UDC 625.73+625.85
DOI: 10.15587/1729-4061.2023.279006

DETERMINING THE RESIDUAL SERVICE LIFE OF POLYMER-MODIFIED ASPHALT CONCRETE PAVEMENT ON ROAD BRIDGES

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The object of research is the asphalt pavement of road bridges. Its residual period was assessed taking into account the joint effect of the ambient temperature and vehicles.

It has been established that a set of negative factors affects the reduction of the service life (residual resource) of asphalt pavement on bridges. These include different modulus of elasticity of reinforced concrete base and asphalt pavement and the difference in coefficients of linear thermal expansion. As well as loads from the wheels of vehicles, temperature fluctuations, alternating freezing-thawing of water in pores and damaged places.

It was found that one of the reasons for reducing the residual life of asphalt pavement on reinforced concrete road bridges is the insufficient study and use of polymers in order to adjust the properties of asphalt concrete.

Taking into account the joint influence of temperature and transport in assessing the crack resistance of asphalt pavement on reinforced concrete road bridges would allow a more objective assessment of the residual life of such coatings and their service life. Arrangement of asphalt pavement with improved properties, due to polymeric latex, could increase its residual life. This, in turn, would lead to a reduction in costs for the repair and maintenance of not only asphalt pavement but also the road bridge as a whole

Keywords: highway, road bridge, residual resource, crack resistance, asphalt pavement, polymers

Received date 10.03.2023
Accepted date 15.05.2023
Published date 30.06.2023

How to Cite: *Onyshchenko, A., Kovalchuk, V., Zagorodniy, O., Moroz, V. (2023). Determining the residual service life of polymer-modified asphalt concrete pavement on road bridges. Eastern-European Journal of Enterprise Technologies, 3 (1 (123)), 41–51. doi: https://doi.org/10.15587/1729-4061.2023.279006*

1. Introduction

The most common on road bridges are asphalt concrete pavements based on reinforced concrete. Increasing the service life of asphalt pavement on such structures is one of the urgent tasks of the road industry of Ukraine. However, asphalt pavement on reinforced concrete road bridges is under difficult operating conditions. It is affected by many adverse factors under operating conditions. The main ones are the different modulus of elasticity of the reinforced concrete base and asphalt pavement and the difference in the coefficients of linear thermal expansion. In addition, asphalt concrete pavement on transport structures warms up faster compared to highways. The service life of asphalt pavement is also affected by the peculiarities of load transfer from the wheels of vehicles and fluctuations in ambient temperature. And it is important to note that the service life is also affected by reagents that are used during the maintenance of roads.

All these factors cause a complex unfavorable stressed-strained condition of the coating in various structural connections, which, in turn, over time leads to premature destruction of the asphalt pavement and the structure as a whole.

Therefore, studies aimed at assessing the residual service life of the coating on road bridges with the joint effect of temperature and vehicles are relevant.

2. Literature review and problem statement

In addition to reinforced concrete bridges, asphalt concrete pavement is also used in small bridges made of corrugated metal structures in the case of laying a highway over the structure [1] or in the middle of a tunnel overpass made of metal corrugated structures [2]. However, in these works, no studies have been conducted on the impact of vehicle loads on the service life of road surfaces on bridges. Also, no assessment of the effect of the polymer on the service life of the coating on transport structures was carried out.

The issue of research into the crack resistance of asphalt pavement from the standpoint of the influence of the temperature factor on the asphalt pavement was tackled by many scientists, as can be seen from work [3]. There are also studies [4, 5] on crack resistance in terms of the influence of the transport factor on asphalt pavement.

In [4], the influence of modified bitumen on the crack resistance of asphalt pavement was evaluated. However, the cited study was conducted only under the action of transport loads without taking into account variable loads from the ambient temperature.

Work [6] focuses on the problems of ensuring the strength and durability of the bridge with asphalt concrete pavement on transport structures. However, no studies have been conducted on the effect of polymers on the durability of the coating.

In [7], the results of forecasting the residual resource of asphalt concrete pavement are given. However, no studies into the effect of polymer content on the residual coating life have been carried out in the cited work.

