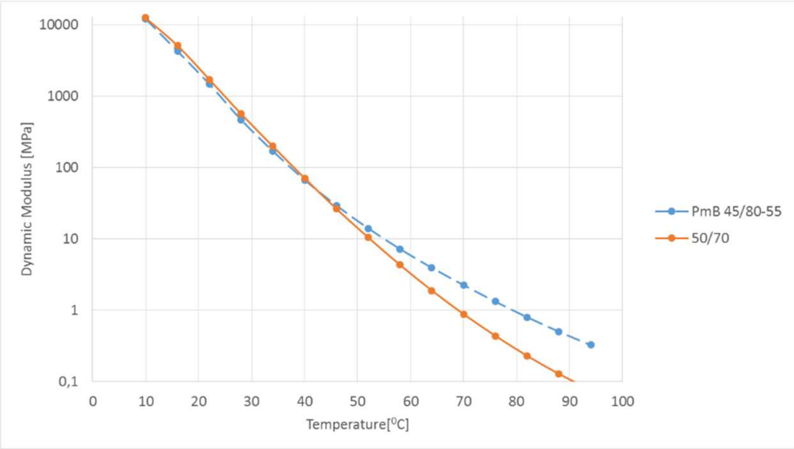

Fig. 3 Dynamic modulus of binder as a function of temperature

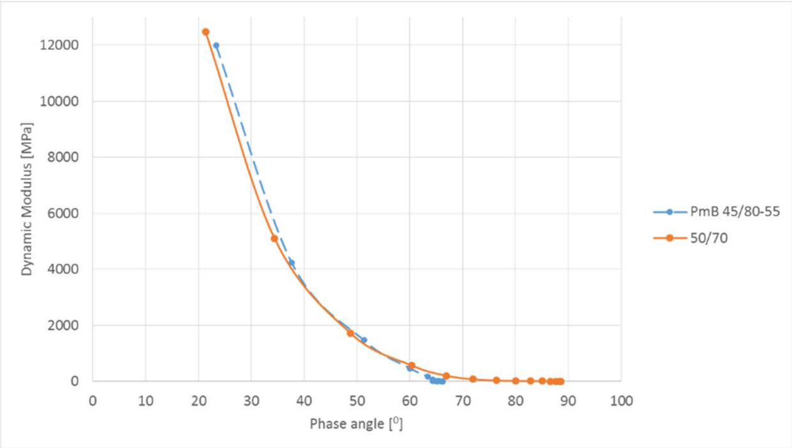

Fig. 4 . Black Curve of binder an the full temperature range

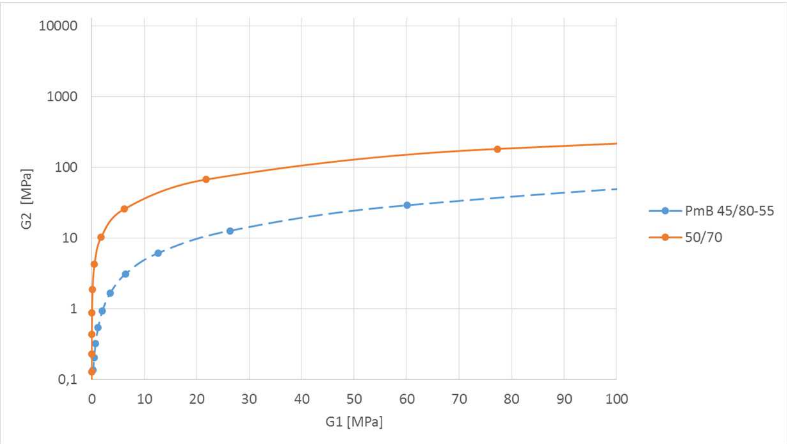

Fig. 5 Cole-Cole plot of binder

Analysing the presented results, it should be noted that the polymer modified binder is characterized by much better visco-elastic properties than the road bitumen. In Figure 3, at high temperatures the PmB 45/80-55 exhibit a higher value for the dynamic modulus. This is advantageous due to the resistance to permanent deformation - rutting. Figure 3 shows the values of the phase angle. It has been found that the phase angle for the polymer modified binder is preferably less than that of the road bitumen. Analysing the Cole-Cole graph (fig.5), the value of the viscosity modulus G2 for the modified binder was significantly lower. The smaller the G2, the higher the deformation resistance.

