Binder performance and testing

Bitumen penetration and shear resistance relation

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Abstract

Over a hundred years bitumen penetration is a criterion for the indirect measuring of the bitumen stiffness. The empirical nature of penetration stimulated researchers to find its relationship with truly rheological characteristics of viscosity (R.N. Saal & G. Koens – 1933) or possibility to replace penetration with complex shear module divided on sinus of phase angle at dynamic deformation (SHRP Superpave – 1991). The conversion of penetration into shear resistance at applied shear rate for the bitumen seems to be more perspective and physic based. Such conversion based on calculation of the shear rate and resistance on the depth of the needle immersion by the G. Carre & D. Laurent viscosity calculation method (1963). Difference in the susceptibility of the resistance to the shear rate for bitumen sol, sol-gel and gel structure accounting is the required condition for this calculation. The determination of this susceptibility based on the fact that equal penetrations bitumen with different structure type have common equipenetration and equirate point at shear. On this point it is possible to calculate shear resistance at different shear rates. The shear rate 1 s-1 is taken as equal for all bitumen in calculations. Relation between viscosity anomaly index and penetration index (PI) as relation between equiviscosity rates / shear resistances and penetration where established on the data of G. Carre & D. Laurent, R.N. Traksler and others authors. To find the bitumen shear resistance by known depths of the needle penetration and penetration index values using established relations is consider as possible. The difference between calculated experimental and shear resistance values no higher than 15 %. The conversion of conditional bitumen index – penetration – into the classical criteria – shear resistance – making the prediction of asphalt concrete shear resistance possible, which has a great practical value.

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1. INTRODUCTION

In the paper by V. Filippov [1] it is emphasized that "Bitumen is a very convenient material for research ..., and its properties change in a wide range with temperature and ... frequency. These results seem to be typical for viscoelastic liquids ... the properties found in other systems are reflected in bitumen particularly sharply." Such conclusions are made based on the studies performed at the Franklin Institute of the United States. Before this, R.N. Traxler [2], using shear deformation, obtained the rate dependency of bitumen shear stresses (τ) which allows indicating the features of its flow both in Newtonian and anomalous systems. The closer the exponent approaches 1, the closer is the bitumen flow to the linear. The higher the shear rate ($\dot{\gamma}$) or the stress, the more prominent is the nonlinearity. In this connection, the comparison of any rheological characteristics of bitumen must be carried out at the equal rates or within the rate range corresponding to the Newtonian flow.

As soon as bitumen is a thermoplastic material, all mechanical characteristics (viscosity, modules of accumulation and loss, thixotropy and anomaly) depend on temperature. The range of bitumen linear behavior is expanding (according to shear resistance, shear modules) if the temperature is increased [3].

In addition to external influence, the rheological behavior of bitumen depends on its composition and the structures corresponding to the composition. There is a division of bitumen into structural types which at the same level of consistency can be: sol, sol-gel, gel (II, III, I types according to the study [4]). Traditionally, for technical purposes, the consistency of bitumen is determined by the depth of the needle penetration. The depth of the needle penetration for more than 100 years is a criterion for the division of bitumen into grades practically all over the world. Only in the USA, since the 90s of the last century, the partial division of the complex shear modulus on the sine of the shear angle phase ($G^* / \sin \varphi$) is accepted as a criterion for the consistency of bitumen. Currently, the European Committee for Standardization (CEN) is attempting to include this indicator as an additional index in the standard EN 12591: 201X.

The influence of composition and structure on the rheological properties of bitumen at its transition from sol type to gel type consists in an increase in its flow anomaly, change in the ratio between shear resistance and shear modulus during increasing rate or deformation frequency, appearance of shear strength limits and thixotropy enhancement [2, 3]. In the chemical aspect, the division into structural types is carried out according to an index of colloidal stability which is the ratio of the sum of asphaltene and saturated hydrocarbons and the sum of resins and aromatic hydrocarbons.

