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ON THE CONVERGENCE OF QUALITY INDICATORS OF ROAD BITUMEN FOR PENETRATION AND SUPERPAVE SYSTEMS

ПРО КОНВЕРГЕНТНІСТЬ ПОКАЗНИКІВ ЯКОСТІ ДОРОЖНЬОГО БІТУМУ ДЛЯ СИСТЕМ ПЕНЕТРАЦІЇ ТА SUPERPAVE

Abstract. *Currently, there are two systems for assessing the quality of road bitumen: European - penetration and American SHRP-SUPERPAVE. The first is based on empirical, the second on rheological indicators. They are considered to be incompatible. The present work proposes a convergent system. This is based on the following postulates: penetration characterizes the resistance of bitumen to shear; at softening point temperature penetration is 800 0.1 mm, and at breaking one is 1.25 0.1 mm; the penetration dependence on temperature in this range is logarithmic. It is shown that the convergent (generalized) system can be supplemented by the median temperature of the plasticity interval and equal shear temperature. The values of these indicators are interconnected within all 37 PG zones.*

Keywords: *indicators, modifications, road bitumen, penetration, polymers, SHRP-SUPERPAVE systems.*

Introduction

1 Problem analysis

The contribution of bitumen to the forming of required properties of asphalt concrete can be objectively assessed with the scientifically based indicators of the quality of the bitumen itself. Currently, there are two systems for such an assessment. The first, historically developed is a penetration system, which includes: penetration, softening point and breaking temperatures, plasticity interval and penetration index. This system was founded in 1889 when H.C. Bowen invented the first version of the penetrometer. By 1910, penetration had become the main method for determining the consistency of bitumen. This method was finally approved by AASHTO (USA) in 1931. The system developed harmoniously. J. Ph. Pheiffer and P. M. Van Dormaal [1] supplemented it with a method for assessing the temperature susceptibility (TSA) of bitumen by penetration, which they proposed to evaluate by the penetration index. In 1903, the first version of the current device and method for finding the softening point was invented, which made it possible, after the development of the Fraass method and device in 1937, to determine the breaking point temperature, to offer an indicator of the plasticity interval. For decades, the penetration system was considered successful and stable, but at the end of the 20th century, its foundations began to waver. Among its indicators, there was not and still is not a single one that would allow taking into account the time factor. The time for determining penetration was strictly defined.

It so happened that almost simultaneously with the development of penetration system, a new science was developing - rheology (the science of the flow of matter). It is significant that bitumen in rheology, especially at the first stage of its development, was perceived as an exceptionally convenient rheological object due to its high susceptibility to temperature and time (rate) of deformation [2]. By the 80s of the last century the main rheological features of bitumen were practically revealed by the efforts of researchers from many countries of the world. Thanks to this, American bitumen rheologists came to the conclusion that it is necessary to change the system for assessing the quality of bitumen. In the book [3] “Hot Asphalt Concrete Mixes…”, which (3rd edition) was compiled by dozens of leading researchers in bitumen and asphalt concrete in the USA, it is said: “Determination of the penetration index is an empirical method by which it is impossible to establish the consistency of the bituminous binder in basic viscosity units.” And then they emphasized: "... the shear coefficient changes, since its value depends on the consistency of the bituminous binder." Looking ahead, it should be noted that in "Superpave" viscosity use only to control process fluidity at a temperature of 135 °C. And this is true, since, according to the author, it is necessary to use shear resistance, one of the leading mechanical and rheological criteria, to assess the performance properties. Given the current situation, the US Congress in 1987 passed the SHRP (Strategic Highway Research Program), in which large funds were allocated to the Superpave system. The object of its development was high-quality bituminous pavements. The essence of the system was to create a set of indicators that make it possible to predict the behavior of bitumen-based asphalt concrete under operational conditions. The system was almost completely formed by 1993. It contains truly rheological characteristics, among which the leading one is $G^*/\sin\varphi$ (inverse pliability) designed to predict and control rutting, crack resistance, fatigue behavior and aging of asphalt concrete. This system is based on a fundamental approach, according to which the same level of regulatory requirements must be provided in all 7 PG-zones, which include a total of 37 road-climatic subzones.

First of all, this concerns $G^*/\sin\varphi$, the value of which must be ≥ 1 kPa to ensure the rut resistance of the layer [4]. The same indicator is used to assess the aging of bitumen and the fatigue strength of asphalt concrete on chosen bitumen. In the system predicts the determining the temperature of bitumen crack resistance by the values of: stiffness modulus at three-point bending on the “rheometer” BBR $\leq$300 MPa; flow velocity coefficient $m \geq 0.3$, according to the temperature of reaching the fracture strain in tension $\geq$1.0%. These characteristics are presented by the developers as true rheological, since their value depends on temperature and time or frequency of deformation. The instruments recommended in the system make it possible to determine: viscosity, complex shear modulus G^* and its components (G' is accumulation and G'' is losses), phase shift angle (φ) between stress and strain sinusoids.

Against this background, the penetration system really looks outdated. For many years, researchers have sought to “enrich” it by replacing penetration with viscosity, based on the existence of a direct correlation between viscosity, $G^*/\sin\varphi$ and penetration [5, 6]. But in this case, the concept of viscosity lost its sense, since neither the strain rate nor the degree of viscosity anomaly was taken into account. In fact, the viscosity of bitumen remains Newtonian only up to certain combinations of temperature and shear rate. Essentially, viscosity is the result of applying stress to the bitumen. The force makes the matter to flow, and the speed of the flow is determined by the ability of the matter to resist the flow, i.e. viscosity (friction in the classical Newtonian interpretation). In the absence of force or stress, viscosity does not exist.

Under such circumstances, there may appear an opinion that a penetration system is unnecessary. However, this is untrue. This system includes characteristics that provide important information about the mechanical behavior of bitumen. In addition, an objective analysis of the penetration system indicates that, despite all the empiricism, for many decades it provided a qualitative assessment of the properties of a wide variety of types of bitumen. As a consequence, the scientific community, especially in Europe, reacted to the new system with a certain amount of doubt. The general reaction was twofold.