The DC-TY test for all mixtures (AC11, SMA 8, MA 8, SMA-MA 8) was conducted with PmB 45/80-55.

4.2. Asphalt mix rheological properties

As an outcome of dynamic modulus measurement obtained by DTC-CY method is a result comprising of two components: a complex modulus (E^*) and phase angle. Depending on these two values real part of the complex modulus can be calculated - E_1 (representing the elastic properties of the material) and the imaginary part of the complex modulus - E_2 (representing viscous properties of the material). In the literature a number of relationships between the above parameters were assumed that illustrate the rheological properties of the asphalt mixtures at different temperatures and at different measurement frequencies.
Fig. 6 shows the isotherms of the relation of dynamic modulus as a function of the load frequency at three temperatures: -10, 20 and 40ºC. The analysis of the test results shown in this figure can be concluded that the asphalt concrete AC 11 mixture shows decidedly highest stiffness at all temperatures, regardless of the loading time. For example, at -10ºC, at a frequency of 10 Hz AC stiffness is about 18% greater than the stiffness of SMA mixture and up to 36% greater than the mastic SMA-MA. High stiffness at low temperatures is unfavourable phenomenon due to induction possibility of low-temperature cracks. At a temperature of 20ºC stiffness difference of AC and SMA mixtures is more than double. Higher stiffness of AC mixture may results in lower resistance on fatigue cracking of asphalt mixture. At high temperatures (40ºC) significant differences in the mixtures stiffness are also retained. Higher mix stiffness at temperatures above 40ºC results in greater resistance to permanent deformation (ruts).