It is considered that bitumen obtained by oxidizing the low-viscosity initial source materials has a sol-gel type structure while bitumen obtained by vacuum distillation from the consistent source materials correspond more to the sol type [5]. Bitumen's temperature susceptibility is important to expand and deepen the understanding of the bitumen's behavior under operational conditions. Due this, the ratio between the properties obtained at a certain temperature value can change oppositely at another lower or higher temperature values. Since bitumen is considered as a system to which the principle of temperature-time analogy (TTA) is applicable [6], similar changes may occur during bitumen deformation with different rates at the same temperature which directly set the asphalt properties.

The purpose of this study is to establish the relationship between the characteristics of the temperature and rate sensitivity of bitumen, i.e. the anomaly of its flow characterized by the flow index "c" in the equation $\tau = \eta \cdot \dot{\gamma}^{c}$ and determination of the shear stresses corresponding to different penetration values.

2. BACKGROUND OF THE STUDY

To establish these dependencies, two parameters are required respectively. The temperature sensitivity of bitumen is characterized by the penetration index (PI) determined by the temperature dependence of penetration within the range from 25 °C to the temperature (T_{800}) at which the penetration is 800 dmm. For practical purposes, it was assumed that this penetration value corresponds to the softening point ($T_{R\&B}$) of all paving bitumen grades. As shown in the latest studies [7], this assumption is well justified for distillation bitumen due their sol structural type. It is not always confirmed for oxidized, fluxed, highly viscous bitumen and, especially, for bitumen modified by polymers [8]. French researchers were guided by this assumption [9] when replacing the softening point with the temperature T_{800} in the penetration index determining. Nevertheless, if proceed from the prerequisite that penetration is a measure of the needle's resistance to shear and take into account the conicity of the needle tip (up to 5.4 mm) [10, 11], then it can be considered that PI is a fairly objective characteristic. In numerous studies, PI is a criterion for the bitumen division into the types mentioned above.

However, this division is incomplete if it is limited only by contributing the fact of a change in one or another property or by the abstractedly description of the bitumen structure based on electronic, luminescent or other microscopy. Thermoplasticity of bitumen is directly related to the rheological behavior and the nature of the change in properties under the influence of temperature. Among the rheological characteristics, the most important is the rate dependence of the shear stress (Fig. 1). The viscosity of non-destructed structure, flow index and shear resistance at a given deformation rate are determined by this dependence.

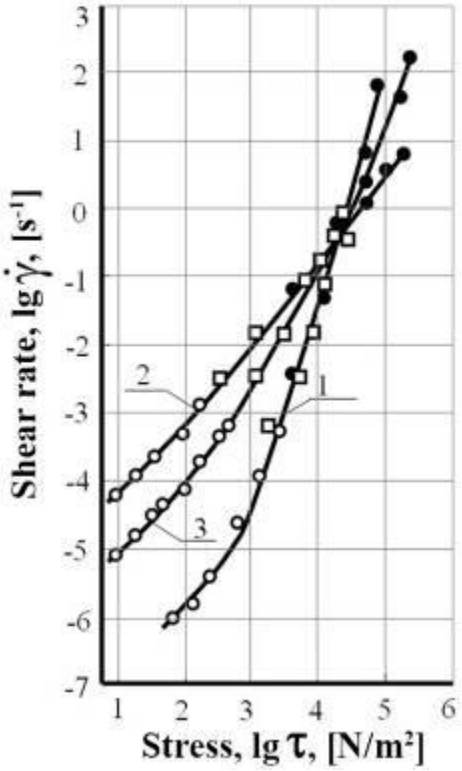

Figure 1: Curves of flow of gel (1), sol (2), sol-gel types bitumen (3) obtained by plastometer - ○, rotational viscometer - □, capillary viscometer - ●.

