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Evaluation of bituminous binder in relation to resistance to permanent deformation

Eva Remišová [a]*, Viera Zatkalíková [b]

[a] *University of Žilina, Department of Highway Engineering, Faculty of Civil Engineering, Univerzitna 8215/1, Žilina 01026, Slovakia*
[b] *University of Žilina, Department of Materials Engineering, Faculty of Mechanical Engineering, Univerzitna 8215/1, Žilina 01026, Slovakia*

Abstract

Bituminous binders are thermoplastic liquids which behave as viscoelastic materials. Their deformation behavior can be determined by rheological parameters. The changes of both viscous and elastic properties with temperature and time are measured as the response of the material to deformation by periodic forces. The paper presents the most used parameters and rheological properties for the characterization of the rutting resistance of bituminous binders and asphalt mixtures. Rheological properties (G^*, δ, η^*) are determined for four bituminous binders (unmodified and polymer modified) at temperature 46 – 60 ^{o}C (80 ^{o}C). And resistance to deformation of asphalt concrete mixtures is determined by rutting test. The higher value of complex shear modulus, the stiffer bituminous binder is able to resist deformation.

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Keywords: bitumen; rheology; complex shear modulus; asphalt; permanent deformation

1. Introduction

The increasing traffic conditions such as higher traffic volume and higher traffic axle loads demand higher performance pavements. The quality of built asphalts and used bituminous binders is one of the requirements for the satisfactory pavements. Loading forms the deformation in asphalt layers. The permanent deformation is condition of pavement failure caused accumulation of small amounts of deformation that occurs each time a load is applied.

* Eva Remišová. Tel.: +421-41-5135949.
E-mail address: eva.remisova@fstav.uniza.sk

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Rutting of asphalt mixture typically occurs during the summer under higher air and pavement temperatures when excessively deformation increases according to amount of load cycles. After unloading the elastic deformation immediately goes back due to materials elastic and relaxation properties. But certain part of deformation (plastic – permanent) remains rest irreversible cause of viscous material properties. The development of permanent deformation is influenced especially asphalt composition and material properties (aggregate, bituminous binder).

The bituminous binder is colloidal system consisting of high molecular weight asphlaltene micelles dispersed in a lower molecular weight oily medium maltenes. This colloidal structure defines the rheological properties of bitumen ranging from sol (Newtonian dominated behaviour) to gel (non-Newtonian dominated behaviour). Bituminous binders are thermoplastic liquids which behave as viscoelastic materials [1]. There are many methods available to determine the rheological properties, the cyclic (oscillatory) and creep tests tend to be the best two techniques for representing the uniqueness of bitumen behavior. The mechanical response of bitumen is a continuous function of time and temperature, an infinite number of loading conditions and responses constitute its overall behavior [2].

The changes of both viscous and elastic properties with temperature and time are measured as the response of the material to deformation by periodic forces (during forced vibration or small-amplitude oscillatory shear). A sinusoidal oscillatory shear stress is used to a sample and the resulting shear strain is measured [3]:

$$\tau(t) = \tau_0 . \sin \omega t \tag{1}$$

and

$$\gamma(t) = \gamma_0 . \sin(\omega . t + \delta) \tag{2}$$

where τ_0 is the stress amplitude (Pa), ω angular frequency (rad.s^{-1}), t time (s), γ_0 the strain amplitude and δ the phase angle of the measured material between the preset and the resulting curve (^{o}). Stress and strain are not in phase, the strain delays behind the stress by a phase angle.

The complex shear modulus G* (Pa) as the resistance to deformation is defined as a ratio of the values of the sinusoidal functions of τ(t) and γ(t):

$$G^* = \frac{\tau(t)}{\gamma(t)} \tag{3}$$

Complex shear modulus, in complex form, consists from two parts - G' (storage modulus) represents elastic behavior of material and is a measure of the deformation energy stores during the shear process, and G'' (loss modulus) represents the viscous behavior of material and is a measure of the deformation energy dissipated during a shear process [3]. Both the modulus are simply indicators of the resistance of a bitumen to deformation under a given set of loading conditions.

The linear visco-elastic properties of bitumen are generally and conveniently represented in terms of complex modulus and phase angle master curves. The behaviour of bitumen becomes more complex with the presence of waxy elements, high asphaltene contents and crystalline structures, as well as polymer modification [4].

2. Experimental

2.1. Materials

Four type of bitumen binders were used for evaluation rheological properties two pave grade bitumen CA 50/70 and CA 70/100 and two polymer modified bitumen Kraton and Sealoflex. Properties of used bitumen binders are in Table 1. Asphalt concrete AC 11 was used to evaluate of resistance to permanent deformation and to compare properties of used bitumens and asphalts. For all mixtures were used the same aggregates (andesite coarse aggregate and limestone fine aggregate) with same aggregate gradation (Fig. 1). The mixtures differed only in used bitumen type (paving grade bitumen and polymer modified bitumen).

