Approximation of testing of asphalt concrete to the actual operating conditions of road surfaces

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Abstract. Existing test methods for asphalt concrete do not consider the actual operating conditions of road surfaces. The method, equipment and results of studies of the influence of the combined effects of vibration vacuum water saturation, ultraviolet irradiation and freezing-thawing on the structural and mechanical properties of asphalt concrete from slag materials are presented.

1. Introduction

Currently, among the improved road surfaces, asphalt concrete is the most widely used, creating maximum convenience for the movement of vehicles. These coatings are used on roads of any cargo intensity.

Asphalt concrete is one of the most complex artificial conglomerates, which is mainly due to the peculiarity of its structure, as well as the great dependence of its properties on many external factors.

The existing GOST 9128-2013 on asphalt mixes and asphalt concrete provides for the determination of compressive strength at temperatures of 20, 50, 0 °С, water saturation of samples, water resistance and water resistance during prolonged water saturation, shear resistance (by the coefficient of internal friction and adhesion during shear), crack resistance by tensile strength when split at a temperature of 0 °С. Laboratory methods for assessing the quality indicators of asphalt concrete do not reflect the conditions of its operation in the coating, in addition, the characteristic is asphalt concrete TV is given according to separate independent indicators, and the complex influence of operational and climatic factors on the properties of asphalt concrete is practically not studied [7].

The practice of road construction shows that the use of various asphalt mixes, even fully meeting the requirements of domestic state standards and other regulatory and technical documents, does not always allow us to provide the necessary overhaul life for road asphalt concrete [2].

In recent years, many studies have appeared on the impact of operational and climatic influences on changing the properties of asphalt concrete. A significant part of these studies is devoted to modeling external influences on asphalt concrete in order to predict its operational reliability [4, 5, 8, 15].

Known methods for modeling operational and climatic effects on asphalt concrete are based on a differential approach to assessing the stability of its structure according to the results of the influence of individual factors [17, 18]. However, such an assessment does not allow to consider the...
simultaneous influence of a set of operational climatic and recipe factors on asphalt concrete, as is the case in actual operating conditions of road surfaces.

DIN EN 13108-1: 2006-08 also does not provide for the integrated impact of factors on asphalt concrete [16].

Thus, it would be advisable to consider the possibility of testing the properties of asphalt concrete according to the methods that most simulate the operating conditions of asphalt concrete in the upper layers of coatings.

The appropriateness of the complex impact method is based on the opinion of a number of researchers [9, 10] about the insufficiency of assessing the influence of individual factors on the change in the properties of asphalt concrete when predicting its service life and on the need to determine the patterns of change in the structure of asphalt concrete under the influence of a complex of factors.

2. Methods and materials

To approximate the nature of testing of asphalt concrete to the conditions of actual operation in road surfaces and to reduce their duration, the most appropriate test cycle seems to be the sequential accumulation of the results of the combined impact of operational and climatic factors in the same samples of asphalt concrete. We have proposed and developed a method for preparing samples of building materials for strength tests [14]. The essence of the method lies in the fact that a complex of factors acts on the same asphalt concrete sample.

For the mathematical description of the influence of a complex of factors in the study of the physical and mechanical properties of asphalt concrete, the method of mathematical planning of extreme experiments (MMPEE) was used, the essence of which is to obtain maximum information with a minimum number of experiments [3].

This method differs from multivariate regression analysis in that the researcher plans his strategy in advance, actively intervenes in the experiment, and is not a passive observer.

1) The mathematical model of the influence of a complex of factors is represented in the form of a polynomial:

\[ Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j + \sum b_{ii} x_i^2 \]

where \( b_0 \) – is a free member;
\( b_i \) – is a linear coefficient;
\( b_{ij} \) – is the interaction coefficient;
\( b_{ii} \) – is the quadratic coefficient.

2) Before planning, factors are scaled to obtain the equation of a polynomial of the second degree with respect to dimensionless quantities \( x_i \).

The transition from physical variables \( X_i \) to encoded \( x_i \) is carried out according to the formula:

\[ x_i = \frac{X_i - X_i^0}{\lambda_i}, \]

where \( X_i^0 = \frac{X_i^u + X_i^v}{2} \) – is the middle of the range of variation of the \( i \) factor;
\( \lambda = \frac{X_i^u - X_i^v}{2} \) – is the step of variation \( i \) factor;
\( X_i^u \) and \( X_i^v \) – are the upper and lower levels of variation of the \( i \) factor respectively.
As a result of encoding variables, the upper level will correspond to the value “+1”, the zero level to “0”, and the lower level to “−1”.