The nature of these dependencies for bitumen of one grade (by the depth of the needle penetration) but of various structural types is fundamentally different. In the low rate range when the bitumen's structure is not destroyed or is capable to recover during the flow, the bitumen of gel type indicates hundreds of times higher shear resistance than the bitumen of the sol type. But due to different susceptibility to the structural destruction which is obtained by the anomaly of viscosity at increased shear rates, the situation changes drastically: shear resistance of the bitumen of gel type sharply decreases and becomes lower than the one of the sol type bitumen. This proves that the assessment of the bitumen quality by the depth of the needle penetration as a conventional indicator without taking into account the temperature and the shear rate is extremely unreliable. The feature of the flow of bitumen of the same penetration depth but different composition and structure is that there is a point (or a restricted area) in which the dependencies intersect. The equal stresses and shear rates correspond to the point of equal penetration. It can be called equipenetration, equirate, or equishear. Its location is changing with the change in the bitumen penetration.

3. OBJECTS AND FEATURES OF THE STUDY

Special studies in which the relationship between the temperature sensitivity (PI) of bitumen and its anomaly (other than Newtonian) flow (c) was considered has not yet been undertaken. Due to this, data from different authors which indirectly contain such information were used in the study. Taking into account that the base temperature for the bitumen consistency determining is 25 °C, it was chosen for the analysis of rheological dependencies. Contributing factor is the choice of deformation rates. They should be available in measuring by the existing viscometric technique and related to the bitumen performance in the asphalt in the pavement under the traffic load.

From the dependencies shown in Fig. 1 it follows that the bitumen of sol type stay as a Newtonian liquid at deformation up to the rate of 10 s^{-1}, the bitumen of gel type turns to anomalous even at the rate of $4.0 \cdot 10^{-6}$ s^{-1}, and the bitumen of the sol-gel type turns to anomalous at the rate of $5 \cdot 10^{-4}$ s^{-1}. It indicates an extreme susceptibility of bitumen of different structures to shear strain. Therefore, in order to establish a correct relationship between PI and flow index "c", it is necessary to get the flow curves of several series of bitumen of a close penetration but of different structural type, similar to the series shown in Fig 1. The research works in this field are few.

4. RESEARCH RESULTS

The flow curves of bitumen of different consistency and structural types are most completely represented in the study

[10] which is devoted to establishing the ratio between penetration and viscosity of bitumen of different types. Many studies have been devoted to the search of this ratio and many different relations have been proposed [2, 8, 9]. But these relations are proved only for bitumen which is represented at a temperature of 25 °C as truly Newtonian liquid. In fact, each value of penetration corresponds to one rate inherent to certain penetration, since for the same time (5 s) the conical needle of the penetrometer is immersed into different depths. Consequently, the obtained values of shear resistance and viscosity corresponding to an individual penetration value cannot be compared with the shear stresses and the viscosity obtained for another penetration value since the deformation rates are different. In this case, even for equal penetration values, the deep anomaly can be inherent to the gel type bitumen and bitumen of the sol type can flow like practically Newtonian liquid.

To obtain a rheologically based result, 20 bitumen samples which were distributed among the groups according to their penetration values (7 groups) - from 380 dmm to 23 dmm penetration were investigated in the study [10]. According to the research results, the authors of the study [10] made the rate dependencies of the viscosities for each penetration group. In each of these groups, the rate at which the viscosity of bitumen of different types (with different penetration index) is the same was determined. Then a relationship between the equiviscosity rate and penetration was established and, in the final analysis, the dependency between penetration and viscosity at equipenetration shear rates was obtained. The obtained dependencies were transformed into a mathematical form and nomographs using which the dynamic viscosity of bitumen can be determined by the penetration value with a high degree of accuracy. For these studies, G.Carréet D.Laurent in 1962 received the Ch. Binoreau award given by the French Association of Oil Workers (AFTP). For the purposes of this study, the data of the study [10] were transformed into dependencies of the shear stress on the shear rate (Table 1). According to these data, the dependencies of the shear stresses on the deformation rate for bitumen of all equipenetration groups were plot (Fig. 2).