The main part

2 Critical perception of the SHRP system

In one of the first critical works, J. Bonnot [7] shared doubts about: the relationship of SHRP indicators with the operational behavior of the pavement (pressure aging); applicability of the system to bitumen modified with polymers;

predictive sense of the value of the cracking resistance indicator according to BBR. With regard to the latter, dissatisfaction was conditioned by the large discrepancies in the crack resistance indicators obtained by E <300 MPa, m >0.3 and by deformation in direct tension ≤1%. On this occasion, in [8], concern was expressed that the breaking temperatures according to SHRP differ significantly from the temperatures obtained using the ABCD, TSRS, and dilatometry methods. However, there was sufficient correlation between the Fraass and BBR data shown in [8].

The negative attitude towards SHRP fracture toughness evaluation was clearly demonstrated in [9]. The author insisted on the need for low strain rates (about 0.15 mm/min) in axial tension; recommended to pay attention to the cooling rate of the samples and its influence on the tensile strength indicators; proposed to provide identical test conditions for bitumen of different consistency and take into account relaxation processes during testing.

In [10], the SHRP program was classified as "revolutionary". However, one draws attention to a number of omissions. This relates to: insufficient attention to the influence of bitumen on the properties of asphalt concrete, compared with the influence of aggregates; lack of technological aspects of production in the field of view of the program; unsatisfactory crack resistance indicators. Denying the leading role of bitumen in the formation of the rheological properties of asphalt concrete, the authors of [10] however showing dependencies that indicate the opposite.

In [11], an attempt was made to agree the SHRP PG criteria to the EN criteria. Based on the Van der Poel diagram [12], it was proposed to link the reverse compliance and complex moduli with the softening point and breaking temperatures of bitumen within the penetration indices from +1.0 to -1.0. As one of the arguments justifying this approach, the authors refer to the proximity of the temperature boundaries of the transition between PG-zones and between bitumen grades according to EN: in terms of penetration within 6 °C, and in terms of softening and breaking point temperatures - 5 °C. The authors of [11], nevertheless, emphasized the unity of the goals of the SHRP program and the EN standardization. However, one can hardly agree that this is achievable using such an empirical characteristic as the softening point temperature, which is not connected with either the stress state scheme or the operating conditions of bitumen in an asphalt concrete road layer. In fact, this was previously confirmed by the introduction into the practice of bitumen testing in France of the softening point temperature as a temperature of penetration 800x0.1 mm (T_{800}). With these remarks, the author in no way encroaches on the validity of the essence of the Van der Pol diagram, who rightly assumed that for bitumen of the “sol” type, the Ring and Ball temperatures and T_{800} are close. But even in this case, to assess the temperature sensitivity of bitumen by two polar points (temperatures of softening and breaking), it is necessary to take into account the principle of uniformity of measurements, that is not presented neither in SHRP (bending and shear) no in EN (needle immersion and outflow from the ring) system.

In [13], based on the test results of 14 bitumens, it was shown that the relationship between the Fraass breaking point temperature and the crack resistance temperature according to BBR_{300} is insufficient in the case of waxy bitumens, that the “m” indicator is not sensitive enough to structural features of bitumen and their changes during aging, as well as the fact that the temperature of cracking, determined by "m" is significantly higher (up to 10 °C) than that obtained by BBR_{300}. On the data of many publications, it is advisable to return to the choice of the breaking temperature in the SHRP system, paying attention to the results obtained by other methods, in particular, ABCD, TSRS, and dilatometry [14, 15]. Naturally, it is desirable that this breaking temperature be determined taking into account ultimate stresses and/or strains.

With this it seems insufficiently reasoned low-temperature zoning according to inconsistent indicators. Maybe this is the reason of proposition to take the temperature of 1% tensile strain in the combination with G*/sinφ equal to 1 kPa in [13] instead of the BBR temperature. It seems that the low temperature criteria is the most vulnerable spot of Superpave.

3 Capabilities and principles of systems convergence

The penetration system for assessing the quality of bitumens, which has been formed over almost 100 years of use, provides an opportunity to predict the behavior of asphalt concrete based on them with a greater degree of probability. However, for some time now, the rheological criteria for designing and calculating pavements have come into conflict with the empirical criteria for assessing the quality of bitumen and asphalt concrete. The paradox lies in the fact that the features of bitumens, as almost ideal rheological bodies, have been studied quite deeply, and the results of such a study are still not used in European regulatory documents.

The first, who were to feel the misunderstanding was the USA experts. They presented the world with a fundamentally new SHRP Superpave system. At the same time, unfortunately, the previous standards were consigned to oblivion. It just so happens that it looks like Superpave has no backstory. However, it is the empirical penetration system that should be considered its backstory.

This system has accumulated a lot of useful things that can be used in the SHRP system. Primarily objectively useful is penetration (consistency) at a fixed temperature; secondary is the plasticity interval between the softening point and breaking temperatures; thirdly is the temperature susceptibility with its inherent abstract penetration index by [1] in the temperature range from 25 °C to the softening point.

In order to bring the scientific achievements of the previous system into the new one, it is necessary to fill it with useful semantic elements of the previous one, i.e., make systems congruent. In the base of such a transformation can be the conversion of penetration into shear resistance [16] and into G*/sin φ [17]. Due to this, the interval of plasticity between softening and cracking forming temperatures takes on a new meaning, because penetration is converted into shear resistance at this transition, which is well matched by the SHRP system. Penetration (800 0.1mm) at a softening point temperature is close to a shear resistance of 0.015 MPa, and penetration at 1.25x0.1 mm with a certain degree of reliability may be obtained at a stress in a range from 25 MPa to 33 MPa [18]. The use of these two critical shear stresses (or close to them) makes it possible to re-evaluate the plasticity interval between the temperatures of the PG subzones.

In addition, the implementing of such limits makes it possible to determine the temperature susceptibility of bitumens by mutually consistent characteristics (shear resistance), and not by non-contiguous G*/sin φ in shear and moduli in bending, or, worse, by the coefficient “m”.

The concepts of "consistency", "plasticity interval" and "temperature susceptibility" give a tangible idea of the quality of bitumen. They are directly related to the group composition of bitumen, with their division into structural types: "sol", "sol-gel", "gel". The wider the range of plasticity and the lower the coefficient of its temperature susceptibility, the closer the bitumen to the "gel" type with all the ensuing consequences: a greater viscosity anomaly, a greater tendency to hardening and less adhesion.