3) After the implementation of the experiments, the uniformity of the experiments at each point is checked by the Student t-test and the sample variances are checked according to the $\chi^2$–Cochren criterion.

4) Check the significance of the coefficients by t-student test.

5) The model is checked for adequacy by the Fisher F-test.

The use of MMPEE is widespread in materials science in the selection of optimal compositions of artificial conglomerates. In our case, this method was used to study the influence of external factors on asphalt concrete [11, 12].

Ordinary asphalt concrete is destroyed by prolonged and periodic wetting, as well as by alternating freezing-thawing in a water-saturated state [1].

To model the complex of influences of external factors from all of their diversity, we took three as an example: vibrovacuum water saturation, cyclic freezing-thawing, and irradiation with artificial sunlight at temperatures up to +60 °C and periodic irrigation with water in an atmosphere containing ozone [11, 12]. We applied a 17-point three-level plan of the second order with the number of factors $k = 3 (N = N_1 + N_a + N_0)$ [3].

Hypodromia studies have proved that the mechanism of accelerated fatigue failure of water-saturated asphalt concrete during the operation of the coating in the cyclic dynamic loading mode is caused to a certain extent by the appearance of pulsed hydrodynamic pressures in water-saturated pores [1].

Introducing the factor of vibrovacuum water saturation into the complex of actions, it was taken into account that when the car moves, depending on the speed and evenness of the coating, the frequency of vibrations transmitted by the car to the coating is from 10 to 25 Hz, and the water is filtered in the pores of the coating mainly under the influence of vacuum created by tires moving on the surface of vehicles.

The vibrovacuum water saturation unit consists of a steel cylinder 10-liter capacity, mounted on a UV-70/100 type vibration stands and an MP-10 vacuum pump.

Pre-weighed and measured samples of asphalt concrete were placed in a vacuum chamber, the inner surface of the walls of which had a rubber coating, filled it with water, and then using a vacuum pump in the chamber a residual pressure of the order of $(0.133–0.199) \times 10^2$ N/m$^2$ was generated and the vibration test rig was turned on (Fig. 1).

To simulate the effect of alternating temperatures on asphalt concrete, an apparatus was used for accelerated freezing and thawing of samples (Fig. 2).

When developing the methods, it was assumed that a high cooling and thawing rate increases the destructive effect of the influence of alternating temperatures on asphalt concrete. The installation was created based on the Gronland T 25/01 low-temperature cabinet, supplemented by an electronic device that provides automatic cooling and thawing in the temperature range from −20 to +5 °C, and a potentiometer for graphically monitoring the magnitude and speed of temperature transitions. Temperature control was carried out by a thermocouple placed inside the control samples. The cooling rate was about 30 °C, and the thawing rate was about 60 °C.

To simulate the processes of thermooxidative aging of bitumen in asphalt concrete, an IP-1-3 artificial weather apparatus was used (Fig. 3), designed for accelerated testing of polymeric materials.

It is known that the most dangerous for polymeric materials is ultraviolet radiation (wavelength less than 400 nm). According to [6, 13], the share of UV radiation reaching the earth's surface accounts for no more than 3–4 % of the total flux of total solar radiation. Moreover, the share of the most effective UV radiation accounts for only 0.1 % of the total radiation. The amount of total solar radiation per year for the central regions of the European part of Russia is 2360 MJ/m$^2$ [13], therefore, the share of UV radiation is $2360 \times 0.001 = 2.36$ MJ/m$^2$. The average value of the light energy incident on a unit area in the ultraviolet region in an artificial weather apparatus with two mercury-quartz lamps of the PRK-2 type for 1 h is 0.67 MJ/m$^2$. 
Asphalt concrete on slag materials has specific properties that are not inherent in asphalt concrete on natural stone materials. Slag materials have hydraulic binders, have a porous structure, their particle size distribution during technological operations (drying, mixing with bitumen, laying and compaction) is optimized. As a result of this, the processes of structure formation in this type of asphalt concrete occur for a long time from the moment of paving. The presence of a hydraulically active mineral component leads to the formation of a coagulation-condensation structure hardened by...
crystallization intergrowths at the contact points of the slag grains. This process is enhanced with prolonged water saturation [12].