Table 1. Shear resistance at the deformation rate ($\dot{\gamma}$), equishear rates ($\dot{\gamma}_{equ}$) and flow indexes (FI) of different structural types of bitumen

Bitumen properties		Shear resistance (Pa) at shear rate (s^{-1})						FI	$\dot{\gamma}_{equ}$ (s^{-1})
P_{25}, 0.1mm	PI	0.02	0.05	0.08	0.2	0.3	0.4		
373	-1.1				10600		17600	0.73	0.67
392	1.7				14800		20200	0.45	
202	-1.2	4700					62400	0.86	0.44
201	0	6000					69800	0.82	
195	2.2	17500					61600	0.42	
116	-1.1	9900				148800		0.86	0.50
118	-0.4			50400		153450		0.69	
113	2.7			76800		124600		0.30	
76	-0.6	25800			238000			0.92	0.22
80	1.1		112500		224800			0.50	
79	3.1		115000		192800			0.37	
54	-1.5	83000			572000			0.84	0.10
54	3.6		240000			444000		0.34	
54	3.7		263000			438000		0.28	
46	-0.4		283500		840000			0.78	0.052
48	1.5		300000		550000			0.44	
46	4.3		310000	344000				0.28	
24	-0.1	800000		1350000				0.56	0.035
23	4.3	970000		1390000				0.26	

In the range of the accepted shear rates, all the dependencies τ on $\dot{\gamma}$ are linear which allow determining the flow index using them. The value of this index with the transition from bitumen of sol to sol-gel and gel type is continuously increased as the flow becomes more and more anomalous.

As follows from the data of Fig. 2, there is an equishear rate for each group of bitumen of close penetration. This rate is moved toward higher values as the bitumen penetration is increased.

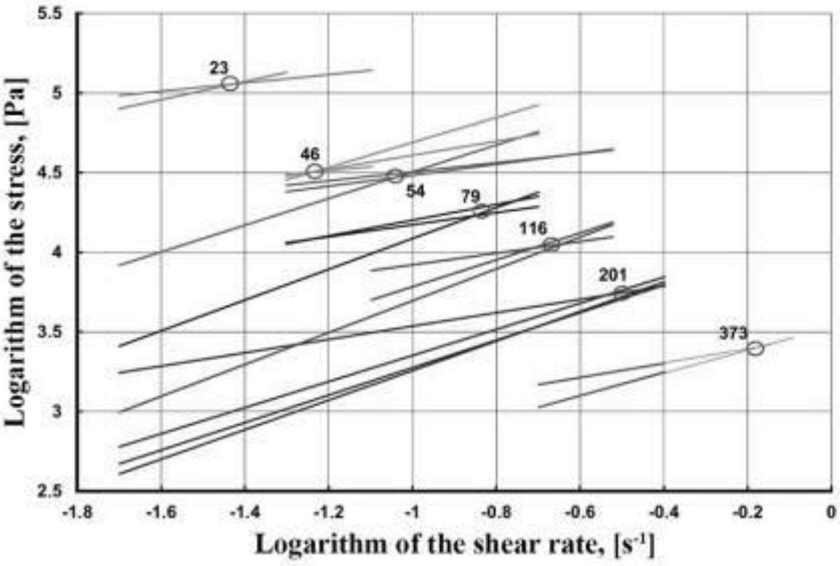

Figure 2: Dependencies of stresses on shear rate for bitumen of different penetration groups (data processing [10], numeral - group designation)

The data in Table 1 and Figure 2 show that the flow indexes are less dependent on the consistency of bitumen than on its structural type. For example, for bitumen from different groups of penetration (373, 202, 116) dmm with the penetration index, respectively minus 1.1, minus 1.2, and minus 1.1, they correspond to: 0.73, 0.86, 0.90. At the same time, within the first penetration group, the flow index range is from 0.73 to 0.45, within the second - from 0.86 to 0.42, within the third - from 0.90 to 0.30. Consequently, the structural type is associated with the penetration index which naturally follows from the fact that the bitumen consider as a system to which the principle of temperature-time superposition is applicable. Its base is the relaxation process which evolves both with the change in temperature and in the deformation rate. This process is estimated by the ratio of the relaxation times at different temperatures which is equivalent to the viscosity ratio at the same temperatures in case of "low molecular weight polymers" [6]. This also follows from the study [3] in which the temperature-invariant characteristics of anomalously viscous systems are considered.

