Cohesion of bituminous binders and asphalt concrete strength in shear

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ABSTRACT

Cohesion of bituminous binders is their fundamental characteristic, which allows predicting the shear strength and rutting resistance of asphalt-concrete. This fact was the base for inclusion of the cohesion index into EN 14023 in polymer modified bitumens. This standard offers three characteristics of cohesion measured in dimensions of tensile energy or rupture.

The classical scheme of determining the cohesion of systems similar to bitumen binders is a one- or two-plane shear; its value is determined by the dimension of strength.

The study of bitumen cohesion and PMB was performed at various shear rate (0,1 – 10 c-1) and at different temperatures (-30 ... +20 °C). Typical dependences of cohesion are expressed in curves with a maximum peak at the point of critical temperature, which separates the elastic-viscoplastic state from the fragile. The peak position of cohesion depends on the shear rate; it is shifted towards lower temperatures with the increasing of deformation rate, and vice versa. This temperature is sensitive to the structural type of the bitumens. It is lower for oxidized bitumens such as "zol-gel" and higher for distillation bitumens such as "zol", both types have almost similar penetration. The temperature dependences of the asphalt concrete durability are similar to the analogic dependencies of bituminous binders.

Cohesion of oxidized and residual bitumens with almost similar penetration 75 x 0,1 mm and 79 x 0,1 mm are respectively equal to 0,12 MPa and 0,11 MPa. Introduction of polymer into the bitumen with a penetration of 96 x 0,1 mm in an amount of 3 %, 6 % and 10 %, results in an increase of cohesion from 0,04 MPa to 0,1 MPa and from 0,1 to 0,14 MPa and from 0,14 to 0,18 MPa respectively, i.e. 2,5, 3,5 and 4,1 times. Between the shear strength of the asphalt concrete and the cohesion of the binder there is a sufficiently strong correlation: the increase of cohesion by 3,6 times leads to increase of resistance of the asphalt-concrete to shear under rotation by 2,4 time from 0,14 MPa to 0,33 MPa. This relationship allows predicting the stability of asphalt-concretes against shear and rutting.

Keywords: Cohesion, Mechanical Properties, Modified Binders, Testing

1. INTRODUCTION

Cohesion of bitumen is its fundamental characteristics allowing prediction of shear strength and rut resistance of asphalt concrete [1]. This fact created the basis for the inclusion of cohesion in the standard EN 14023 [2] for modified bitumen (PMB). At the same time, defining the influence of cohesion of binder on strength is equally important for both asphalt and asphalt polymer concrete. EN 13703:2003 standard recommends defining the cohesion of dumbbell specimens according to the scheme used for determining the ductility of classical bitumen. As cohesion indicators, it is recommended to consider the force corresponding to the maximum ductility value or energy value corresponding to the area on the stress-strain diagram. The disadvantage of this test is the section-variability of the sample during stretching and the impossibility to define it after the rupture of a binder thread.

The classical cohesion determining involves testing the binder at one-plane or two-plane shear [3]. Limit shear strength of the binder in the gap between two coaxial cylinders at certain temperature and shear rate can serve as an indicator of cohesion. A reflection of this is the requirement of EN 12591 [4] to dynamic viscosity at 60 °C. A feature of this test is the need to determine the area of linear flow of the binder which essentially depends on the type of bitumen, "sol", "sol-gel", "gel" [5]. Shear strength testing of bituminous binders is the easiest way allowing determining the cohesion in terms of binder layer resistance force to the initial area. The research results presented in [6] testify to the interest in assessing the cohesion of bitumen and PMB.

2. RESEARCH METHODS

For the purposes of this work, cohesion of bitumen was determined by shearing the disc binder sample of 200 microns thickness at fixed temperature and shear rate using a cohesion measuring device developed at Kharkiv Automobile Road University (KhNADU) [7].

Its design feature is that bitumen is applied on a flexible but strong polymeric tapes ensuring self-adjusting alignment of the surfaces of bonded tapes and excluding the effects of misalignment accompanying the tests on metal or other solid plates. Furthermore, organic nature of tapes provides cohesive type of separation due to better adhesion of binder to the surfaces of tapes than to metal or mineral plates.

For an objective comparison of cohesion of bitumen and asphalt concrete shear strength, the latter was determined by torsion of asphalt concrete samples [8].

The torque was applied to the asphalt-concrete sample with the specified loading rate 1,09 kg/cm^2 per minute. Shear resistance was determined by the maximum stress that caused the destruction of the sample. Torsional resistance was determined at 50 °C. In the process of loading general screw cracks occur in asphalt concrete sample (at an angle of about 45°). The results of tests of samples in which cracks developed in the lower or upper zones of fastening specimens when determining the average value of the shear strength was not used.

