Binder performance and testing

ON THE RELATIONSHIP BETWEEN PENETRATION AND RUTTING FACTOR IN SUPERPAVE (G*/sinφ)

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Abstract

Bitumen properties have a decisive influence on asphalt concrete parameters and the ability of the asphalt concrete to resist environmental and traffic conditions. The residual deformations are a result of influence of these conditions. Bitumen must have a specific consistency to prevent the residual deformations. For many decades this consistency was evaluated with empirical indexes such as depth of a needle immersion and a softening point temperature. In the middle of 90th last century it was proved theoretically and experimentally that reverse pliability as a result of dividing of complex modulus at shear on sine of phase angle (G*/sinφ) is a more proper characteristic for rutting resistance evaluating. In USA SHARP Superpave evaluating system normalizes this parameter as equal or more than 1 KPa for the virgin bitumen for all PG regions. At the first stage of the implementation of this system it was made a lot of attempts to link G*/sinφ with a conventional indexes of the bitumen such as penetration and a softening point temperature. This simplified approach isn't taking into account rheological aspects of the problem. In this research work is made an attempt to ground the shear character of process of needle immersion, to find the shear stress at immersion, to calculate shear stress value at shear rate 10 rad/s and 60 °C with G. Carre & D. Laurent method and to compare shear stress values with G*/sinφ values, founded with shear rheometer. The results of experimental research and calculation with other authors' data show connection between G*/sinφ and shear stress that calculated with depth of needle immersion. Rheology seen this states proportionality between viscous modulus G'' and shear stress at equal frequency and shear rate for sol and sol-gel type of bitumen. Key words: bitumen, penetration, complex shear modulus, elastic modulus, viscous modulus, phase angle, penetration index, viscosity anomaly

1. INTRODUCTION

Empirical characteristics of bitumens (such as penetration, softening point temperature, ductility, and Fraas breaking point) are a standard of quality assessment of paving grade bitumens and their grading for many decades. The area of bitumen application has been appointed by taking into account environmental conditions of road in a specific region. Meanwhile, conventional mechanical and rheological properties of bitumen could be more reliable for predicting the quality of asphalt concrete and its durability under traffic loads in road construction. Though the reorientation of mechanical and rheological properties is complicated with the temperature susceptibility of bitumen and the influence of applied frequency or shear rate. The temperature susceptibility of bitumen is a peculiarity that has attracted attention from founders of rheology [1, 2].

A key factor in rheological research of bitumens is the method of harmonic oscillations. This method enables determination of the complex shear modulus (G*) and its components (elastic modulus (G′) and viscous modulus (G″)), as well as the applicability of the time–temperature superposition law by Williams–Landel–Ferry (WLF) equation [3]. With help from the WLF principle, a wide range of module changes with frequencies at different temperatures of recalculation can be considered.

Rheological research is complicated, requiring unique equipment and highly professional specialists. Therefore, numerous attempts have been made in the past to quantify the relation between rheological properties and penetration as one of the priority indexes of bitumen consistency. The most effective work was on a graph that shows the value of the stiffness modulus at a given loading time [4]. This graph was based on empirical indexes, such as penetration and softening point temperature. Meanwhile, Van der Pool warned that this graph shows relevantly reliable values of stiffness modulus at low stress. This fact highlights the need to restrict the test by the linear stress-strain zone, as reaching a rectangular-shape impulse load was difficult 70 years ago.

In the late 1980s, American researchers performed global dynamic research of bitumen that led to the creation of Strategic Highway Research Program (SHRP) Superpave, which is free from conventional indexes of bitumen quality [5]. Reverse pliability G*/sinφ is implemented as a measure of rooting resistance. In this equation, φ is the phase angle between stress and strain at a PG region temperature (from 46 to 82ºC) and a shear rate of 10 rad/s. Experimentally, bitumen with G*/sinφ higher than 1 kPa was found to guarantee shear resistance of the asphalt concrete in any region.