There is no a temperature susceptibility indicator in the Superpave system. In the penetration system, such an indicator is the penetration index (PI). In both systems there is a conditional interval of plasticity: in the EN-system, this is the interval between the softening and breaking point temperatures; in the SHRP system, this is the formal interval between the temperature, at which G*/sin φ is equal to 1 kPa, and the crack resistance temperature, at which obtains the one of the three normalized in SHRP indicators. In the accepted interpretation, this is a simple formal designation of the bitumen grade. As it will be shown later these bitumen quality indicators of the EN system can be included into the SHRP system, which gives it a physical meaning and increases its predictability.

To achieve this, several postulates must be followed. First, it is necessary to admit that the penetration depth of the needle characterizes the shear resistance of bitumen when a cylindrical rod with a truncated conical end is immersing in it [19]. Secondly, to agree that, according to W. Heukelom [20], the softening point temperature, at least for pavement bitumen, refers to a penetration of 800x0.1. Thirdly, to agree that the breaking temperature, according to W. Hekelom, refers to a penetration of 1.25x0.1 mm [20]. Fourth, to agree that the relationship between penetration values (consistencies) at these limiting temperatures is a linear logarithmic one [20]. On this dependence, according to [21], the temperature of the middle interval is also located at a penetration of 31x0.1 mm.

To find the middle of the plasticity interval between the stresses at penetrations of 800x0.1 mm and 1.25x0.1 mm, it is necessary to convert the penetration values into shear stress. For this, the Carre-Laurent method [19] was used, thanks to which authors calculated the viscosity of 22 bitumens from the values of stresses and shear rates at each penetration. It follows from their own research that the dependences of stress on shear rate for bitumen of the same penetration but different types have one intersection point, which can be called equipenetration, equirate, or equishear. Based on these data, the authors of [19] calculated the values of viscosity, although the calculation of shear stresses would be more substantiated, which is shown in [16]. Previously, similar patterns were obtained by Van Der Poel [12] and then R.N.J. Saal [22] for the stiffness moduli of forty bitumens at different durations of the load. Therefore, the existence of such equi points cannot be in doubt. However, the viscosity values obtained in this way in [19] were not in sufficient agreement with the results of determining the viscosity by the single-plane shear method. The reason for this, according to the author, was that in [19], when converting penetration into viscosity, the anomaly of bitumen viscosity was not taken into account. This was taken into account in publication [16].

The need to assess the temperature susceptibility of bitumens (TSA) was realized in the 30s of the twentieth century. Initially, J.Ph. Pheiffer and Van Der Poel used the formula for this:

$$TSA = \frac{lg800 - lgP_{25}}{T_{R\&B} - 25} \tag{1}$$

However, the difficulties in determining T_{800} forced the authors of [1] to replace it with the softening point temperature by Ring and Ball test ($T_{R\&B}$) and limit the lower temperature of 25 °C available at that time, when determining penetration. For ease of calculation and obtaining a conveniently perceived indicator, the authors proposed a penetration index, which, in terms of its values, could vary from -3 to +7 [12] (which is now hard to imagine). Well-known nomograms for its determination simplify the use, but complicate the perception of the physical essence of the indicator.

It is logical and necessary, when considering the possibility of the relationship between the criteria of the EN system and the SHRP system, to return to the original indicator of temperature susceptibility:

$$TSA = \frac{lgP_{T1} - lgP_{T2}}{T_1 - T_2} \tag{2}$$

In the 30s of the last century, it was assumed that the value of this temperature susceptibility coefficient for bitumen could vary from 0.015 to 0.06.

4 Practical aspects of using EN-system criteria in the SHRP system

4.1 Temperature susceptibility

The adaptation of temperature susceptibility to the SHRP system is associated with the need to find answers to at least two questions. The first is whether the TSA measured in the range from the breaking temperature to the softening point temperature will match the TSA obtained in the range from the softening point temperature to 25 °C [1]. A negative answer to this question would unequivocally testify to the impossibility of the relationship between the two systems due to the incompatibility of the indicators. The second question is not so radical, but quite important from the point of view of the influence on the TSA values of the method for determining the softening point temperature by the "Ring and Ball" test or by the temperature at which the needle is immersing to 800x0.1 mm. The fact that the authors of [1] decided to replace the T_{800} with its "Ring and Ball" temperature is encouraging, but need to be checked. The search for answers to these questions was placed at the head of the study undertaken here.

The results given below answer the first question. Figure 1 shows the relationship between temperature sensitivity and penetration index in two temperature ranges. The first one is between the temperature of 25 °C and the softening point temperature (according to [1]). The second one is between the softening point temperature and the breaking temperature (markers ×). The entire set of points (there are 53 of them) is described by the equation Y = –0.0043x + 0.0413 with the standard deviation R^2_{XY} = 0.88.

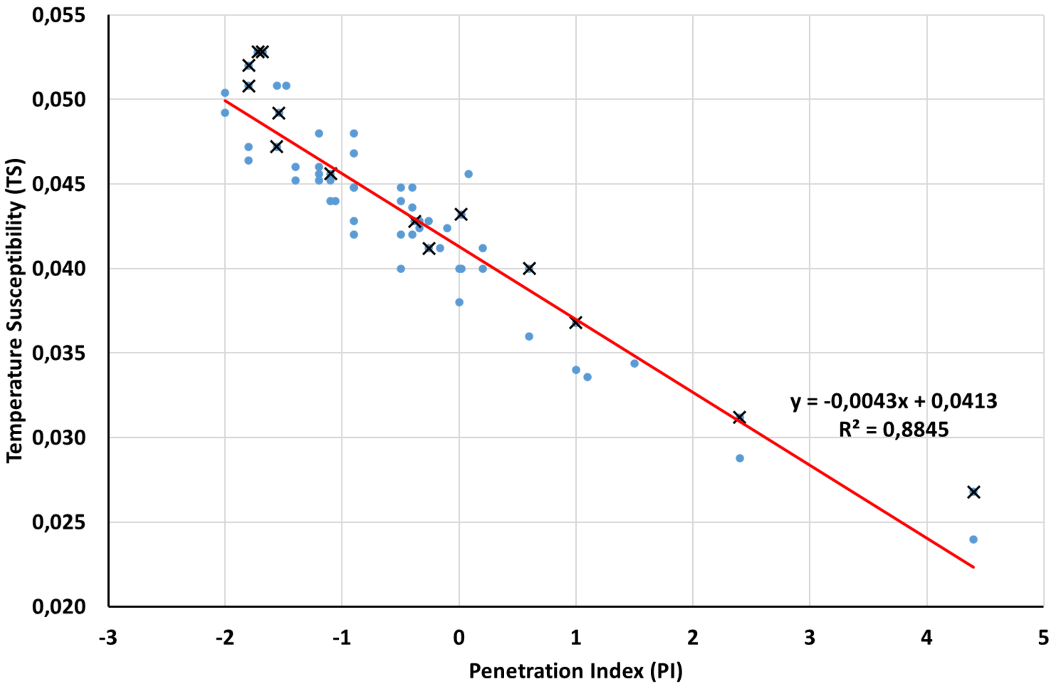


Figure 1. Dependence of the calculated coefficients of temperature susceptibility (TSA) on the penetration indices for the temperature range 25 °C – $T_{R\&B}$ (×) and T_{Fraass} – $T_{R\&B}$ (○)