3. EXPERIMENTAL STUDIES

Cohesion of bitumen depends on the temperature at a certain shear rate (see Figure 1) and on the shear rate at a fixed temperature (Figure 2). Dependencies shown in (Figure 1) indicate a high sensitivity of cohesion to the structural type of bitumen. The structural type of bitumen was defined by the index of colloidal instability (C. Gastel). The index for bitumen 1, 2, 3 is respectively equal 0,56; 0,42 and 0,49. The specified data indicate that the maximum of cohesion strength shifts towards higher temperatures during the transition from the bitumen with “gel” structure (1) to the bitumen with “sol” structure (2).

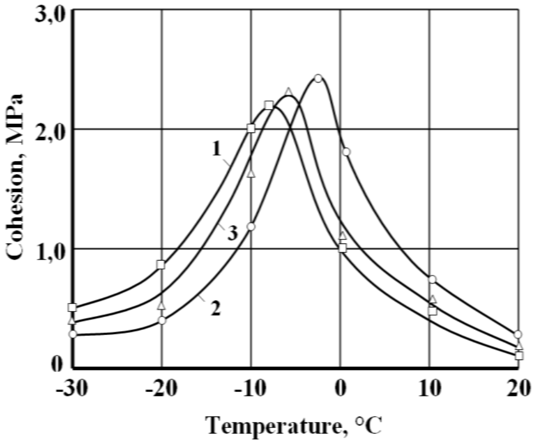

Figure 1: Temperature dependence of cohesive strength of bitumen with a structure of "gel", "sol-gel", "sol" types (curves 1, 3, 2) at a deformation rate $\dot{\gamma}$ = 1 s^{-1}, by the [9]. The bitumen penetration is 67×0.1 mm.

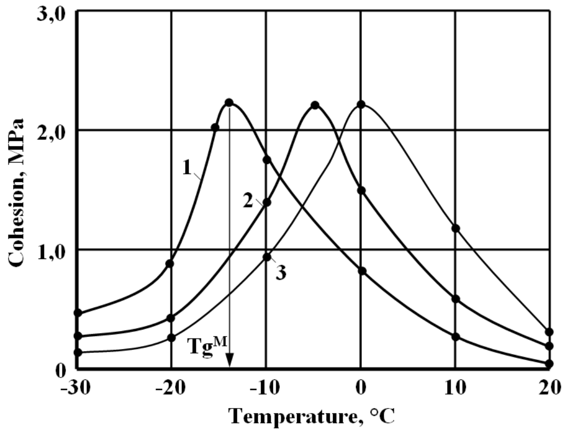

Figure 2: Temperature dependence of cohesive strength of bitumen with a structure "sol-gel" with penetration 67×0,1 mm at deformation rates of 1 – 0,083 s^{-1}, 2 – 1,0 s^{-1}, 3 – 10 s^{-1}, by the [9]

At the same time, cohesion of bitumen as well as its other mechanical characteristics such as viscosity and shear modules depends on the shear rate. Temperature dependencies of cohesion with increasing shear rate are shifted to higher temperature ranges. At that, increase in the shear rate by one order leads to a shift in temperature corresponding to the maximum cohesion value (it can be called mechanical vitrification temperature) towards higher temperatures by 5 - 7 °C. Such shifts fully meet the principle of time-temperature superposition (WLF) [10].

The relationship between cohesion of bituminous binders and shear strength of asphalt concrete was defined using asphalt concrete containing bitumen varying in the penetration depth of the needle, bitumen with 3 % SBS of polymer in the bitumen of different penetration, PMB based on bitumen with penetration of 96×0,1 mm, containing 1,5 %, 3 %, 6 % and 10 % of SBS. Modification of bitumen by polymers was performed in a laboratory blade mixer with a capacity of 1,0 liters. The rotational speed of the mixer spindle was 1000 rev/min. The temperature of mixing was controlled depending on the initial bitumen penetration (180 °C for bitumen BND 40/60 and 160 °C for bitumen BND 130/200). The mixing time for bitumen BND 90/130 with polymer was increased while enhancing the polymer content: ranging from 1 hour for PMB with 3 % of SBS to 1,5 hours for PMB with 6 % of SBS and 2 hours for PMB with 10 % of SBS. Bitumen cohesion was measured at 25 °C and shear rate of 1 s^{-1}.The properties of bituminous binders are given in Table 1.