2. ATTEMPTS TO ESTIMATE RHEOLOGICAL PROPERTIES OF BITUMEN WITH PENETRATION

Nevertheless, attempts to estimate rheological properties of bitumen with penetration continued by gathering comprehensive knowledge of bitumen rheology. The method and equations of G. Carre and D. Laurent are estimated to be the most successful [6]. Seven groups of bitumen, with close penetration in each group but various penetration indexes (PI) (from –1.1 to +4.3), were tested to obtain the quantitative relationship. Twenty bitumens were tested, in general, this way. Viscosity was obtained by a monoplanar shear method, and the values of viscosity at equal shear rate (for each group) were found. Despite great appreciation for this advancement (award of Ch. Bihoreau was given in 1962 by the Association Francaise des Technicians du Petrole—A.F.T.P.), these equations were not implemented with a practical purpose because viscosity values were obtained at various shear rates, which changed from 0.02 to 2 s^{-1} with penetration. A more important reason these equations have not been used could be because the obtained viscosity at 25ºC is a technological characteristic. However, for practical purposes, deformation-strength properties at an environmental temperature of road pavement are required. These strain-stress properties are presented in a Superpave system, but a situation, similar to the one mentioned for viscosity, were repeated for reverse pliability (G*/sinφ). Due to the complexity of the required test procedure, attempts were made to change PG gradation on G*/sinφ with penetration and softening point temperature limits [7, 8, 9].

Publication [7] suggested using appropriate bitumen penetration values for each PG region in the U.S.A. (from 34 to 84ºC), not taking into account temperature and frequency susceptibility of bitumen. Chappat M. & Ferraro M. and Ramond G. & Such Ch. [10, 11] warned against unreasonable use of SHRP criteria in Europe because European bitumens differ from American bitumens, as do the environmental conditions of road pavement. To connect both European and American bitumen quality systems in research [12], the Van der Poel graph and penetration index was used. Also, use of the SHRP system in Europe can lead to changes in the conventional choice for the optimal amount of bitumen in the mix for a specific region. Meanwhile, the implementation of rheological parameters of bitumen (mostly obtained with Dynamic Shear Rheometer) receives a positive rating by [11]. Moreover by [9, 11, 13], finding the temperature where G*/sinφ=1 kPa·s is advisable.

The vulnerability of replacing G*/sinφ by penetration and softening point temperature can be explained by following. At first, the parameters of penetration and G*/sinφ cannot be compared by units. Secondly, for bitumens with the same penetration but various structural types (sol, sol-gel, or gel), temperature and shear rate susceptibility are not taken into account. Thirdly, penetration is not related to a shear rate of 10 rad/s, where complex modules and viscosity are obtained.

3. REASONS FOR FINDING G*/SINφ BY SHEAR STRESS AT BITUMEN PENETRATION

The penetration test can be considered an immersion of the cylindrical indenter with the frustum tip [14]. Good contact of the all needle surfaces with bitumen, without slipping in the immersion process, is the main condition of the test. Taking this into account, the penetration test scheme was considered identical to the same scheme of a planar shear by [15]. As a result of this consideration, G. Carre and D. Laurent proposed equations for calculation of the shear stress and deformation rate in the penetration range from 10 to 530 dmm. These characteristics were compared with shear stress and viscosity values at a monoplanar shear. Thus, penetration was proven to be a shear characteristic. The calculation of shear resistance on a penetration value with equations from G. Carre and D. Laurent and its comparison with shear resistance at the viscosity test in a rotary viscometer has shown good agreement with results from [15].

Later, values of the viscous modulus (G″) and shear stress (τ) were found to be relevantly close at equal shear rates and circular frequencies for sol- and sol-gel-type bitumens [16], confirmed by the data in Table 1 and Figure 1. The viscous modulus (G″) for sol-type bitumen (penetration index of –1.13), in a wide range of deformation frequencies from $4\cdot10^{-3}$ to 17 s^{-1}, is in linear correlation (on a power dependency) with shear stress at appropriate rates, even at 25ºC. Naturally, with a temperature rising up to 60ºC, agreement between these parameters is increasing. For sol-gel-type bitumen (penetration index is 0), such a correlation at 25ºC is limited to a shear rate of 0.1 s^{-1} and, at 60ºC, to a shear rate of 100 s^{-1}. For a gel-type bitumen with a PI equal to 3.03, there is no agreement between G″ and τ at either 25 or 60ºC, even at a shear rate of $8\cdot10^{-4}$ s^{-1}.

Table 1. Influence of the composition and structure of bitumen on their rheological properties.