The dependence of temperature susceptibility for the range between the temperature of 25 °C and the softening point (41 bitumen) is described by the equation Y= –0.0044x+0.0408 with a standard deviation R^2_{XY} = 0.87. Thus, a positive answer to the first question opens up the possibility of further consideration of the problem.

Figure 2 shows the dependence of the calculated values of the TSA coefficients on the penetration index for 50 bitumens. Among them, attention is drawn to the bitumen tested by Van Der Poel [12] (there are 12 of them, marked ○) and four bitumen tested by J.-F. Corte [23], which are the most deviated from the obtained straight-line relationship. This can be explained by the presence in the sample of solid bitumens with penetration from 13x0.1 mm to 22x0.1 mm, for which the softening point temperature and the temperature of the penetration of 800x0.1 mm are significantly different due to their difference in the structural types.

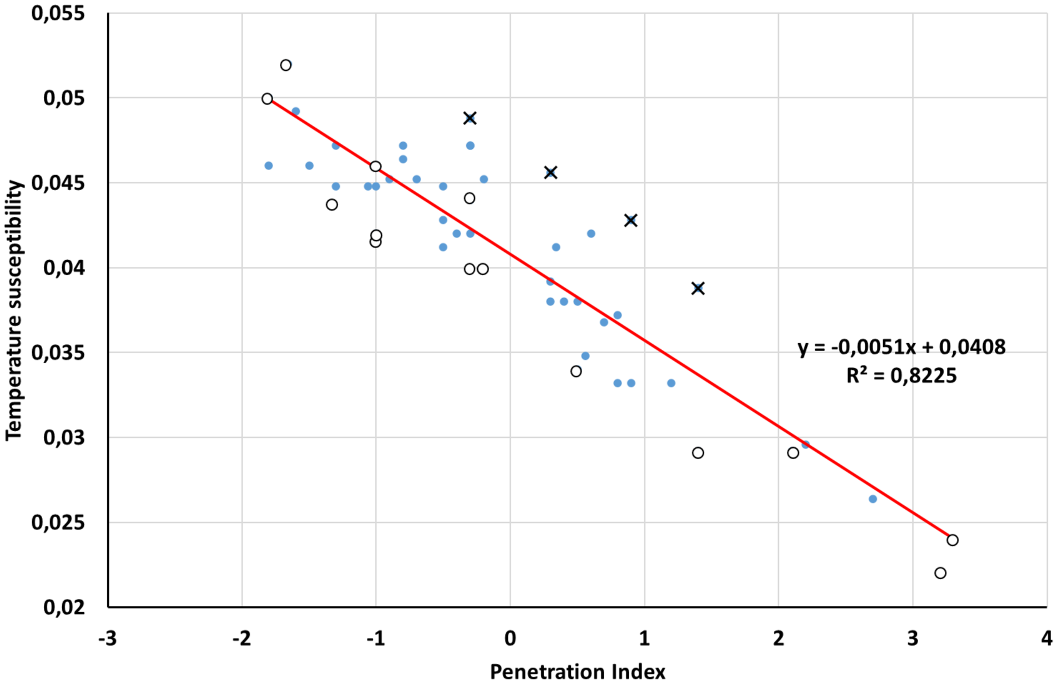


Figure 2. Dependence of temperature susceptibility (TSA) on penetration indices for distillation bitumen, compounded and low-penetration bitumen according to data Van Der Poel (○) [12], J.F. Corte (×) [23], D. Sybilski [24], F. Migliori [8], B. Eckman [15], V. Zolotaryov [25]

The total data sampling shown in Fig. 2 is described by the equation Y = – 0.0051+0.0408 with the with the standard deviation R^2_{XY} = 0.82. The exclusion from this set data [23] for high-viscosity bitumen increases the correlation reliability Y= – 0.0053+0.0403 with standard deviation R^2_{XY} = 0.88.

Figure 3 shows, similar to the previous two, the dependence of the coefficients of TSA calculated from the softening point $T_{R\&B}$, breaking T_{Fraass} temperatures and temperatures T_{800} (15 bitumens). For the entire data set (61 bitumens), the correlation dependence describes with the equation Y= –0.0051x+0.0405 with a standard deviation of 0.85. In the case of the T_{Fraass} - $T_{R\&B}$ range (without T_{800}) the standard deviation coefficient slightly increases (up to 0.86).