Table 1. The empirical parameters of used bitumens.

Bitumen properties	CA 50/70	CA 70/100	PMB Sealoflex	PMB Kraton
Softening point, in °C	48.2	46	89	82.8
Penetration, in 0.1 mm	58	82.7	71.5	82
Penetration index	-1.1	-1.0	6.5	6.2
Viscosity at 60°C, in mPa	209000	167000	342000	347000
Viscosity at 130°C according EN 13302, in mPas	1271	471	10042	4200

Particle size distribution of tested asphalt concrete with different bitumen is in Fig. 1. The mixtures were produced in the laboratory according to EN 12697-35+A1. Laboratory specimens were prepared by roller compactor.

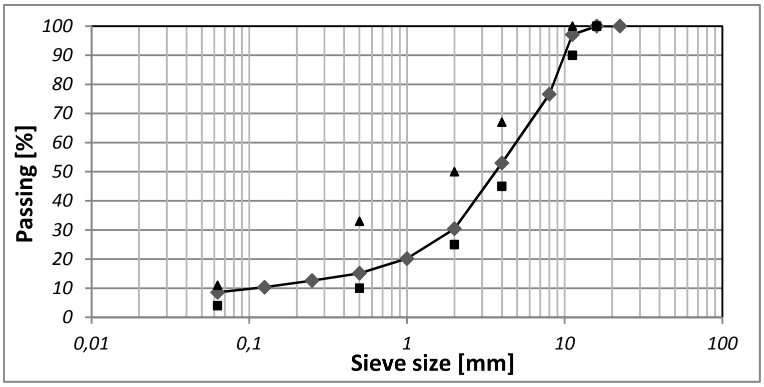

Fig. 1. Particle size distribution of aggregate mixture.

2.2. Dynamic shear rheometer test

Measurements were performed according to EN 14770 using the oscillatory Physica Rheometer MCR301 with convestion heating device CTD 450. The applied method was Frequency Sweep test that enables monitoring of rheological parameters G', G'' and η^* in the chosen interval of angular frequencies. A thin asphalt binder sample fitted between two parallel plates (PP25 system) with 25 mm in diameter and a small gap of 1 mm. The test is performed under the following conditions:

- the test temperatures 40, 46, 50, 54, 60 and 80 °C
- amplitude of deformation γ_A 5 %
- and angular frequencies ω in the range of 10 - 200 rad.s^{-1} at temperatures 46, 50, 54 and 60 °C, and in range 10 - 600 rad.s^{-1} at temperatures 60 and 80 °C.

The complex modulus G^* and phase angle δ is calculated from recorded values of rheological parameters.

2.3. Wheel-tracking test

Test method EN 12697-22 determines the susceptibility of bituminous materials to deform under load. The resistance to permanent deformation is assessed by the rut formed by repeated passes of loaded wheel at constant temperature. The slabs of asphalt placed in small-size device is subjected to 10 000 tracking (forward and backward moves at distance 230±10 mm and frequency 26.5±1 load cycle/60s) at temperature 50 °C. Vertical position of the loaded wheel was measured automatically and recorded in data acquisition system. The resistance to permanent deformation is characterized by a wheel tracking slope WTS_{AIR} in mm/10^3 load cycles between cycle 5000 and cycle 10000 and a proportional rut depth PRD_{AIR} in % at 10000 load cycles.

3. Results and discussion

The rheological characteristics, studied in dynamic shear rheometer are showed in Fig. 2. In case unmodified bitumens (50/70, 70/100) phase angle is larger and characterizes a bitumen as more viscous material. The measurements show the phase angle is responsive to type and chemical structure of bitumen as [5] presents. The modification of bitumen improves elastic response (reduced phase angle). The results of complex modulus *G** show an increase with load frequency and a decrease with temperature. Compared to unmodified binders, the increase in *G** for modified bitumens is given by storage modulus *G´* that is associated with the elastic part of material behavior. This signifies the modified bitumens are more resilient and a bit stiffer than unmodified binders. At temperature 80°C, the increasing loading frequency the bitumen more viscous behavior. The stiffness of bitumen is one of the main factor affecting stiffness modulus of asphalts and so it can be used for initial assessment of the resistance to rutting in the asphalt mixture designing process as [6, 8] present.