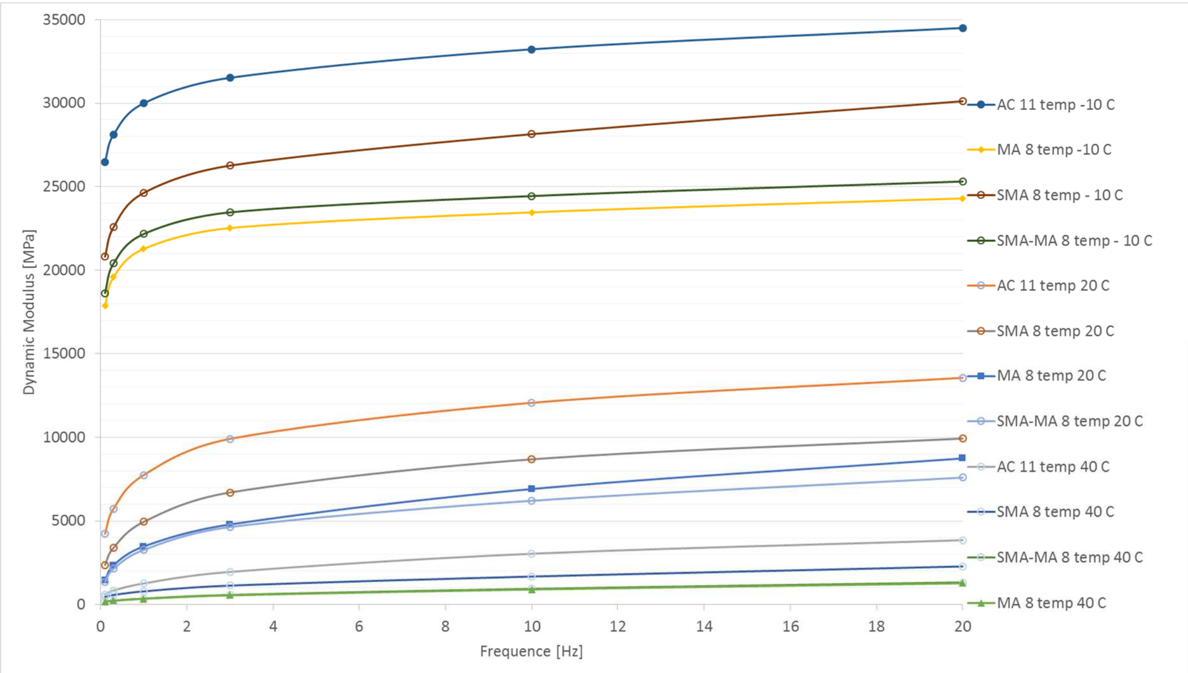

Fig 6. Isotherms of dynamic modulus E * as a function of load frequency

A good method allowing for characterization of the rheological properties of asphalt mixtures is to present the results of the relation of complex modulus as a function of the phase angle. This diagram is called Black curve. Small phase angle indicates the prevalence of the elastic properties of the material. As temperature increases the phase angle increases, reflecting the increased participation of viscous part. A decisive influence on the angle offset value is the type of the binder. In all tested mixtures the same type of binder was used. The differences in the phase angle and the stiffness of the mixtures in this case therefore depend primarily on the type of the mineral skeleton and the quantity of the binder used. Fig. 7 shows collectively Black curves of tested mixtures at full range of test temperatures.
Analysing obtained results it can be concluded that all mixtures are similar in sensitivity to temperature. At high temperatures SMA and SMA-MA mixtures show increased phase angle, AC mixture - has smaller share of viscous part.