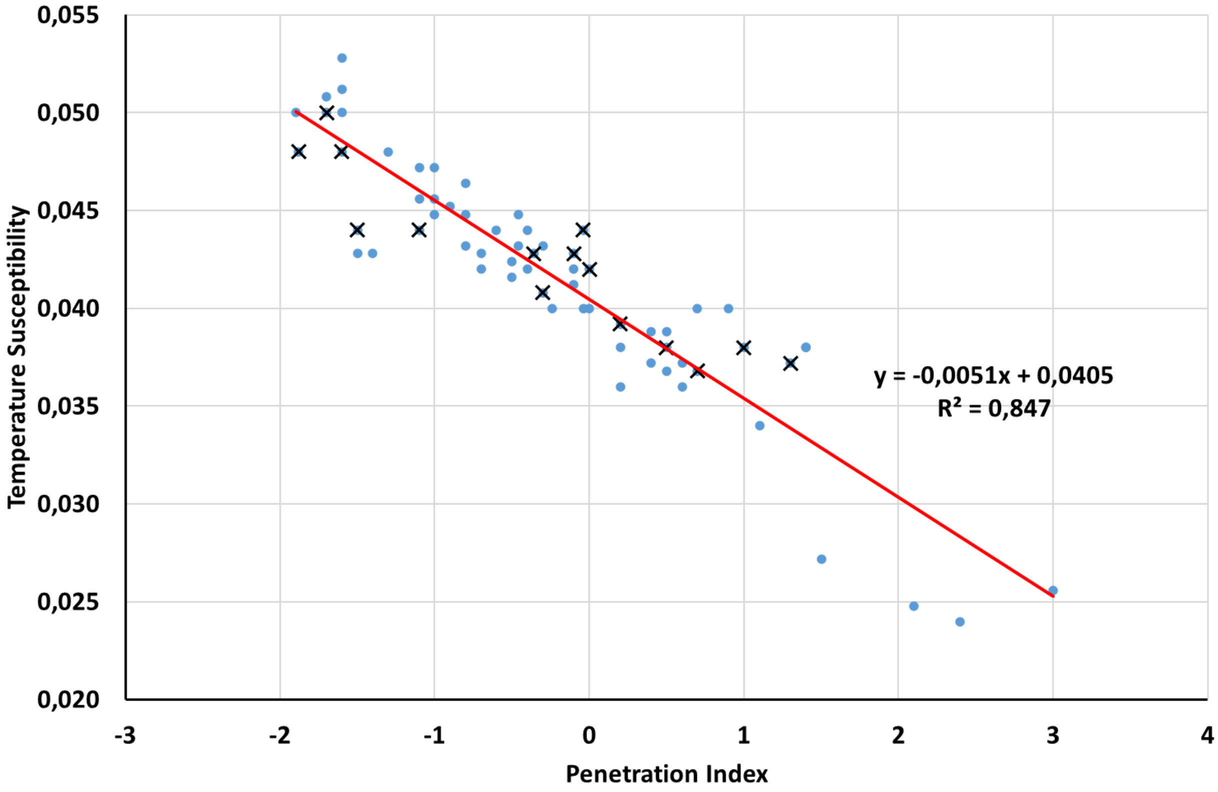


Figure 3. Dependence of temperature susceptibility (TSA) on penetration indices for ranges T_{Fraass} - $T_{R\&B}$ (●) and T_{Fraass} - T_{800} (×)

From data shown in Fig. 1-3 it follows that good convergence of temperature susceptibility coefficients is inherent in all three ranges of critical temperatures: ($T_{R\&B}$ – 25 °C, T_{Fraass} - $T_{R\&B}$ and T_{800}- T_{Fraass}). At the same time, it should be taken in the account the fact that in the region of high values of the penetration index, the spread of TSA coefficients increases due to the change in the bitumen structure from sol, sol-gel to gel. Quite a long time ago, this was observed by J. Samanos [13] when studying the influence of methods for determining the softening point temperatures of bitumen by the “Ring and Ball” and the temperature at which penetration of 800x0.1mm (LCPCh method - France). It according to the pointed above premises allows to characterize the temperature transitions of bitumen by values of their shear stresses.

An additional confirmation of the possibility of the relationship between the EN-system and the SHRP-system proposed here is the dependence shown in Fig.4. It concerns the TSA coefficients calculated on the base of Superpave data for the natural middle of the temperature intervals (plasticity) for each PG zone. For example, for PG-52-10 the natural middle of the plasticity interval is 31 °C, and its TSA coefficient calculated from the formula (3) is 0.069.

$$TSA = \frac{lg\tau_{1.25}^{-10} - lg\tau_{800}^{52}}{T_{800}^{52} - T_{1.25}^{-10}} \tag{3}$$

In formula 3 the stress shear $\tau_{1.25}$ is at the minimum temperature -10 °C, τ_{800} is at the maximum temperature +52 °C. Shear stress at minimum temperature is taken as 33 MPa [18], at maximum temperature is 0.015 MPa. Natural interval of plasticity is 62 °C.

Surprising is the fact that in all considered cases there is a reference point, the coordinates of the penetration index and TSA of which coincide. The author considers it appropriate to quote here from [1], which states that “that a penetration index equal to 0 refers to a temperature sensitivity equal to 0.04”. Precisely, all the dependencies presented here pass through this point (Fig. 1-3).

Moreover, the dependence shown in Fig. 4 indicates a functional relationship between the temperature susceptibility of bitumen and the natural middle of plasticity interval, obtained according to the PG-zoning criteria. Linear relationship has a dispersion 0.974, polynomial function, shown on Fig. 4, 0.998. At the same time, the values of the temperature susceptibility coefficient are within the limits set for traditional bitumen (Fig. 1-3).

All the dependences considered above indicate the expediency of introducing into the suggested system the requirements for bitumen of the temperature susceptibility indicator in its original interpretation [1]: as the ratio of changes in bitumen consistency indicators to the range of critical temperatures of softening point and breaking. In the EN system this is the difference in penetrations; in the proposed system, this is the difference in shear stresses at these temperatures.