Table 1: Properties of bitumen and SBS polymer modified bitumen and asphalt concrete

Name and content of bituminous binder	Properties indicators *					Shear resistance of asphalt concrete, MPa	Optimal content of binder, %
	P_{25}, 0,1 mm	$T_{R\&B}$, °C	T_{fr}, °C	E_{25}, %	τ_c, MPa		
BND 40/60	53	53	-17	-	0,102	0,21	5,2
PMB (40/60+3 % SBS)	36	66	-17	79	0,154	0,29	5,4
BND 60/90	75	49	-19	-	0,079	0,16	4,7
PMB (60/90+3 % SBS)	47	63	-20	82	0,132	0,26	5,4
BND 90/130	96	47	-21	15	0,044	0,15	4,5
PMB 90/130+1,5 % SBS)	67	54	-20	-	0,081	0,18	4,8
PMB 90/130+3 % SBS	53	63	-21	86	0,105	0,24	4,9
PMB 90/130+ 6 % SBS	48	91	-	98	0,143	0,28	6,0
PMB 90/130+10 % SBS	40	112	-35	95	0,182	0,35	6,5
BND 130/200	145	43	-23	-	0,036	0,12	4,3
PMB P 130/200 +3 % SBS	70	59	-24	93	0,080	0,20	4,9

* Note: P_{25} – penetration, $T_{R\&B}$ - softening point, T_{fr} – brittle temperature, E_{25} – elastic recovery, measured at temperature 25 ºC, τ_c - cohesive strength, measured at temperature 25 ºC and shear rate 1 s^{-1}.

Accepted for the research purposes asphalt concrete is close by its grading to the medium size crushed rock mixes (Table 2) accepted in France [11]. The content of the binder in such mixes is taken as optimal, i.e. so at which their shear strength at 50 °C was the highest.

Table 2: Grading of asphalt concrete

Residue type	Sieve residue, mesh size, mm							
	10	5	2,5	1,25	0,63	0,315	0,14	<0,071
Partial, %	20	20	13	10	9	8	6	3
Full, %	20	40	53	63	72	80	86	89

Increasing the cohesion of bitumen associated with the decrease in its penetration leads to a virtually linear increase in shear resistance of asphalt concrete (Figure 3). At that, the ratio of the properties indicators of two extreme bitumen with the penetration of 145×0,1 mm and 53×0,1 mm is as follows: 2,74 for penetration and 2,83 for cohesion. The corresponding ratio of shear resistance values of asphalt concrete on this bitumen is 1,75.

Introduction of 3 % SBS into each of the four bitumen reduces penetration: for bitumen having the penetration 53, 75, 96 and 145×0,1 mm - respectively for 1,47; 1,59; 1,91; 2,07. The degree of bitumen reinforcement increases with the decrease in bitumen consistency due to improving the dissolution conditions of the polymer therein. For PMB based on the same bitumen cohesion values ratio with respect to the initial cohesion of bitumen increases respectively by: 1,51; 1,67; 1,84 and 2,2 times. The corresponding ratio of shear strength values of asphalt concrete and asphalt polymer concrete meet the following series: 1,38; 1,62; 161; 1,67 times.

The relationship between shear resistance of asphalt concrete based on 3% SBS bitumen, as in the previous case, within each of the four PMB is linear (Figure 3). At the same time, the straight line corresponding to PMB based asphalt concrete is located slightly above the straight line corresponding to the asphalt concrete based on pure bitumen. In the area of equal cohesion values (0,079 - 0,102 MPa) shear resistance of asphalt concrete is by 0,03 - 0,04 lower than that of asphalt polymer concrete.

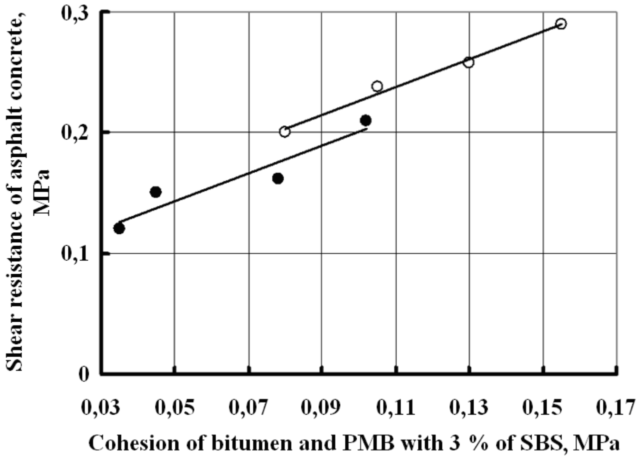

Figure 3: Dependence of shear resistance of asphalt concrete on cohesion of bitumen (●) (BND 40/60, BND 60/90, BND 90/130 and BND 130/200 and PMB (○) on its basis with 3% SBS