Structural type of bitumen	Penetration, P_{25}, dmm / PI	Softening point temperature Ts, ºC	Dynamic modulus, kPa			Sine of phase angle sin φ	G*/sinφ, kPa	Experimentally τ_{60}, kPa
			elastic G′	viscous G″	complex G*			
sol	80 / –1.13	45	0.195	1.0	1.03	0.98	1.06	1.10
sol-gel	82 / 0	50	0.251	1.58	1.59	0.96	1.66	1.51
gel	82 / 3.03	63	6.31	7.94	10.14	0.78	13.0	4.00
sol-gel	57 / –0.04	53,5	2.15	4.34	4.84	0.89	5.44	5.10
sol	72 / –0.43	49,5	0.69	2.15	2.25	0.95	2.37	2.54
sol	120 / –0.20	45	0.2	0.86	0.86	0.96	0.90	1.44

Note: Temperature of the test is 60ºC; circular frequency is 10 rad/s

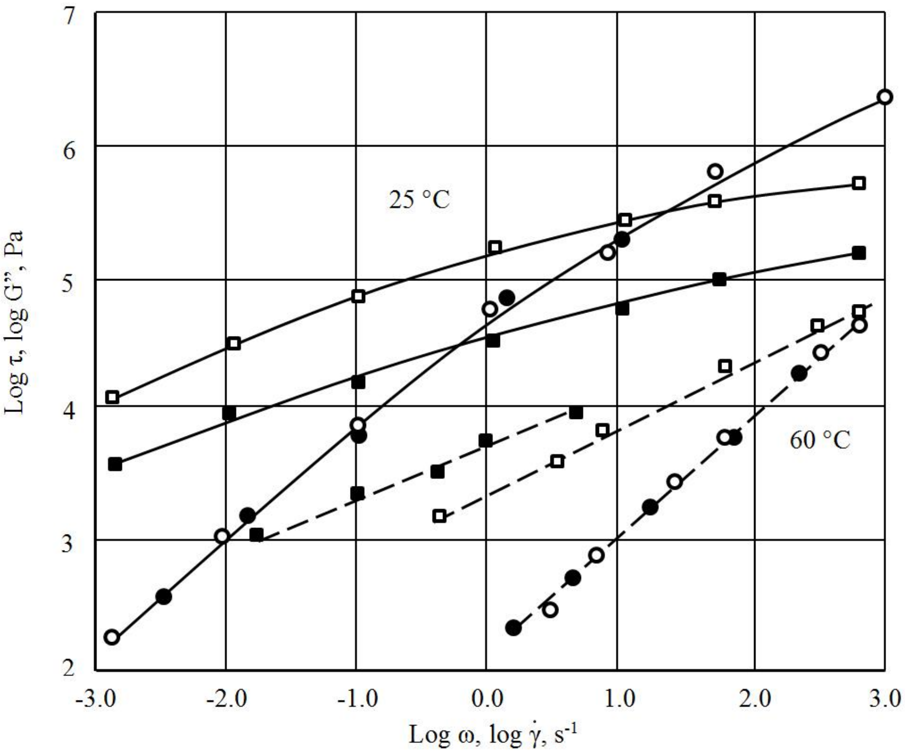

Figure 1: Influence of temperature (25 °C –, 60 °C --), shear rate ($\dot{\gamma}$) and rotary friquency (ω) on viscous modulus G'' (○□) and shear resistance τ (●■) of bitumen sol (○●) and gel (□■) type

Further, for the sol-type bitumen at 60ºC, the viscous modulus (G″) is 5.1 times higher than the elastic modulus (G′). Meanwhile, for the gel-type bitumen at 60ºC, this ratio reduces to 1.25. The phase angle at 60ºC for the sol-type bitumen is 79º, and for the gel-type bitumen, it is 51º. The viscous component of the complex modulus for the sol-type bitumen at 60ºC is much lower than for the gel-type bitumen. For the gel-type bitumen, unlike the sol-type bitumen, the differences between complex modulus (G*) and viscous modulus (G″) become significantly higher. Meanwhile, the value of G*/sinφ for bitumen sol and sol-gel are close to the value of G″. The same tendency can be observed for bitumen of high penetration, in contrast with more viscous bitumen.