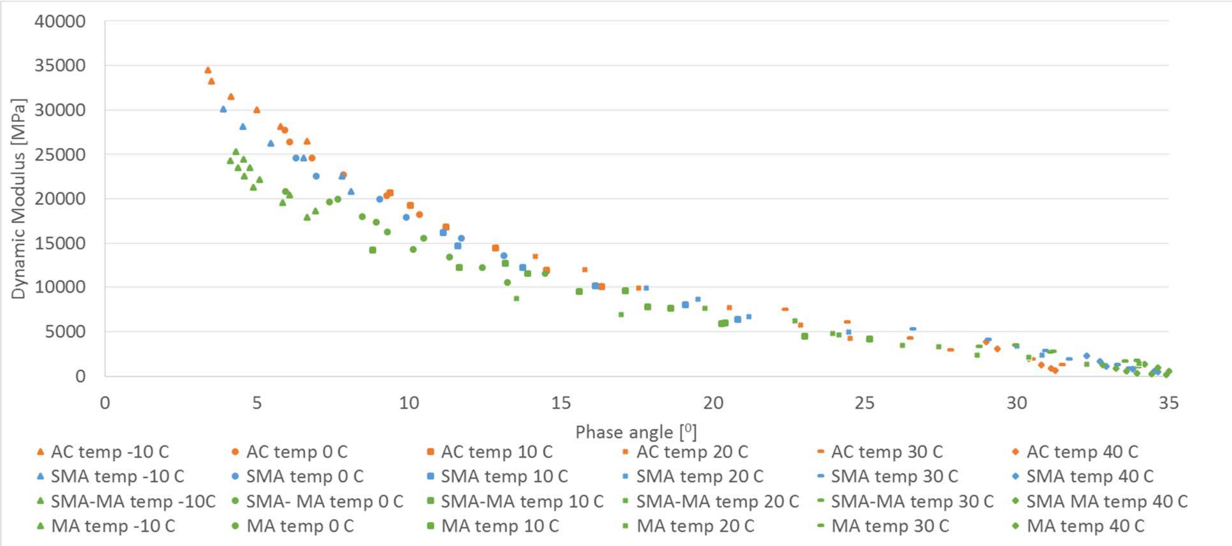

Fig 7. Black Curve of asphalt mixtures at the full temperature range

The behaviour of asphalt mixtures depends on the temperature and load time. The graph of master curve, which is based on the assumption of the equivalence of time-temperature and on Boltzmann superposition allows to describe the variable module with a single curve. Load condition at high temperature and short time load may be equivalent to a load at low temperature in a long load time. The master curve shows the relationship of the complex dynamic modulus and reduced frequency or load time and describes material by a wide range of operating temperature. The properties of the material designated at one temperature can be transposed to a different temperature according to Williams-Landel-Ferry superposition principle. On the basis of the master curve the values of dynamic modulus can be determined depending on the load time and temperature. These relationships are used for mechanistic designing of pavement structure. Fig. 8,9,10 and 11 show master curves of asphalt concrete AC, stone mastic asphalt SMA, mastic asphalt MA and mastic with high grit content SMA-MA, for example for the results of the module designated at 10°C.