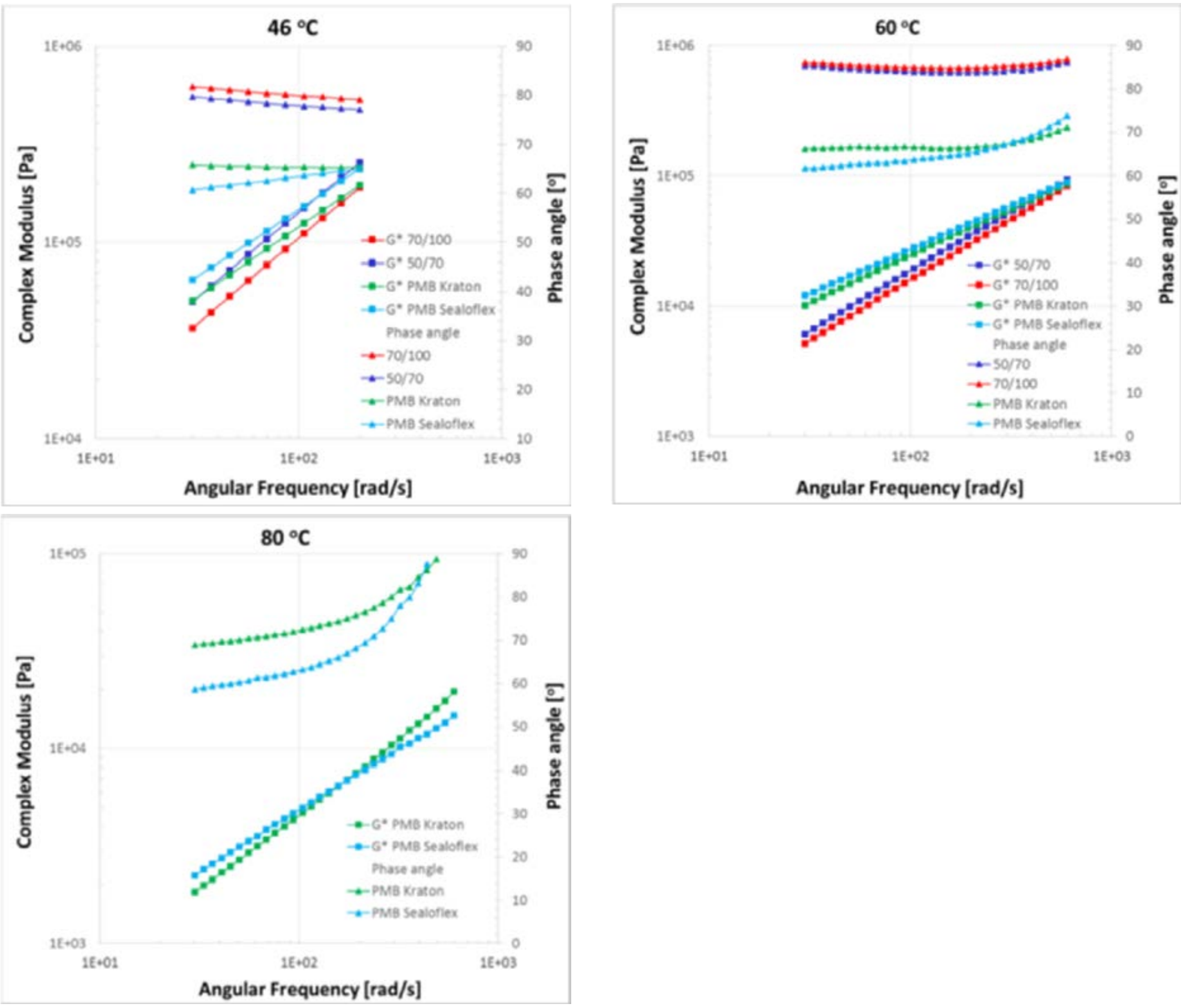

Fig. 2. Complex modulus and phase angle of tested binders at temperatures 46, 60 and 80 °C [7].

Permanent deformation is the accumulation of the non-recoverable component of the responses to load repetitions at high service temperatures. The Superpave specification defines and places requirements on a rutting factor, $G^*/\sin\delta$ (Fig. 3), that represents the high temperature viscous component of overall binder stiffness. Higher values of G^* and lower values of δ are considered desirable attributes from the standpoint of rutting resistance.