The shown data allows a statement to be made that values of G*/sinφ and of shear stress getting closer upon higher values of the phase angle between the elastic and viscous components. Shear stress values, which were experimentally obtained for sol- and sol-gel-type bitumen, are also close to the values of the complex modulus and the viscous modulus. However, for gel-type bitumen, this parameter differs significantly. Similarity of the complex modulus and shear stresses can be based on closeness of the sol- and sol-gel-type bitumen to a Newtonian liquid. The phase angles of all three bitumens, sol, sol-gel, and gel, are 79º, 74º, and 51º, respectively, meaning the difference between G″=G*·sinφ and G*/sinφ is 9% for sol-type bitumen (1.01 and 1.05 kPa) and 65% for gel-type bitumen (7.9 and 13.0 kPa).

4. THE ABOVEMENTIONED STATEMENTS LET TO SUBSTANTIATION THE GOAL OF RESEARCH WORK.

It consists in finding the rutting factor, G*/sinφ (a strength characteristic by its nature), with the depth of a needle penetration at 60ºC and on values of shear resistance founded with temperature-penetration dependencies of bitumen and implementing this parameter for predicting asphalt concrete properties at this temperature. The main idea of this finding is as follows. Penetration is a shear characteristic, and its calculation is possible with an approach used by [6]. Shear stress (τ), at constant shear rate, is in relation with the viscous modulus (G″) that was obtained in a region of linear deformation. Meanwhile, the reverse pliability G*/sinφ is a shear characteristic, as well. The phase angle is high for bitumen, with a low penetration index, which makes G*/sinφ, G″, and τ close. This makes correlation between values of G*/sinφ and shear stress calculated with penetration possible.

Finding shear stress with penetration, which is possible at 25ºC, becomes more reliable at 60ºC. However, experimentally finding penetration at this temperature is quite complicated. Meanwhile, Van der Poel [4] and W. Heukelom [17] graph a linear correlation between the logarithm of penetration and test temperature in a range limited by a breaking point temperature (stiffness modulus is $3{\cdot}10^9$ N/m^2) and softening point temperature (penetration value is 800 dmm). The linearity of the logarithmic dependence in [4], between viscosity and penetration, makes reasonable use of the method of extrapolation for finding the penetration value at 60ºC. This is suitable for bitumens with penetration indexes no higher than +0.7, softening point temperatures around 60ºC, and penetration values no lower than 30 dmm. This extrapolation method may be reasonable for all bitumen grades that are normalized by EN 12591:2009.

5. RESULTS OF THE EXPERIMENT AND CALCULATION

Data, obtained by the author and experimental results, published by [18], that relate bitumen PG 58 and PG 64 (30 binders) are used to prove the possibility of calculating bitumen shear resistance with a penetration value. Further data references are included [8, 19, 20, 21]. With the abovementioned concept, the specific sequence of the analysis tests and calculation are used for this research.

Penetration at 60ºC is obtained by an extrapolation of experimental data in a range from 15ºC to the temperature of an 800 dmm penetration value (Figure 2). There is no further extrapolation on temperatures higher than 60ºC, but the data from [18], which is higher on 4ºC and lower on 2ºC, is recalculated to this temperature. This process is provided with recommendations from [22].