Considering the above circumstances, it is logical to find and analyze the relationship between the flow index and the penetration index which symbolize and reflect the susceptibility of bitumen to the temperature and deformation rate. The curve (Fig. 3) is plot by the data of bitumen types presented in the study [10], [3] and [2] (Table 2). This curve is characterized by a gradual decrease in the flow index to a level of penetration index that is close to 0.7-0.8. Hereby, the flow index approaches to 0.55-0.58 which indicates a critical anomaly and destruction of the bitumen structure during deformation. Then, the flow index decrease is slowed down reaching the value of 0.3 at the penetration index about 4.0 which is very far behind the commonly accepted penetration index standards.

Table 2. Properties of oxidized bitumen of different structural types according to the study [2, 3]

Bitumen			Bitumen properties				
			P_{25}, dmm	**$T_{R\&B}$, °C**	**D_{25}, cm**	**PI**	**Flow index**
A sol		[2]	50	50	200	-1.2	1.0
Б sol-gel		[2]	55	55	164	0.2	0.8
B gel		[2]	53	65,6	55	2.1	0.5
C sol		[2]	59	46,1	–	-1.9	1.0
Type	1 – gel	[3]	82	63	4	3.03	0.35
Type	sol-gel	[3]	82	50	52	0.07	0.58
Type	sol	[3]	80	46	> 100	-1.13	0.83
Type	sol	[3]	86	46	200	-0.93	0.85
Grade	40/60	[3]	57	53,5	44	-0.04	0.52
Grade	60/90	[3]	72	49,5	75	-0.43	0.58
Grade	90/130	[3]	120	45	100	-0.20	0.68

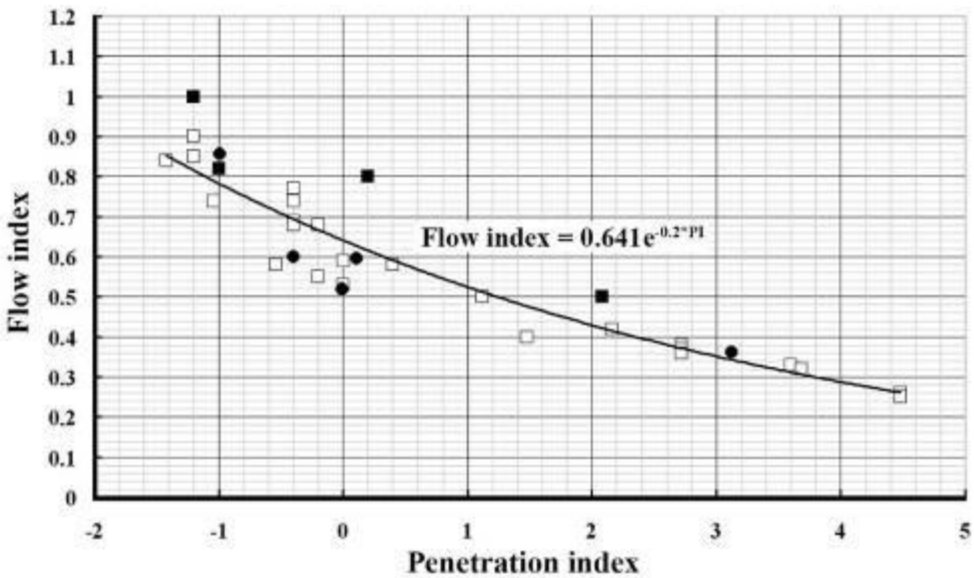

Figure 3: Dependency of flow index on penetration index (data processing ● - [3] and □ - [10]), ■ –data [2]