A review of existing methods and criteria for assessing the crack resistance of asphalt concrete pavement against the effects of temperature and the action of vehicles led to conclusions that previous studies were fragmented [8, 9]. Assessment of crack resistance of the coating is carried out separately under the action on the coating of the ambient temperature and separately the action of the transport load. Such a crack resistance assessment may not be informative enough to predict the service life of the coating.

Analysis of work [10] showed that the cited work does not fully enough take into account the peculiarities of the asphalt concrete pavement on reinforced concrete transport structures in the design schemes. In addition, the work did not assess the impact of temperature and transport on the service life of the coating.

Work [3] reports a study on increasing the resistance of asphalt pavement to the formation of rut on road bridges. However, studies have been conducted only on the action of power loads from vehicles. Studies of rut in the coating under the action of ambient temperature have not been conducted.

In [11], a method for assessing the relative efficiency of unstabilized materials of the base layer regarding the formation of a track is given, which is then used to assess the quality of coating materials. A general method for calculating the track depth arising on non-rigid coatings is also proposed. However, the cited work did not assess the service life of the coating, taking into account the effect of transport loads and temperature.

Increasing the residual resource of asphalt pavement on reinforced concrete transport structures using bitumen modified with polymers is relevant and requires additional research [12]. In work [13], it is indicated that the influence of the time of modification of bitumen by polymers on the properties of asphalt concrete has not been fully investigated, so it is necessary to conduct such studies. In addition, existing technologies for the preparation of asphalt concrete mixtures by modifying them with polymer latex during its introduction directly into the asphalt mixer are not perfect.

In [14], a laboratory assessment of asphalt binder for adhesion and its effect on rut formation in the coating was carried out. However, the studies were conducted at a constant temperature and without taking into account the polymer content in asphalt concrete.

The influence of temperature on the stressed state of bridges is described in [15]. It was established that at the border of various metal beams and reinforced concrete slabs there is a jump in temperature stresses. This is due to the influence of materials that have different modulus of elasticity. This phenomenon shows the relevance of taking into account the difference in ambient temperature to the thermally-stressed state of asphalt pavement.

The issue of the use of polymeric materials is relevant to increase the bearing capacity of transport structures. In [16], the results of the assessment of the thermally-stressed state of reinforced concrete bridge beams restored by methyl methacrylate polymers are reported. As a result, it was found that the strength of the restored beams increases.

From the review of works [1–20] it follows that the assessment of the residual resource of asphalt pavement on reinforced concrete road bridges, taking into account the influence of temperature factors with the influence of time and the action of transport load, is a necessary and urgent task of scientific research. It is also necessary to devise a unified methodological basis for a comprehensive method for calculating the residual life of asphalt concrete pavement using SBR polymers on reinforced concrete road bridges, taking into account the joint effect of temperature (seasonal annual and daily temperatures) and vehicles.

As studies in recent years show, one of the promising ways to increase the durability of asphalt concrete is the use of thermoplastic and thermoelastic-plastic polymers as modifiers of bitumen and asphalt concrete mixture [3–8]. One of such modifiers is the cationic SBR-type latex, which, according to the results of research by American and Ukrainian scientists, increases the heat resistance, elasticity, and adhesion properties of bitumen [8]. This statistical copolymer of styrene and butadiene, including those with conglomerated sulfur SBR-type, meets the requirements set out in [5, 8].

3. The aim and objectives of the study

The aim of this work is to devise a method for estimating the residual life of asphalt concrete pavement using complex SBR-type polymers on reinforced concrete road bridges, taking into account the joint effect of temperature and vehicles. This will make it possible to increase the service life of asphalt pavement on transport structures.

To accomplish the aim, the following tasks have been set:

– to work out a concept of a method for assessing the residual life of asphalt concrete pavement on road bridges taking into account the amount of polymer;

– to analyze the working conditions and state of asphalt pavement on transport structures, taking into account the joint influence of temperature and vehicles;

– to calculate the residual resource of asphalt pavement for crack resistance, taking into account the thermal-rheological behavior of asphalt concrete depending on the joint effect of temperature and transport.

4. The study materials and procedure

The object of our research is the asphalt pavement of road bridges.