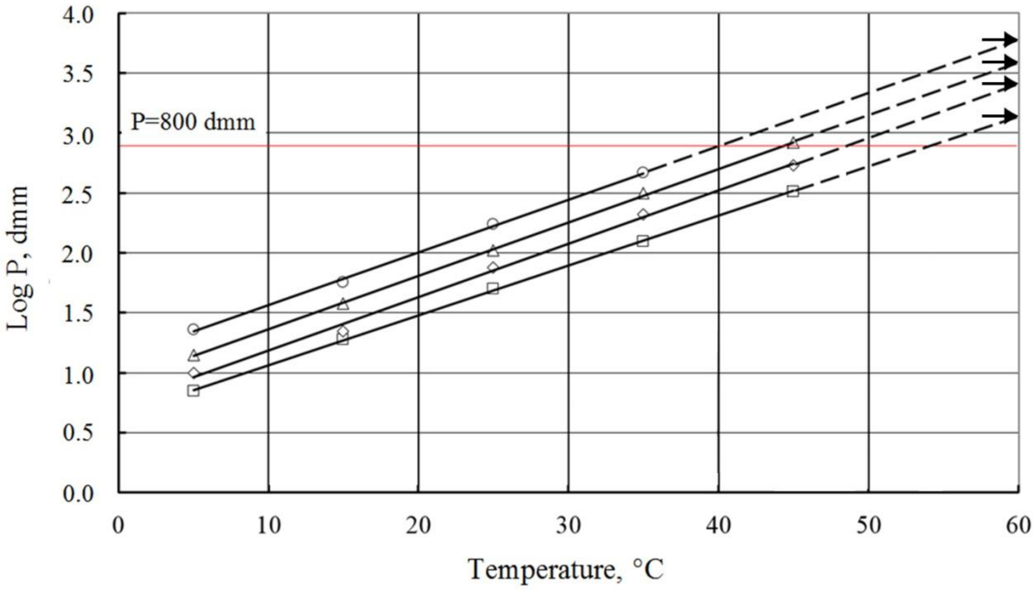

Figure 2: Determination of penetration at 60 °C with temperature dependancies of bitumens with penetration at 25 °C (dmm): 50 (□), 75 (◊), 105 (Δ), 172 (○)

Equations (1–3), from reference [6], are used to calculate shear resistance at 60ºC (τ_p) and a respective shear rate ($\dot{\gamma}_p$) with penetration P_{60}.

$$\dot{\gamma}_p = 1.44 \cdot 10^{-3}\ P^{1{,}04} \tag{1}$$

$$\tau_p = \frac{3.95 \cdot 10^2}{(P_{25}^2 + 19P)}\ , \tag{2}$$

with $P_{25} \leq 54$ dmm and

$$\tau_p = \frac{3.12}{P_{25} - 22.88}\ , \tag{3}$$

with $P_{25} > 54$ dmm.

Penetration dependencies of these characteristics are shown in Figure 3.

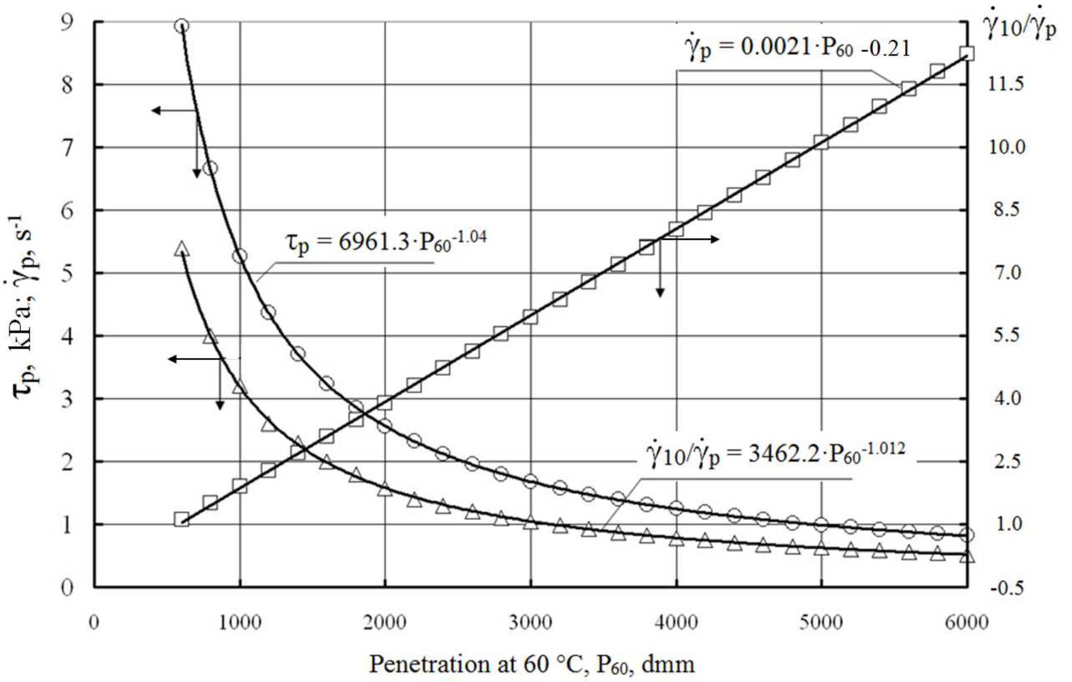

Figure 3: Influence of penetration at 60 C on shear stress τ (○), shear rate $\dot{\gamma}_P$ (□) with the immersion of the needle and $\dot{\gamma}_{10}/\dot{\gamma}_P$ proportion (Δ)