Increasing the polymer content from 1,5 % to 3 %, 6 % and to 10 % SBS reduces penetration of binder by 1,43; 1,81; 2,0 and 2,4 times (Table 1). The corresponding ratio values of their cohesion are distributed as follows: 1,84; 2,39; 3,25, 4,14 times. Cohesive strength ratios are more sensitive to an increase in the polymer content than the penetration ones. At that, penetration may strongly depend on the uniformity of the distribution of polymer particles in the bitumen medium: the more particles, the higher polymer content. When the content of the polymer is higher than 3,5 – 4,5 %, the polymer phase attains the properties of such medium where the needle immersion conditions may differ from the needle immersion conditions for bitumen. The dependence of asphalt concrete shear resistance on the cohesion of PMB with different content of polymer is substantially linear.

The relationship between the values of shear strength of asphalt concrete based on bitumen BND 90/130 and PMB with a polymer content from 1,5 to 10 % is distributed as follows: 1,23; 1,61; 19; 2,38. These ratios are naturally lower than the cohesion values ratios of the mentioned above binders.

Dependencies of asphalt polymer concrete resistance on cohesion and penetration of PMB presented in Figure 4 differ significantly. The first dependency testifies to a direct proportionality between the cohesion of binder and asphalt concrete shear resistance, the second dependency, on the contrary, steeply increases with decreasing penetration which is associated with the transition to the immersion of a conical part of the needle in the binder and the change in the stressed state scheme of the binder in this connection.

The experiment described herein has a drawback. It consists in the fact that the comparison of cohesion for bituminous binders with the shear strength was performed for the results obtained at different temperatures: cohesion of binders at 25 °C, and shear resistance of asphalt concrete at 50 °C. This is due to the fact that it is very difficult to determine cohesion at 50 °C or 60 °C: it is very low because bitumen (e.g. with P_{25} = 80×0,1 mm) is converted into a viscous liquid with a shear strength at 1 s^{-1}, is close to $4×10^3$ Pa [5].

At the same time, it can be assumed that the ratio between cohesion values at 20 °C and 50 °C for bitumen of "sol" type, to a greater extent, and for "sol-gel" type, to a less extent, will be relatively close. Then we will be able to confirm that the ratio shown above will change quantitatively and it will remain valid qualitatively.

The test of the needle penetration into bituminous binder, although treated as an empirical one, is actually a shear test performed by means of immersing an indenter of variable shapes: of the cone to the depth of 5,4 mm first, and then of the cylinder to the depth of 33 mm or more. It is the mixed nature of immersion that makes it difficult to recalculate the depth of penetration of the needle to viscosity terms. This recalculation is justified only in cases when using bitumen corresponding to Newtonian fluids or low-viscosity bitumen at 25 °C. High viscosity bitumen currently used in road construction having a penetration of 20×0,1 mm to 50×0,1 mm are generally not the case. The truer it is in case of BMP. They display Newtonian type of flow at very low strain rates that are not higher than 10^{-4} s^{-1}. A comparison of viscosity of different bitumen beyond linear deformation range has no physical meaning, since bitumen viscosity values with the same penetration value of different structural types even at penetration index within the range from -1 to + 0,7 may vary by tens of times [5].

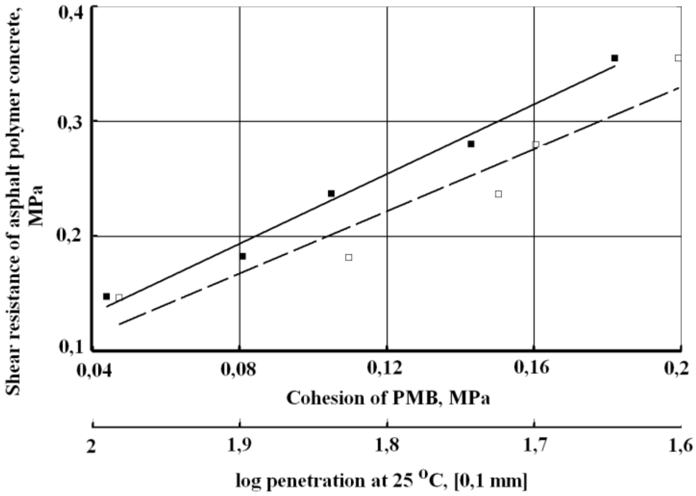

Figure 4 - Dependence of shear resistance of asphalt polymer concrete on PMB cohesion with 0; 1,5; 3,0; 6,0; 10 % SBS (■) and the logarithm of the penetration(□)

The paper by Carre G. and Laurent D. [12] attempted to objectively compare viscosity of bitumen obtained by penetration and experimentally for different structural types of bitumen with a penetration index from -1 to + 4,3 at equipenetrational shear rate. At that, equipenetrational rates are shifting relative to each other towards increasing as penetration increases. Even with this approach [12] they failed to reduce the discrepancy between calculated and experimental results below 50 %. The use of proposed in [12] formulas allowed determining stresses in the binder with increasing the needle immersion depth [12].