Underlying the method for assessing the residual life of asphalt pavement is the possibility of taking into account the polymer. These studies are based on the following: during the predefined service life, asphalt pavements must be resistant to water and frost. In addition, proper adhesion between the coating and the base of the wheels of rolling stock must be ensured. Coatings must be resistant to cracking at the combined effect of vehicles and seasonal annual and daily ambient temperatures. At the same time, resistance to water-frost influences is envisaged to provide with an appropriate choice of the type of material for asphalt concrete pavement of reinforced concrete transport structures, the establishment of appropriate requirements for it, and the technology of its arrangement.

Estimation of the residual life of asphalt pavement of reinforced concrete road bridges is based on obtaining analytical dependences. They will make it possible to determine stresses from the general ambient temperatures and the actions of vehicles. Assessment of the residual life of asphalt pavement should be based on the condition of the boundary state. In addition, to predict the formation of cracks in the coating, it is necessary to take into account the joint effect of stresses that arise from the action of vehicles and the influence of ambient temperature.

To solve the tasks, two estimation schemes (Fig. 1, 2) of asphalt concrete pavement work on reinforced concrete road bridges are considered. This takes into account fluctuations in ambient temperatures and the action of vehicles. They are used to derive analytical dependences for predicting stresses and assessing the residual life of asphalt pavement. For these estimation schemes (Fig. 1, 2), analytical dependences are further built to calculate the horizontal normal stresses arising in the asphalt pavement and its layers from fluctuations in seasonal annual and daily temperatures, as well as the action of vehicles.