With penetration changing from P_{60} = 800 to 6000 dmm, the calculated values of stress decrease with a factor of 8.2 times (from 6.6 to 0.8 kPa). Each penetration relates to its own speed of needle immersion. For the same penetration limits, the speed of needle immersion increases 9.4 times (from 1.3 to 12.2 s^{-1}).

With the individual speed for each penetration, the shear resistance at various penetrations cannot be compared. The same relates to all equations suggested earlier for the calculation of viscosity with penetration. Even the unique research by [6] is not flawless. The shown values of viscosity are calculated with different shear rates and for bitumens of various structural types. The dependencies of flow for bitumens with equal penetration but differing penetration indexes are varying (Figure 4). From the point of equal penetration, they form a fan of lines. This is always repeats on shear rate or frequency dependencies of viscosity, shear stress, elasticity modulus, viscous modulus, and complex modulus [16].

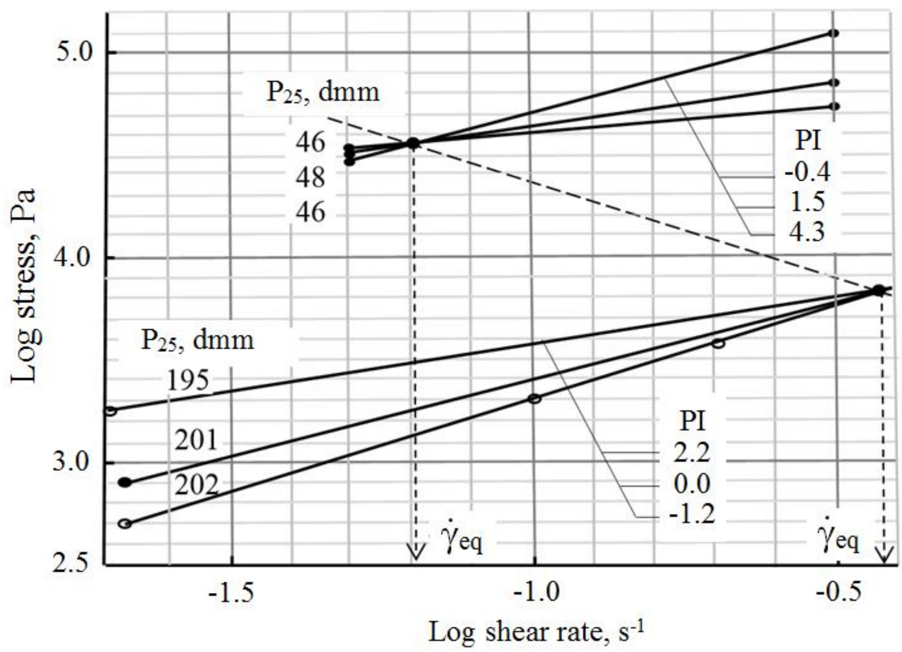

Figure 4: Relation between shear stress and shear rate of bitumen with various penetration and penetration index (example for two penetration groups), calculation of data [6]

Thus, it is necessary to take into account the viscosity anomaly (VA) of each bitumen at 60ºC in the conversion of the shear rate at penetration ($\dot{\gamma}_p$) to the shear rate of 10 rad/s, pointed in SHRP. Viscosity anomaly is obtained with the same method described by [15] for 25ºC and considers the relationship of viscosity anomaly and penetration index. The dependence of the viscosity anomaly on penetration index at 60ºC is made based on the author's data and previous publications [6.23]. Two correlations at 25ºC [15] and 60ºC are shown in Figure 5. Naturally, with the temperature increasing, the behaviour of any bitumen becomes more Newtonian, and its viscosity anomaly increases to 1.0. With the limited amount of data on the viscosity anomaly of bitumen with a penetration index higher than +1.0, the use of the right part of the curve can lead to less precise result than the left one.