We studied asphalt composition: slag sand of the Novolipetsk Metallurgical Plant – 100 %, bitumen grade BND 60/90 – 9 %. The output parameter was the adhesion at a temperature of +20 °C.

Planning conditions are given in table 1. The parameters for modeling external factors for the highway 3 of the technical category located in the Voronezh region are substantiated in [11].

Table 1. Conditions for planning an experiment for studying structural and mechanical properties of asphalt concrete from slag materials

| Factors | The physical meaning of variables | Coded value of variables |
|----------|----------------------------------|--------------------------|
| X1 – duration of vibrational water saturation, h | X2 – number of accelerated freeze-thaw cycles | X3 – duration of artificial exposure, h | x1 | x2 | x3 |
| Upper level X_i^a | 60 | 100 | 60 | +1 | +1 | +1 |
| Lower level X_i^u | 20 | 24 | 40 | -1 | -1 | -1 |
| Main level X_i^0 | 40 | 62 | 50 | 0 | 0 | 0 |
| Variation step | 20 | 38 | 10 | - | - | - |

The transition from physical to coded variables is carried out according to the formulas:

\[ x_1 = \frac{X_1 - 40}{20}, \quad x_2 = \frac{X_2 - 62}{38}, \quad x_3 = \frac{X_1 - 50}{10} \]

3. Results

As a result of the experiments and calculation of the planning matrix, a mathematical model was obtained, and graphs were constructed in different coordinate systems (Fig. 4):

\[ C = (6.35 + 0.42x_1 + 0.55x_1 + 0.35x_1^2 + 0.89x_2^2 + 1.38x_3^2) \times 10^{-1}, \text{ MPa} \]

Analysis of the mathematical model and Figure 4 constructed from it made it possible to determine the influence of the studied factors on adhesion at a temperature of 20 °C:

- of the coefficients of the variables of the first degree, only the coefficient was found to be significant for the duration of the vibrovacuum water saturation, (x1), which increases the tensile strength at split;
- the coefficients for the paired variables x1 · x2 and x3 · x2 turned out to be insignificant;
- coefficients with quadratic variables increase adhesion (the “+” sign): ultraviolet irradiation has the greatest impact, then freeze-thaw and vibro-vacuum water saturation.

The influence of factors is more clearly seen in the analysis of the data shown in Figure 4. With an increase in the duration of vibro-vacuum water saturation up to 40 h, the adhesion decreases and then increases. With an increase in the duration of ultraviolet irradiation to 50 hours, adhesion also decreases, and then an increase also occurs. With an increase in the number of accelerated freeze-thaw cycles to 62, a decrease occurs, and then – an increase in adhesion.
The duration of the vibratory vacuum saturation, h

Number of freeze-thaw cycles
The numbers on the curves – the duration of ultraviolet radiation, h

Figure 4. The influence of the combined effects of vibration vacuum water saturation, ultraviolet irradiation and accelerated freezing-thawing on adhesion at a temperature of 20 °C of asphalt concrete composition: slag sand – 100 %, bitumen grade BND 60/90 – 9 %.

Thus, under the influence of all factors, destructive processes occur in the initial stages of the test, and then constructive ones.

The results can be explained by the fact that slag sand is a hydraulically active mineral material. When exposed to water and UV irradiation at a temperature of + 60 °C, micro-steaming chambers arise [10], hydrolysis and hydration processes in slag sand are accelerated, and the coagulation structure of asphalt concrete is strengthened by crystallization intergrowths at the contact points of slag grains. Crystal hydrates continue to form under the influence of freezing and thawing [12].

4. Conclusion
1. A method and apparatus are proposed that allow modeling the complex effect of external factors on the same samples of asphalt concrete.
2. The presented modeling method will allow to more objectively characterize the work of the material of the road surface and choose the most optimal composition of asphalt concrete for specific areas of construction and operating conditions of the road.
3. Using a mathematical method for planning extreme experiments, a mathematical model has been developed that allows predicting the behavior of asphalt concrete from slag materials for operating conditions of a highway of the third technical category in the Voronezh region.

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