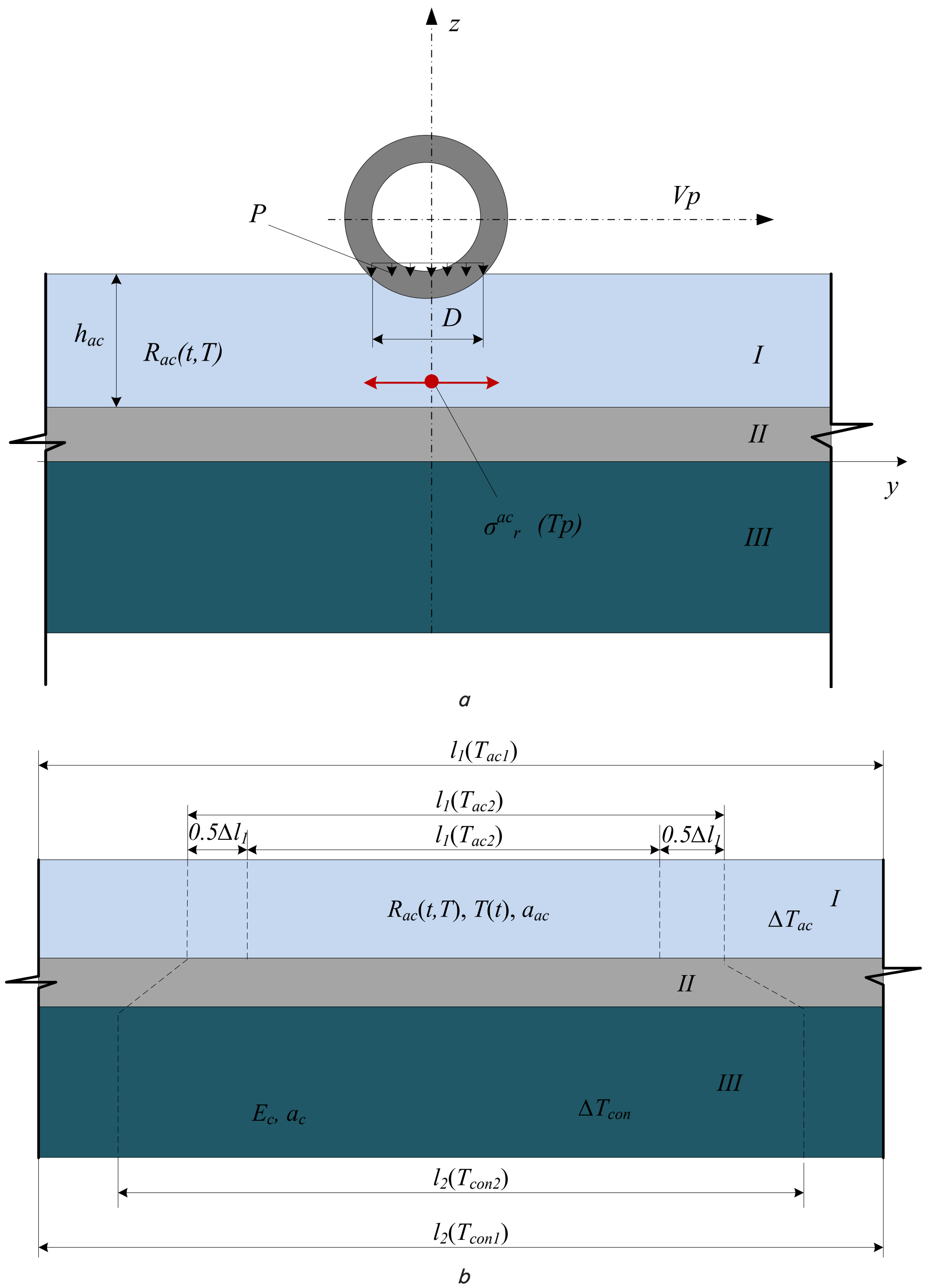
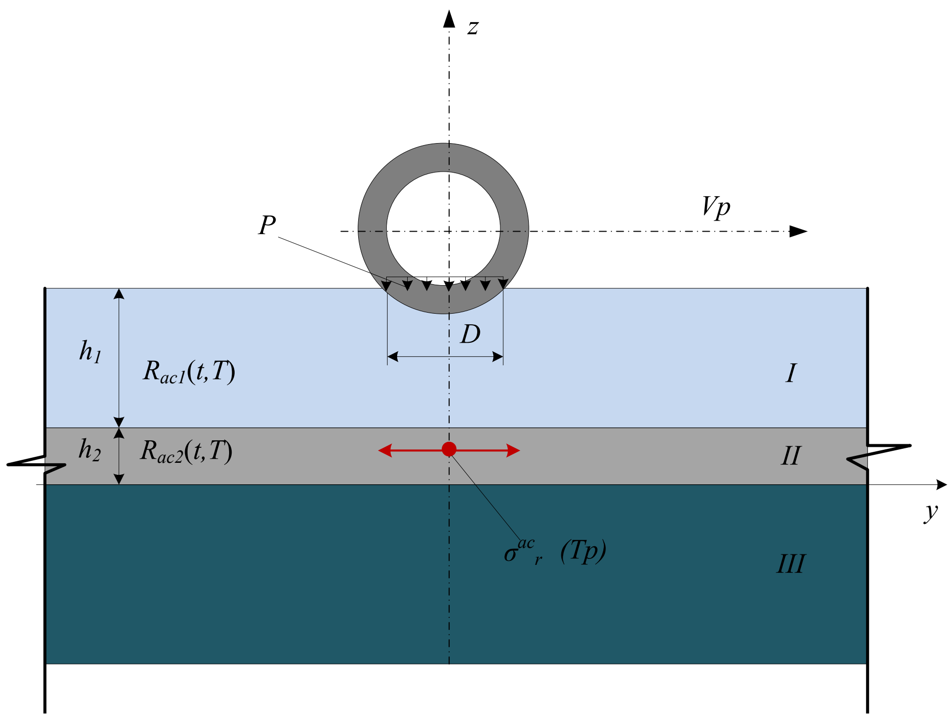
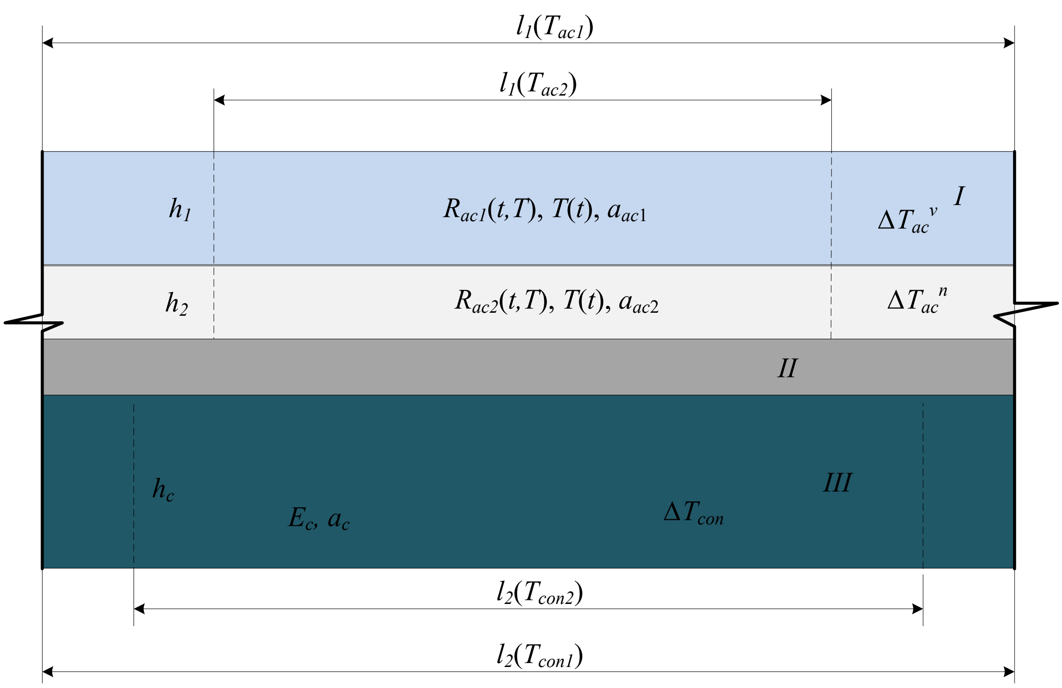