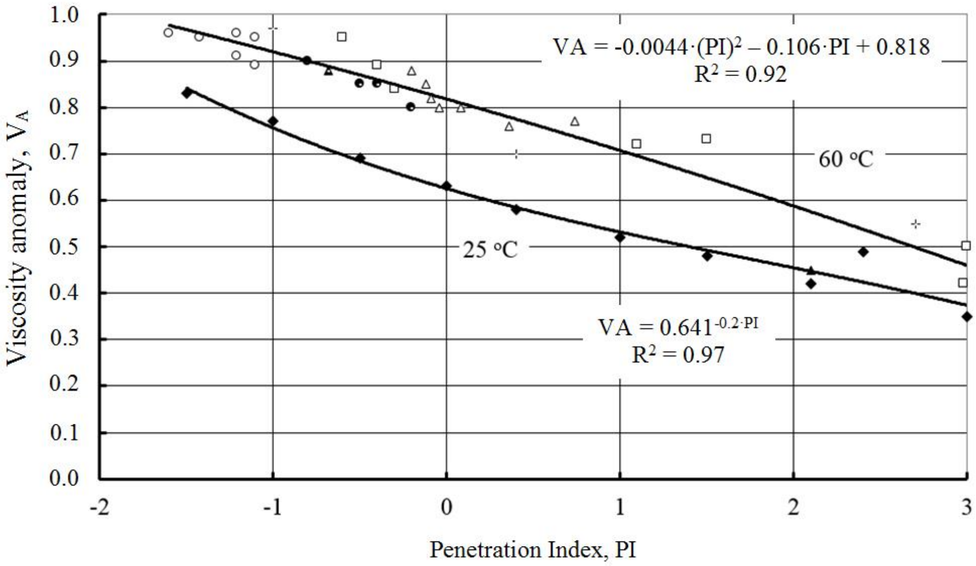

Figure 5: Relation between Viscosity Anomaly (VA) and Penetration Index (PI) by the authors data (○,●,+, Δ), by [6] (□), by [15] (◊)

The proportions between shear rate ($\dot{\gamma}_{60}$) at each penetration at 60ºC and shear rate of 10 s^{-1} (Figure 3) are calculated to convert stress values (τ_p) under the same conditions with equation 4.

$$\tau_{10} = \tau_p \left(\frac{10}{\dot{\gamma}_p}\right)^{VA} \tag{4}$$

VA is the viscosity anomaly in the equation. According to equation 4, the calculation algorithm is included in the finding of initial penetrations at 25 and 60ºC. The penetration index is calculated with the softening point temperature at a penetration value of 800 dmm [24], and stress is calculated (with equations 2 and 3) at a needle immersion rate ($\dot{\gamma}_p$) that corresponds to each penetration value at 60ºC (with equation 1). Proportions are calculated with $\frac{\dot{\gamma}_{10}}{\dot{\gamma}_p}$, viscosity anomaly with dependence on Figure 5, and shear stress τ_{60} with equation 4.

With obtained results, the dependency of G*/sinφ on τ_{60} is shown in Figure 6. The distribution of calculated points forms a relationship that can be described with the equation G*/sinφ = 0.717·τ_{60} + 0.448, with a correlation coefficient of 0.61. The low correlation coefficient can be explained with a few reasons. First, the stress scheme changes when switching from a conical to a cylindrical part of a needle at an immersion on a depth of 54 dmm. The influence of the conical part of the needle decreases to an insignificant level after reaching an immersion depth around 70 dmm. Secondly, an error at the penetration test (from 2 to 27 dmm) and softening point temperature (from 1.7 to 3.3ºC) may also contribute to the low correlation coefficient [18]. This can lead to a change in the penetration index, in first case, from 0.05 to 0.70 and, in second case, from 0.35 to 0.80, that cannot omit an influence on viscosity anomaly values. With research on statistic deviations of bitumen quality indexes, authors [13] stated that that reproducibility in determining the softening temperature corresponds to 3ºC, and repeatability, 2ºC. The reproducibility of the complex module at 60°C is 54%, and the repeatability is 39%. The phase shift angle reproducibility is 11% and repeatability, 10%. According to previous work [13], the shift of softening point temperature on 1ºC changes the value of stiffness modulus by 10%, a shift on 2ºC changes by 30%, and a shift on 3ºC changes on 45%.