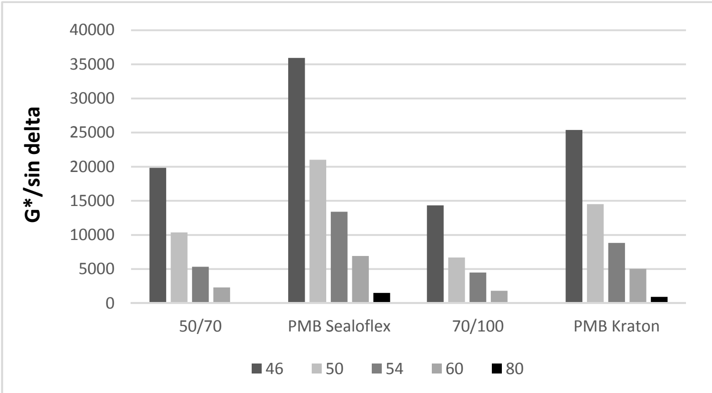

Fig. 3. Results of parameter $G^*/\sin\delta$ of tested binders at temperatures 46, 50, 54, 60 and 80 °C.

The results of performance of the asphalts (with different binders) under wheel-tracking load according to EN 12697-22 are presented in Table 2. The results at typical test temperature 50 °C of all test parameters are better values for using modified bitumen in mixture. Mixtures AC11 with paving grade bitumen 70/100 and 50/70 led to higher deformation rate. As expected bitumen with softening point below the test temperature has higher values of deformation parameters.

Table 2. Wheel-tracking test results of asphalt concrete AC 11 with different binder.

Properties	AC11; 50/70	AC11; 70/100	AC11; PMB Sealoflex	AC11; PMB Kraton
Bulk density, in $Mg.m^{-3}$	2.36	2.40	2.33	2.37
Rut depth RD_{AIR}, in mm	1.6	2.4	1.2	0.9
Proportional rut depth PRD_{AIR}, in %	4.2	5.8	2.8	2.1
Wheel-tracking slope WTS_{AIR}, in $mm.10^{-3}$ load cycles	0.06	0.08	0.03	0.02

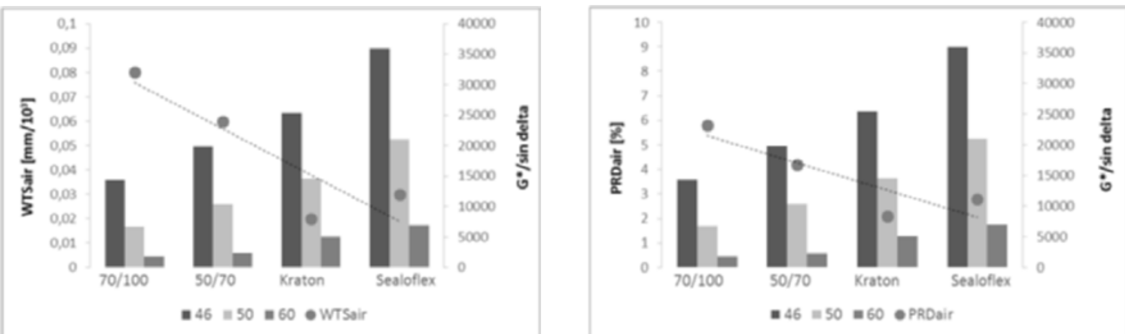

Fig. 4. Comparison of results of wheel-tracking test of asphalts and rheological properties of bituminous binders.

Presented results in Fig. 4 show dependence between deformation properties of mixtures and binders. The rate at which rut depth increases with time under repeated passes of loaded wheel (WTS_{AIR}) and proportional rut depth (PRD_{AIR}) show difference between unmodified and modified binders. This difference is also represented by the value of rutting factor ($G^*/\sin \delta$) which decreases with increasing temperature. Higher values of rutting factor (at higher service temperatures) determine higher resistance of binder to deform and represent mixture with modified bitumen.

4. Conclusion

The resistance of asphalt mixtures against permanent deformation is one of important requirements that have to be verified in the design process of asphalt mixtures. Standard test methods as wheel-tracking test or uniaxial and triaxial cyclic compression tests verify deformation behavior of asphalts. In design process it is possible on the base testing of bituminous binder properties to predict susceptibility of asphalts to deformation. Besides basic bitumen properties as penetration and softening point, the performance tests as determination of complex shear modulus and phase angle are used. The DSR provides a more complete picture of the behavior of bitumen at pavement service temperatures. From laboratory measurement of bitumens and asphalts properties there are some conclusions.

Polymer modified binders achieve higher values of evaluated rheological parameters G', G'', η^* in the defined interval of angular frequencies at the temperatures of 46 to 80 °C.

The results of complex modulus G^* show an increase with load frequency and a decrease with temperature. Higher values of G^* and lower values of δ determine higher value rutting factor ($G^*/\sin \delta$) and so resistance to deformation.

To compare with susceptibility of asphalt mixtures to deform under load (wheel-tracking) higher resistance of mixture using polymer modified bitumen was confirmed.

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