Fig. 1. Estimation scheme of asphalt concrete pavement (I), connected to the base of reinforced concrete (III) through waterproofing material (BIGUMA-ICP Gusstex) (II) under the action of: *a* – vehicles; *b* – temperature



a



b

Fig. 2. Estimation scheme of asphalt concrete pavement (I) with adhesion of asphalt concrete layers, connected to the base of reinforced concrete (III) through waterproofing material (BIGUMA-ICP Gusstex) (II): under the action of: *a* — vehicles; *b* — temperature

In Fig. 1 and Fig. 2, we adopted the following notation: $R_{ac1,2}(t,T)$ – relaxation function of asphalt pavement; $\sigma^{ac}_{yr}(T_p)$ – tensile stresses depending on the time of action of vehicles and the function of relaxation of asphalt concrete pavement; V_p – vehicle speed; E_c – modulus of elasticity of reinforced concrete base; $\alpha_{ac1,2}$, α_c – coefficient of linear thermal expansion of asphalt concrete (using the SBR-type polymer) and reinforced concrete, respectively; ΔT_c, ΔT_{con} – change in the temperature of the coating and reinforced concrete base, respectively; $l_1(T_1)$, $l_2(T_1)$ – length of the coating and reinforced concrete base before the beginning of temperature reduction ($l_1(T_1)=l_2(T_1)$), respectively; $l_1(T_2)$, $l_2(T_2)$ – length of the coating and reinforced concrete base after temperature reduction ($l_1(T_2)\neq l_2(T_2)$) respectively; $l_1'(T_2)$ – coating length in the case of free temperature reduction.

Our theoretical and experimental studies make it possible to estimate the residual life of asphalt concrete pavement on a reinforced concrete transport structure, taking into account seasonal annual and daily temperatures, as well as the effect of transport load. For this purpose, experimental research methods were used, namely standard and special methods of studying the physical and mechanical thermal-rheological properties of asphalt concrete and static analysis for processing the results of experimental studies.

5. Results of the construction of a method for assessing the residual life of asphalt concrete pavement on road bridges taking into account the amount of polymer

5. 1. Devising the concept of the method

In order to determine the crack resistance depending on the action of vehicles for estimation schemes (Fig. 1, 2), the exact solution from the theory of elasticity, derived in [3], was used. When applying this solution and while performing numerical studies, functions for assessing stresses in the horizontal direction of asphalt concrete pavement were established and approximated using dependence [1]:

$$\sigma_{Tp} = A_i\left(R(t,T)\right)\cdot h_1 / D^{-B_i(R(t,T))}\cdot p\cdot K_s, \qquad (1)$$

where $A_i(R(t, T))$, $B_i(R(t, T))$ are constants that depend on the relaxation function. Variables depending on load time and temperature: h_1 – thickness of asphalt pavement; D – area of circle; K_s – a coefficient showing the peculiarities of the stressed state of the coating under the wheel of a car with twin cylinders; p – pressure on the asphalt pavement, taken from calculation, MPa.