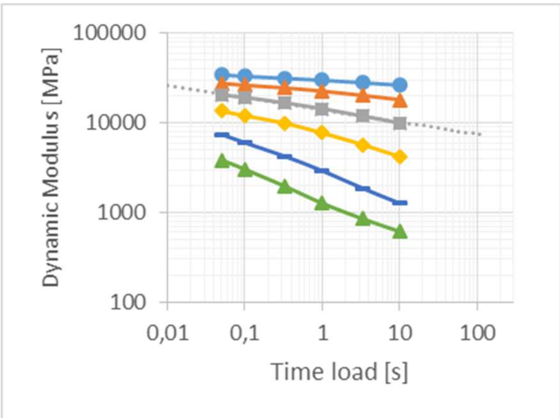

Fig. 8 Master Curve of AC 11

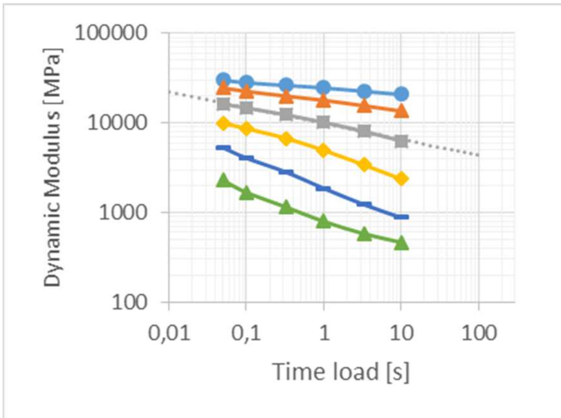

Fig. 9 Master Curve of SMA 8

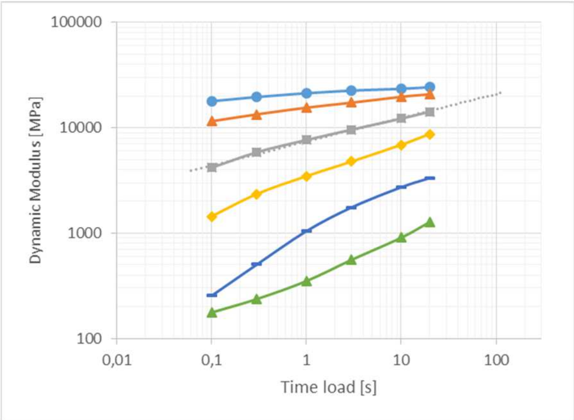

Fig. 10 Master Curve of MA 8

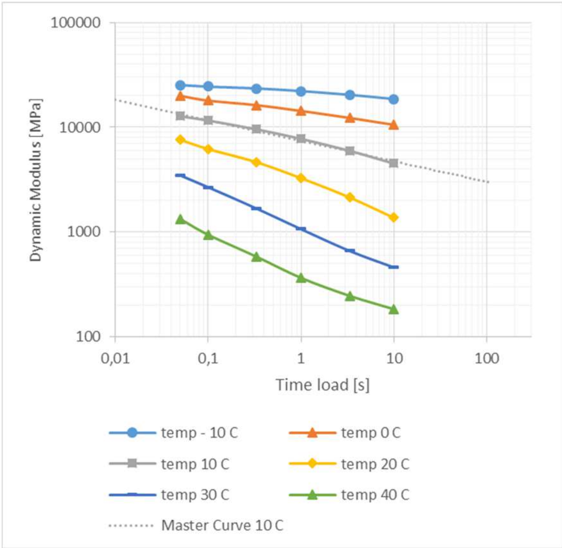

Fig. 11 Master Curve of SMA-MA 8

By analysing Figures 8-11 it can be confirmed that mastic asphalt with high grit content SMA-MA has the lowest stiffness at the test temperatures -10 to 40°C, and an AC asphalt concrete highest stiffness. At high operating temperatures (40°C) the greatest stiffness changes versus applied load time display SMA-MA mixtures (7-fold) and AC (6-fold), and the smallest SMA (4-fold). These differences stem from the type of the mineral skeleton of the individual mixtures. Due to the high content of binder SMA-MA mixture at high temperatures has a reduced resistance to static loads.

Another way of graphical representation of the test results of E * complex modulus determined by the DTC-CY is Cole-Cole plot, which allows for establishing a correlation between $E_1$and E_2 as a function of the frequency of the applied load and test temperature. By analying the results of complex modulus shown in Fig.12 it should be noted that the greatest stiffness in the full range of operating temperature shows asphalt concrete AC 11 and the lowest mastic mastic with high grit content SMA-MA 8. Both elastic part of module E_1 and viscous part E_2 is the greatest for AC 8 mixture regardless of the temperature. These differences increase with lowering measurement temperature. The stiffness of the mixtures at high temperatures, the structure of mineral mix and the amount and type of the binder have an impact on the pavement's resistance to rutting. Use of the same type of binder in all mixtures results in similar proportions between the elastic and the viscous part at high pavement operating temperature. This may indicate their similar resistance to permanent deformation. At low, negative temperatures MA 8 and SMA-MA 8 mix show the lowest stiffness, followed by stone mastic asphalt SMA 8. Low stiffness of these mixtures at negative operating temperatures is essential for pavement resistance to low-temperature cracking. Lower stiffness of asphalt mixtures at the measurement temperature of about 10°C proves their expected greater resistance to fatigue cracking.

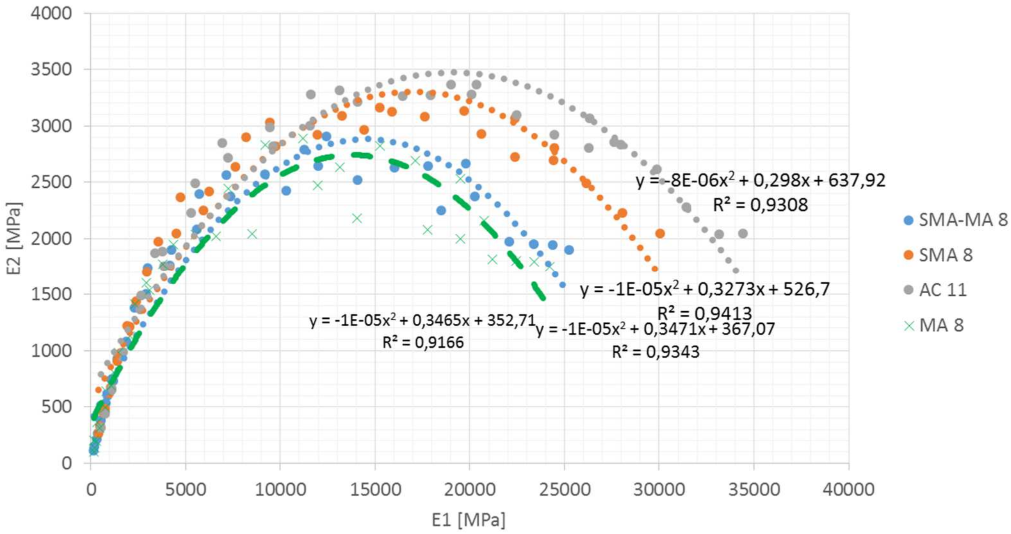

Fig 12. Cole-Cole plot of asphalt mixtures

4.3. Asphalt mix functional properties

The fatigue life and rutting resistance of mixtures for bridge deck were compared. Figure 13 shows the results of fatigue life tests for asphalt mixtures used for bridge deck pavements.