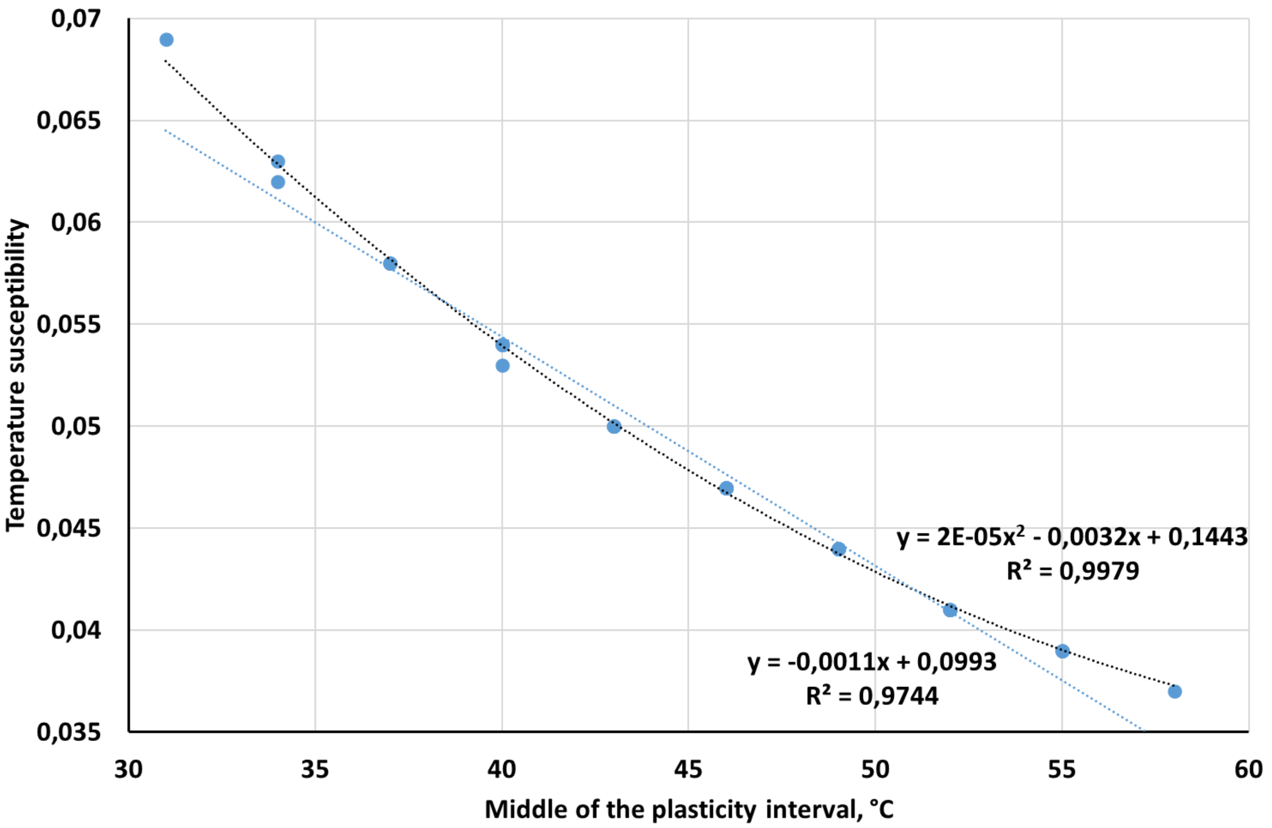


Figure 4. Dependence of temperature susceptibility on the natural middle of the plasticity interval for subzones

4.2 Median temperature of the logarithmic dependence by shear stress in PG-zones

In publication [25] it was shown that the temperature dependences of bitumens of the same penetration but of different structural types intersect at a temperature of penetration of 31 01 mm. This equipenetration temperature was determined by the formula 4 where Ts and Tb, respectively, are the softening point and breaking temperatures.

$$T_{31} = \frac{T_s + T_b}{2} \qquad (4)$$

Then it was experimentally established that the single-plane shear stress at this temperature is close to 0.21 MPa [26.] In presented research, a similar approach is used for analysis of the temperature intervals

(PG zones) of the SHRP, which are limited not by penetration indicators but by shear resistance at pole high (0.015 MPa) and low (33 MPa) temperatures. The feasibility of this approach is shown in [27]. These data were used to calculate temperatures according to formula 5 and determine, based on graphical dependences, the values of shear stresses at the corresponding equishear temperature for each PG zone. The author expresses gratitude to Professor B.S. Radovsky for the recommendation to use formula for determining the midpoint P = 31 0.1 mm of a power law dependence.

$$T_M^{PG} = \frac{T_{max}^{PG} + T_{min}^{PG}}{2} \tag{5}$$

The classical EN system includes a standard temperature of 25 °C, at which the consistency of each bitumen is determined and its grade is determined. As noted above, the SHRP-Superpave system does not contain such a temperature. The introduction of the average temperature of the plasticity interval into it in terms of shear stresses can be useful for predicting the degree of approach of bitumen to the area of rutting or winter cracking in one or another PG subzone. The median temperature (T_M^{PG}) is determined by the limits of low (T_{min}^{PG}) and high (T_{max}^{PG}) subzone temperature boundaries by formula 5.

The temperature range from the coldest PG 46-46 to the hottest PG 82-10 covers the range of median temperatures from 0 °C to +36 °C. The nature of their change in each PG-subzone and throughout the US is shown in Fig.5. Each subzone has its own median temperature. At the same time, with each neighboring subzone, it changes with a step of 3 °C with a decrease or increase in the low-temperature boundary of the subzone by 6 °C. For example: in subzone PG 64-22 it is 21 °C, in subzone PG 64-10 it is 27 °C, and in subzone PG 64-34 it is 15 °C.

The middle of each subzone has its own TSA, which decreases as the low-temperature boundary of the subzone decreases or the penetration index that still exists in the EN system increases.

The identification of pole points proposed in [27] as stresses corresponding to crack resistance and rutting makes it possible to determine the median stress in each subzone. Graphic dependencies and calculations using formula 6 showed that for all 37 subzones there is one median shear stress.

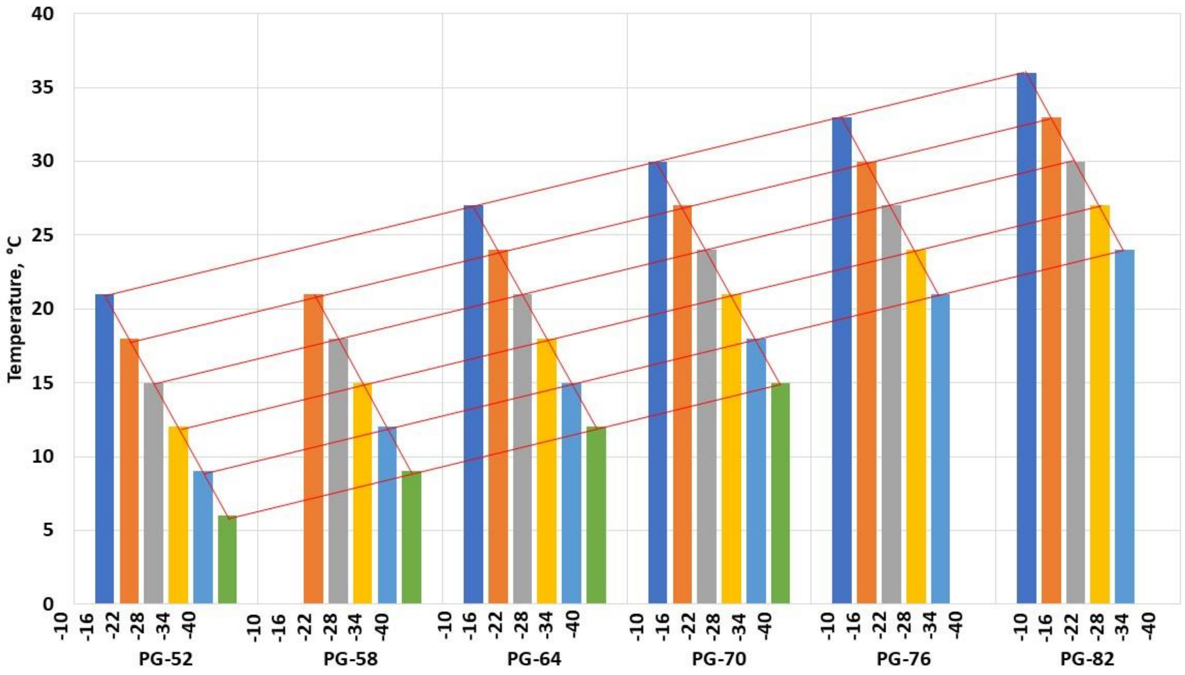


Figure 5. Distribution of the median temperature of plasticity intervals obtained by formula 6 in terms of shear stress for PG zones