Established dependencies (Fig.3) can be described by the following empirical equation:

$$FI=0.64\cdot e^{-0,2xPI} \quad (1)$$

The determination index of this equation is 0.842, the correlation index is 0.92 and the approximation error is 0.076%. In addition to the data of the studies [3, 9], an attempt to use the research results of R.N. Traxler's study [2] published in 1952 was made to find the dependence of the flow index on the penetration index. The flow indexes given in the study [2] are higher than the ones given in the studies [3, 9]. It can be assumed that the stiffness of the measuring dynamometers, various schemes and other circumstances of the measurements fulfilled during 1940s-1950s of the last century [10] caused an influence on the results of measurements [2]. Nevertheless, the bitumen flow index [2] with a high penetration index (2.1) approaches the dependence obtained here.

Finding of equishear stresses for different penetration groups allows determining their dependency on penetration (Fig. 4a). It is logarithmic and more pronounced than the dependency of viscosity on penetration in the study [10]. A similar dependency exists for the pair: equiviscous deformation rate - penetration (Fig. 4b). These dependencies allow determining the equipenetration deformation rates and the corresponding stresses using the given penetration. Using the relationship between the flow index and the penetration index it is possible to find shear resistance of bitumen taking into account the anomaly of its flow.

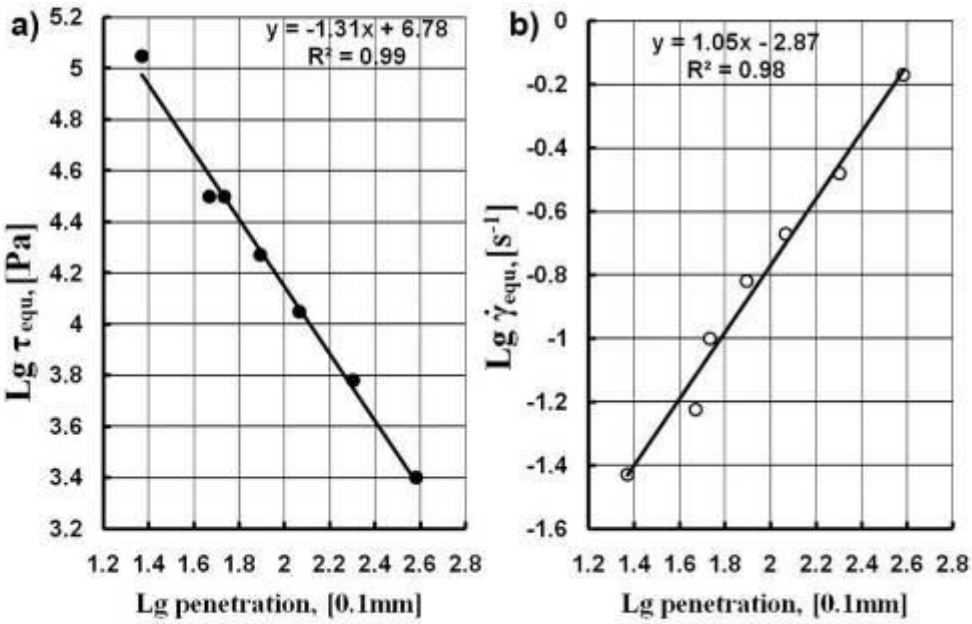

Figure 4: Dependencies of equishear stresses (a) and deformation rates (b) on penetration

Using these functions it is possible to quantitatively predict the shear resistance of bitumen at 25 °C of the chosen shear rate by its penetration and the penetration index.