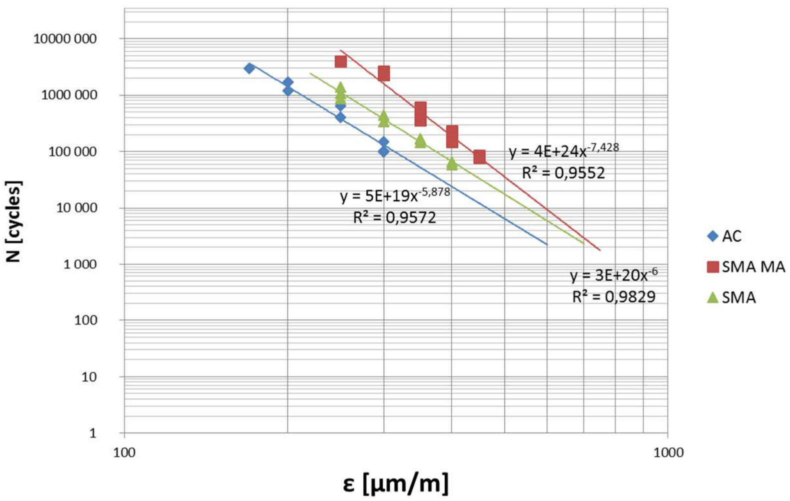

Figure 13. Fatigue life of AC 11, SMA 8 and SMA-MA 8 asphalt mixtures

An analysis of the fatigue life assessment results presented in Fig. 13 showed that for the tested asphalt mixtures, the fatigue life curves were clearly shifted towards higher fatigue life levels in the following order: asphalt concrete AC, stone mastic asphalt SMA, mastic asphalt with high grit content SMA-MA.

For the same deformation amplitude, e.g. $\varepsilon = 300$ µm/m, the fatigue life of stone mastic asphalt SMA is about 4 times greater, and that of mastic asphalt with high grit content SMA-MA about 20 times greater than the fatigue life of asphalt concrete AC.

Fig. 14 shows the rutting resistance of mixtures. The test was conducted in the wheel tracker tester. The highest rutting resistance showed SMA. In the case of a MA mixture, the test was stopped due to exceeding the maximum rut depth (20 mm). To summarize the test results, it should be stated that the SMA-MA has better rutting resistance than MA mixture.

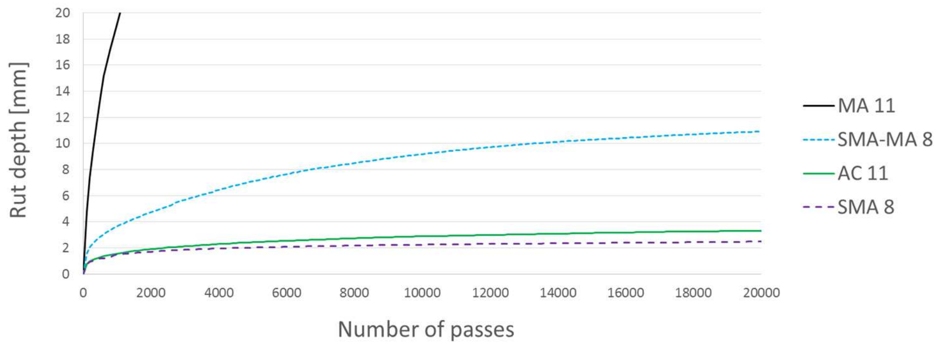

Fig 14. Rutting resistance of asphalt mixtures

5. Conclusions

Materials and technology selection for bridge pavements has a major impact on ensuring durability, safety and travel comfort. During operation the bridge pavement is exposed to greater deformation and faster temperature changes than the typical road pavement. Measurement of the dynamic modulus in the direct tension-compression on cylindrical samples (DTC-CY) enables to determine this factor in a wide temperature range (from -10°C to 40°C), and at different load frequencies (0.1 Hz - 20 Hz) .The rheological properties of asphalt mixtures can be described using the Black curve, the master curve and Cole-Cole plot.