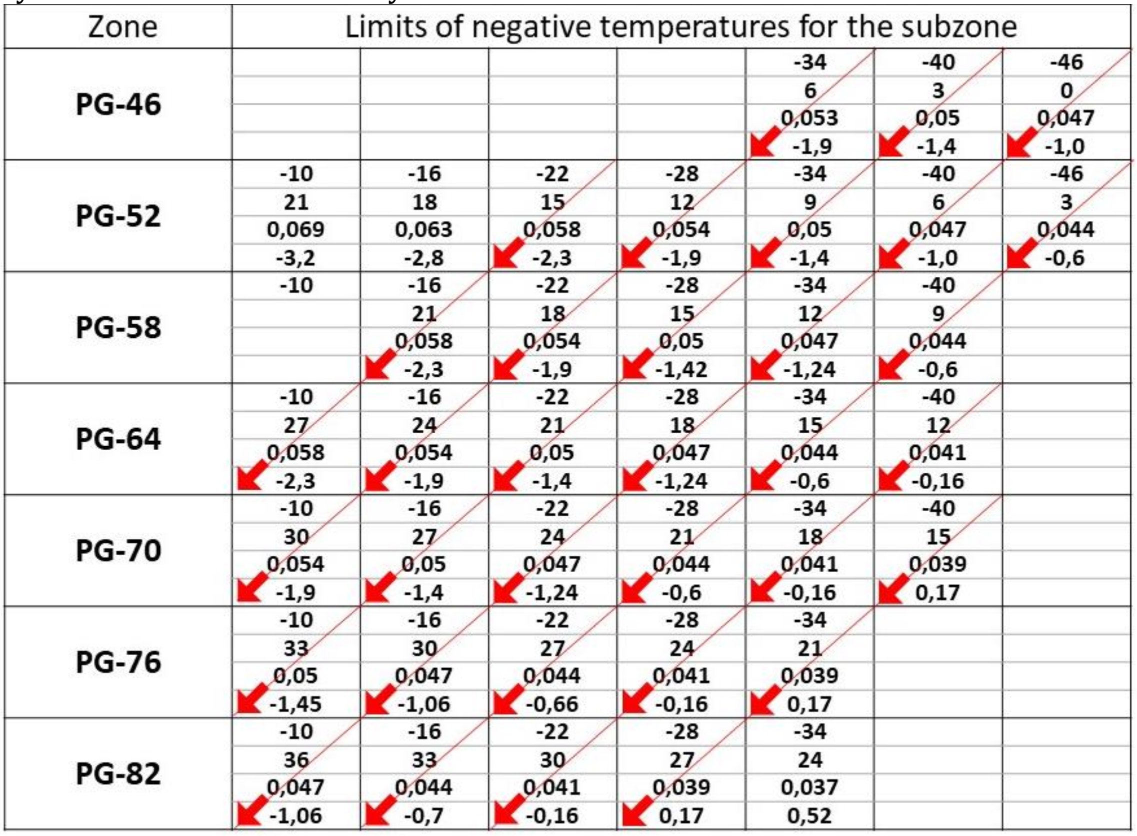
$$\tau_m^{PG} = \sqrt{\tau_{1.25}\cdot\tau_{800}} \tag{6}$$

It is almost equal to 0.21 MPa. Moreover, this value corresponds to the average equipenetration temperature between breaking and softening point, at which penetration is 31 0.1 mm. Analytically and experimentally it has been shown [26] that this penetration corresponds to a stress of 0.20-0.22 MPa. This correspondence of the results for SHRP and EN is another argument in favor of the congruence of the two systems and compliance with the principle of the SHRP Superpave system in relation to maintaining the same value of the indicator (for example G*/sinφ) in all PG zones of the USA.

For 17 objects accepted for calculation with a range of median temperatures of the plasticity interval from 3 to 36 °C by formula 6, the shear stress in 12 cases was 0.21 MPa, in three cases 0.18 MPa, in one case 0.25 MPa. Thus, the stresses corresponding to penetration turned out to be close to the cohesion stresses, experimentally obtained cohesion values for five bitumens with penetration from 54 to 27 0.1 mm [26].

5 Generalized indicators of bitumen properties for the EN and SHRP systems

The approaches outlined here and the results of experimental data processing make it possible to present Superpave in its original tabular form (Figure 6). The positive temperatures of each zone are located in ascending order along the vertical straight line, and the negative temperatures along the horizontal line. The set thus formed displays 37 subzones (cells).



Zone	Limits of negative temperatures for the subzone						
PG-46					-34 6 0,053 -1,9	-40 3 0,05 -1,4	-46 0 0,047 -1,0
PG-52	-10 21 0,069 -3,2	-16 18 0,063 -2,8	-22 15 0,058 -2,3	-28 12 0,054 -1,9	-34 9 0,05 -1,4	-40 6 0,047 -1,0	-46 3 0,044 -0,6
PG-58	-10	-16 21 0,058 -2,3	-22 18 0,054 -1,9	-28 15 0,05 -1,42	-34 12 0,047 -1,24	-40 9 0,044 -0,6	
PG-64	-10 27 0,058 -2,3	-16 24 0,054 -1,9	-22 21 0,05 -1,4	-28 18 0,047 -1,24	-34 15 0,044 -0,6	-40 12 0,041 -0,16	
PG-70	-10 30 0,054 -1,9	-16 27 0,05 -1,4	-22 24 0,047 -1,24	-28 21 0,044 -0,6	-34 18 0,041 -0,16	-40 15 0,039 0,17	
PG-76	-10 33 0,05 -1,45	-16 30 0,047 -1,06	-22 27 0,044 -0,66	-28 24 0,041 -0,16	-34 21 0,039 0,17		
PG-82	-10 36 0,047 -1,06	-16 33 0,044 -0,7	-22 30 0,041 -0,16	-28 27 0,039 0,17	-34 24 0,037 0,52		