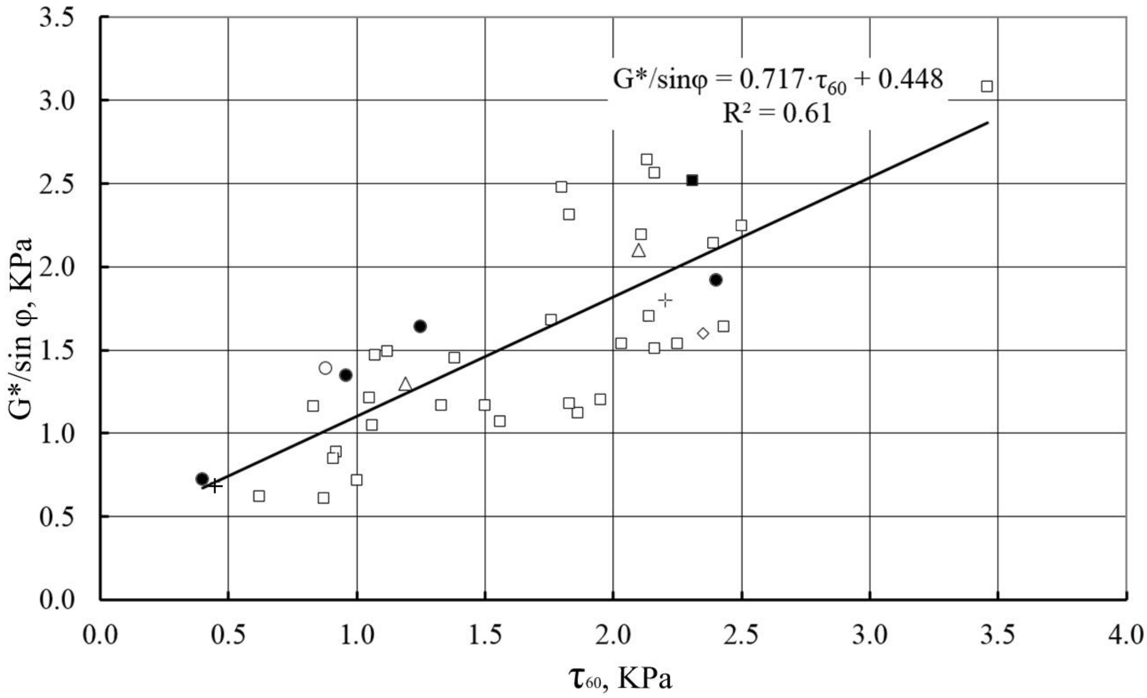

Figure 6: Correlation between G*/sinφ and shear stress τ_{60} by [18] (□), [8] (+ ■), [20] (Δ), [21] (●)

The base condition of the suggested method uses a penetration index, founded by a temperature at a penetration of 800 dmm. This is caused by a significant difference that may appear between the softening point temperature by the Ring and Ball test and T_{800} [24], especially in a case of bitumens with high values of PI. Applying the automatic measurement systems significantly decreases test errors, but the influence of the "human factor" and permissible test errors still remain. Values of G*/sinφ, obtained by author and marked in Figure 6 with - ○,●, +, Δ, from data by [6] and marked with □, and from data by [23] and marked with – ■, correlate reasonably well with the dependence in Figure 6. This is related to the results of work from [15], too.

In favour of the solution proposed here, numerous empirical attempts to estimate the stiffness modulus of the bitumen with penetration and penetration index are evidenced. Which was shown in the common Van der Poel's graph [4] and proved by dependencies of the bitumen stiffness modulus of varying types of penetration, as shown by Heukelom [17], J.M. Molenlaar [24] and given in [25].

6. CONCLUSION

The shear stresses that appear in sol- and sol-gel-type bitumens (with penetration indexes ≤ 0.7) at stationary deformation are close to their values of viscosity modulus (G′′) and rutting factor (G*/sinφ) at 60ºC. These stresses can be calculated with penetration values, recalculated to a temperature of 60ºC and shear rate of 10 rad/s. The usage of the suggested method can simplify the choice of bitumen grade and type for specific conditions, according to the Superpave principles.

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