Based on test results analysis it can be concluded that the durability of the asphalt pavement significantly affected by its rheological properties. The type of mineral skeleton affects the stiffness of the asphalt mixture at high operating temperatures. The share of the elastic and the viscous parts in the dynamic modulus depends primarily on the type and quantity of the applied binder. The study of asphalt mixtures indicate that SMA, AC and SMA-MA show positive viscoelastic properties in high operating temperature (approximately 40°C) of the pavement. It has been shown that the SMA-MA has much better rutting resistance than MA in wheel tracker test. At 10°C lower stiffness is beneficial for pavement's fatigue cracking which was confirmed in the 4-pb fatigue life test. In cold, negative temperatures far the most advantageous, therefore of the lowest stiffness showed mastic asphalt MA and mastic asphalt with high grit content SMA-MA. Low stiffness in negative temperatures has a positive effect on the durability of asphalt pavements in terms of low temperature cracking. Mastic asphalt with high grit content SMA-MA shows good rheological properties and provide material and technological alternative for use in the lower courses of bridge pavement structure.

The above analysis can serve as an introduction to the discussion on the use of modern technological solutions and materials for asphalt bridge deck pavements.

6. References

Dougan Ch. E., Stephens J. E., Mahoney J., Hansen G.:,2003. E* - Dynamic Modulus Test Protocol – Problems and Solutions. University of Connecticut, Connecticut.

Timothy R. Clyne, Xinjun Li, Mihai O. Marasteanu, Eugene L. Skok., 2003. Dynamic and Resilient Modulus of Mn/DOT Asphalt Mixtures, Minnesota Department of transportation, Minnesota 2003.

Asphalt pavements on bridge decks, 2013. EAPA European Asphalt Pavement Association , Brussels, Belgium.

Pokorski P., Radziszewski P., Sarnowski M., 2015: Rheological properties of asphalt mixtures for bridge pavements, Procedia Engineering Volume 111, Pages 637-644.

Radziszewski P., Piłat J., Sarnowski M., Kowalski K., Król J., 2016. Polish experience with usage of the innovative asphalt rubber to construct road pavements. Awtomobilnyje Dorogi i Mosty, Nr 1(17), Mińsk, p. 30 – 35

Sybilski D., 2010. Weryfikacja zależności między wartościami modułu sztywności uzyskanego różnymi metodami laboratoryjnymi według PN-EN 12697-26. Praca na zlecenie Generalnej Dyrekcji Dróg Krajowych i Autostrad Warszawa.

Piłat J., Radziszewski P., 2010. Nawierzchnie asfaltowe. Wydawnictwo Komunikacji i Łączności, Warszawa.

Piłat J., Radziszewski P., Kowalski K., 2007. Nawierzchnie asfaltowe i betonowe na obiektach mostowych. Seminarium „Nawierzchnie, izolacje i inne elementy wyposażenia mostów". Warszawa , p. 49-52.

Kilarski R., 2006. Trwałość nawierzchni ma pomostach drogowych obiektów mostowych. Materiały Budowlane 4/2006, p. 86-89.

Radziszewski P., Piłat J., Sarnowski M., Król J., Kowalski K., 2016. Nawierzchnie asfaltowe na obiektach mostowych. Monografia, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa.

Madaj A., Wołowicki W., 2001. Budowa i utrzymanie mostów. Wydawnictwo komunikacji i łączności, Warszawa.

Gaweł I., Kalabińska M., Piłat J., 2014: Asfalty drogowe. Wydawnictwo Komunikacji i Łączności, Warszawa.