Figure 6. Cyclogram of bitumen properties according to the system Superpave-EN: temperatures of zones and subzones, median temperature, plasticity interval, temperature susceptibility of PG-zones, shear index (similar to penetration index)

A distinctive feature of the PG-table is its harmony and periodicity. In addition to the simple designation of positive negative temperatures taken in SHRP, its lines and columns represent an arithmetic progression with a step (excess in both temperatures) of 6 °C. Each cell of the table presented here in this way is supplemented with indicators, the proposed expediency of which is discussed above. In each cell, from top to bottom, the negative temperature of the subzone, the median temperature of the plasticity interval, the temperature susceptibility coefficient and the referring penetration-shear index according to the EN-system are given.

In each line of PG cells, for example, line PG-52, the median temperature increases with a step of 3 °C when moving to a higher (by 6 °C) negative temperature. At the same time, in the whole series (from -46 °C to -10 °C), the temperature susceptibility increases from 0.044 to 0.069 with a step close to 0.003-0.005, and the penetration index also decreases in almost arithmetic progression from -0.6 to -3.2 with a step of from 0.3 to 0.5. This sequence is typical for all lines. In cells diagonally from right to left, with an increase in negative and positive temperatures (from PG 52-46 to PG 82-16), all temperature susceptibility indicators remain constant (0.044), with their referring shear indices close to –0.60 (except two cells). This is inherent for all cells located on parallel diagonals.

Along diagonals running from left to right (for example, from PG 52-10 to PG 76-34), i.e. with an increase in summer temperatures and a decrease in winter temperatures, the median temperatures remain constant (21 °C), i.e. with such an opposite change in the temperatures of the zones, their influence is balanced. This inherent for all other such diagonals from left to right. The values of the TSA coefficients fall from 0.069 to 0.039 with a varying step from 0.011 to 0.05. The plasticity index for the same diagonal decreases in increments of 0.8-0.9.

In each cell of the column of the PG-subzones of low temperatures, the median temperature increases from a lower to a higher temperature on 3 °C. With the transition from PG 52-10 to PG 82-10 it increases from 21 °C to 36 °C. For PG 70-40 it increases from 3 °C to 15 °C with a step of 3 °C. The TSA coefficient decreases by 0.003-0.004 when moving to a higher temperature zone. Accordingly, the plasticity index (not taking into account several deviations) increases by 0.4-0.5.

For each line cells: the average temperature decreases with decreasing temperatures in the zone in increments of 3 °C; the TSA coefficient decreases with a step of 0.003-0.004, and the penetration index increases mainly with a step of 0.4-0.5.

The classification of bitumen into types sol, sol-gel and gel is provided for in the EN-system by the norms of the penetration index <–1.5; 1.5…+0.7; >+0.7. The temperature susceptibility for them, according to the results presented here, can be described by the series: >0.05; 0.05–0.031; <0.031. The introduction of the indicators considered here into the Superpave system will make it possible to simplify the indexation and recognition of different types of bitumen, as well as the features of their behavior in different PG subzones.

Conclusion

1. The SHRP Superpave system, which is now widely used, has almost completely separated itself from the decades-old penetration system. This violated the evolutionary principle of cognition. In addition, in the current situation, this has placed researchers and practitioners associated with bitumen binders in a difficult situation for at least two reasons: the difficulty of understanding SHRP and the lack of funds to equip the laboratory with complex, expensive instruments.

2. In view of this, it seems appropriate to look for ways to converge the “old” and “young” systems, based on the merits of each of them. The formulation of the problem proposed here is based on the following principles: the depth of needle penetration is a characteristic of shear resistance; at the softening point temperature penetration reaches 800 ·0.1 mm and a shear stress is 1500 Pa·s for conventional bitumens of the sol and sol-gel types; the penetration at breaking temperature is 1.25 ·0.1 mm and a shear stress is from 20 MPa to 33 MPa; the logarithmic relationship between these indicators is straightforward; the median temperature on the logarithmic penetration dependence is 31·01 mm, the shear stress at

this penetration is from 0.20 to 0.21 MPa. This is also the same median logarithmic value of the plasticity interval within each PG zone.

3. These premises and the quantitative relationship between the characteristics of the two systems made it possible to propose a temperature sensitivity coefficient for the SHRP Superpave system in the range of polar softening point and breaking temperatures instead of a penetration index determined in the range from the softening point to 25 °C. The expansion of the temperature range to the natural and necessary one became possible due to the establishment of a close relationship even with the actual reproducibility of temperature susceptibility indicators, determined in the range from the softening point temperature to temperatures of 25 °C and below to the breaking temperature. This fully corresponds to the linear logarithmic dependence of the penetration of W. Hekelom.

4. Establishing a relationship that includes the shear characteristics of shear resistance (0.015 MPa) and crack resistance (33 MPa), as well as the average temperatures of the logarithmic relationships between them, equishear temperatures for each PG subzone, temperature susceptibility coefficients, allows to determine the shear stress of bitumen at any temperature within each subzones and, accordingly, to ensure, to the maximum extent, the objectivity of bitumen quality indicators for specific operating conditions of asphalt concrete.

5. As a result of the analytical and experimental studies performed, the work provides a cyclogram of bitumen properties for all 37 SHRP Superpave subzones with information for each subzone regarding the median temperature of the logarithmic plasticity range, the temperature susceptibility of bitumen and temperature susceptibility indices, which can serve as guidelines for choosing the optimal bitumen in a specific PG zone.

6. Analysis of the effectiveness of critical quality indicators of pavement bitumen is complicated by the fact that the crack resistance criterion does not sufficiently meet their operating conditions and stress state patterns in road layers. The problem of choosing the most acceptable criterion among at least four currently used remains relevant.

7. The author is aware that some of the trends and quantitative estimates presented here can and should be clarified by special research. However, he hopes that a reasonable combination of the two existing systems can be useful for practical purposes in the field of assessing and predicting the quality of asphalt pavements.

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