For this purpose it is necessary: using the dependencies shown in Fig. 4 - find equishear stress ($\tau_{\mathbf{equ}}$) and equishear deformation rate at the given penetration, then it is necessary to determine the bitumen flow index using the dependency of the equishear deformation rate $\dot{\gamma}_{equ}$ on the penetration index. Using the values of these indicators, the required shear stress (τ_p) can be determined by the formula 2:

$$\tau_p=\tau_{equ}\cdot \dot{\gamma}_{equ}^{-FI} \qquad (2)$$

As an example, the data related to the bitumen with penetration of 76 dmm and penetration index -0.6 (sol type) and bitumen with penetration of 79 dmm and a penetration index of +3.1 (gel type) can be used. Their flow indexes are 0.96 and 0.37 respectively. Their equishear stress is 0.23 MPa, the equishear deformation rate is 0.22 s^{-1}. According to these data, the shear stress at the rate of $1s^{-1}$ of the first bitumen is 0.098 MPa, and of the second - 0.04 MPa.

$\tau_1 = 0.023\cdot 0.22^{-0.96} = 0.098$ MPa.

The equishear stress of the second bitumen is:

$\tau_1 = 0.023\cdot 0.22^{-0.37} = 0.040$ MPa.

The experimental values according to the data of the study [10] are 0.1 MPa and 0.0398 MPa respectively.

For the validation of the proposed method of determining the shear resistance, 14 bitumen samples were calculated. The maximum deviation of the calculated value from the experimental value did not exceed 15 %. The deviation grows at the increase of the needle penetration depth because of the difficulty in determining the low shear resistances and the increasing of the influence of the test errors proportion on the shear resistance of the bitumen. The dependence between the calculated and experimental values of the bitumen shear limit at a speed of 1 s^{-1} and a temperature of 25 °C is shown in Fig. 5. Qualitatively and quantitatively but with less dispersion of the results, this dependence correlates with the dependence of the penetration cohesion reported in the study [11].

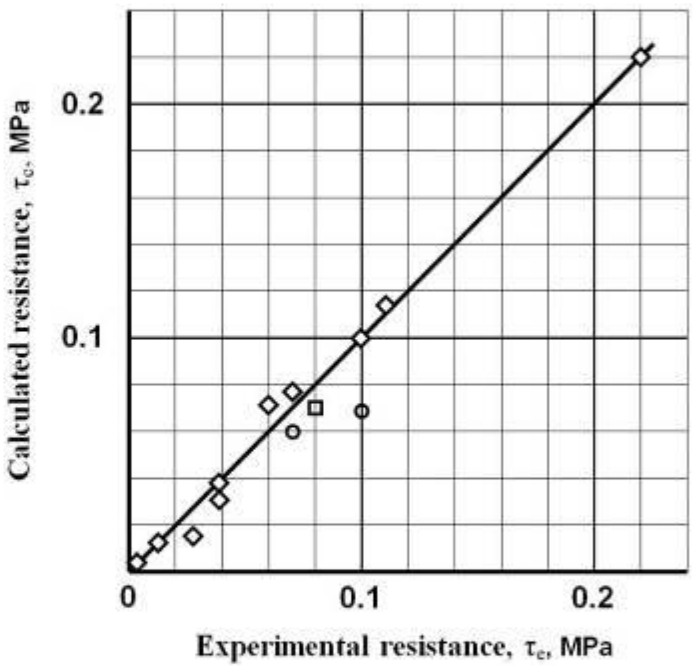

Figure 5: The relationship between the experimental (τ_e) and the calculated (τ_c) shear stresses

5. CONCLUSIONS

The relationship between the flow index and the penetration index established in the study allows fulfilling the qualitative assessment of the bitumen structural type, therefore making conclusions on its homogeneity and colloidal stability, ability to anomalous flow, thixotropic properties, and plasticity range.

Based on the nature of the dependence of the flow index on the penetration index and its relationship with the ductility predicted by R.N. Traxler, it is rational to optimize the limits of the penetration index recommended by the standards restricting them to the limits at least from minus 1.5 to plus 0.7 which ensures the minimum allowable ductility of oxidized bitumen.

The dependencies given in the study allow objective determining the shear resistance of bitumen by its penetration, the penetration and the flow index. The latter allows solving the issue of calculating the shear resistance of asphalt.

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