The relationship between penetration and calculated on its basis stresses is shown in Figure 5. This relationship consists essentially of two parts: with the decrease in penetration below (60-70)×0,1 mm, rapidly growing stresses occur in the binder. This corresponds to the area of a conical part of the needle. With growing penetration in a cylindrical part of the needle the rate of stresses increasing is significantly reduced. The nature of this dependence is similar to the relationship between penetration of PMB and shear resistance of asphalt concrete.

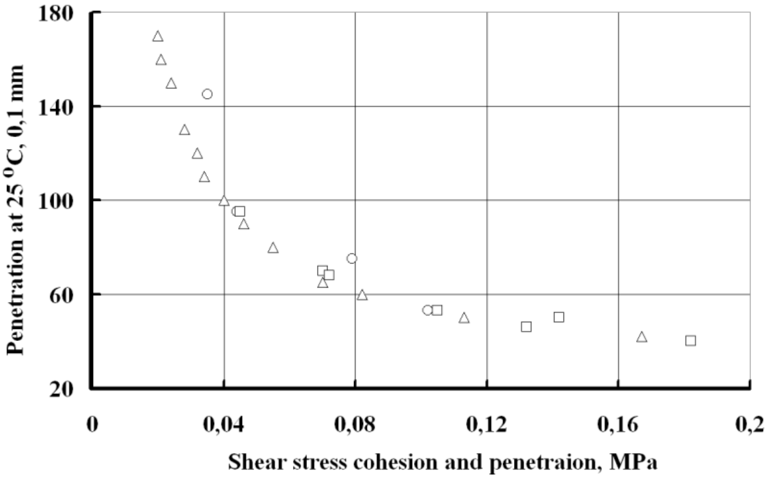

Figure 5 - The relationship between the depth of needle penetration, calculated stress, corresponding to them, and the experimental cohesion values (△) of the bitumen (○) and PMB (□)

Cohesion indicators of bitumen and PMB in the entire range of measurements follow the same dependence on the penetration as the stresses calculated by penetration forming almost a generic curve. On the one hand, it confirms the assertion that penetration is a shear characteristic of bituminous binders instead of conventional viscosity. On the other hand, it indicates that because of a complicated configuration of a penetration needle, directly proportional relationship between penetration and cohesion of bitumen cannot be obtained, and most importantly - between penetration and shear resistance of asphalt concrete.

At the same time, it is possible in case of assessing shear characteristics of bituminous binders by cohesion in a thin layer. This eliminates the need to consider and carry out tests at low shear rates and stresses that are required at determining the dynamic viscosity, as cohesion corresponds to shear resistance at limit destruction of the structure of bituminous binder. For obtaining comparable cohesion indicators of different bituminous binders, the conditions of equality of test temperatures and relative shear rates should be met.

CONCLUSIONS

Penetration of bitumen is a characteristic of bituminous binder resistance to the penetration of a cone-cylindrical indenter inside it. Each penetration value corresponds to a certain stress value and shear rate. Thus, when comparing shear strength performance of various binders by penetration, equality condition by shear rate is not met. This and the change in the shape of a needle at the height level of 5,4 mm sets conditions to the curved nature of the dependence penetration versus design shear stress.

Cohesion of bituminous binders can be determined at a strictly fixed shear rate; it is more sensitive to the peculiarities of different bituminous binders than penetration. Its value is determined by the dimensions provided by the SI system.

It should be noted that there is quite stable rectilinear correlation between shear resistance of asphalt concrete and cohesion of binder within the penetration range (40 – 200)×0,1 mm. This creates the opportunity of developing a method of quantitative prediction of asphalt concrete shear strength and its resistance to shearing stresses leading to plastic deformation of pavement.

Determination of cohesion by two-plane shear method without given temperature and shear rate is not difficult from technical viewpoint. This eliminates the problem of assessing the area of linear deformation, since the shear occurs far beyond its limits and corresponds to the transition of shearing stress in the binder over the maximum value.

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