In determining the temperature stresses, the thermoviscoelastic properties of asphalt concrete, which reflect the dependence of relaxation and temperature-time displacement, were taken into account. The thermoviscoelastic properties of asphalt concrete are determined experimentally.

Analytical dependences for determining the temperature stresses of asphalt concrete pavement for the proposed calculation schemes shown in Fig. 1, 2:

– variant 1:

$$\sigma^{ac}_{r,(Tem)}(t) = (\alpha_{ac}-\alpha_A)\cdot\varphi k_{ac}\times \times\left(\begin{array}{l} E_{\partial z}+\left(E_{ia}-E_{\partial z}\right)\times \\ \times\int\limits_0^e\left(1+\dfrac{\dfrac{e^{P(T_0+k\cdot t-T_s)}}{Pk}\left(e^{-P\cdot k\cdot(t-t_1)}-1\right)}{\eta}\right)^{-\lambda}\mathrm{d}\tau\end{array}\right), \qquad (2)$$

– variant 2:

$$\sigma^{ac}_{r,(tem)}(t) = \left(k_{ac}\frac{\alpha_{ac1}+\alpha_{ac2}}{2}-k_c\alpha_c\right)\cdot\varphi\cdot\delta\times \times\left(\begin{array}{l} \bar{E}_{\partial z}+\left(\bar{E}_{ia}-\bar{E}_{\partial z}\right)\times \\ \times\int\limits_0^t\left(1+\dfrac{\dfrac{e^{\bar{P}(T_0+k\cdot t-T_s)}}{\bar{P}k}\left(e^{-\bar{P}\cdot k\cdot(t-t_1)}-1\right)}{\bar{\eta}}\right)^{-\bar{\lambda}}\mathrm{d}\tau\end{array}\right), \qquad (3)$$

where φ is the coefficient taking into account the presence of an elastic layer based on organic binders, which is placed between the asphalt pavement and the reinforced concrete base; Δ – coefficient taking into account friction between asphalt concrete layers; λ and η – constants established experimentally using a SBR-type polymer; E_{ie} and E_{ia} – long-term and instantaneous modulus of elasticity of asphalt pavement, respectively (using a SBR-type polymer); k_{ac}, k_c – respectively, the cooling rate of asphalt concrete and reinforced concrete base; t – observation time; t_1 – time preceding the moment of observation; P – parameter of the temperature-time displacement function; T_0, T_S – starting temperature and temperature of asphalt concrete.

An analytical dependence for calculating the residual resource in terms of crack resistance of the coating on reinforced concrete transport structures was obtained, taking into account the joint effect of vehicles and seasonal annual and daily temperatures.

Estimation of the boundary condition of the coating on reinforced concrete bridges in terms of residual resource is defined as a multiparameter dependence. The residual life of asphalt pavement ($Z_p(t, T)$) is a function of two variables:

$$Z_p(t,T) = C_{TP}\cdot K_y - K_{vid}\left(M_{tem}(t,T)+M_{Tp}(t,T)\right), \qquad (4)$$

where

$$M_{tem}(t,T) = \int\limits_0^{t_p}\frac{\sigma^{ac}_{r,(tem)}(t)^{b(t,T)}}{B_t(t,T)}\mathrm{d}t$$

is the degree of damage to the coating on reinforced concrete bridges under the influence of temperature changes;

$$M_{Tp}(t,T) = \sum N_p\int\limits_0^{t_n}\frac{\sigma_{TP}(t)^{b(t,T)}}{B_t(t,T)}\mathrm{d}t$$

is the degree of damage to the coating on bridges under the action of vehicles; K_y is the coefficient that takes into account the aggressive effect of anti-icing reagents. It is derived experimentally; K_{vid} – coefficient reflecting the degree of coating recovery; B, b – values of the function of durability of asphalt concrete pavement using an SBR-type polymer; $[C_{TP}]$ – maximum permissible value of the amount of damage to the coating on bridges. It is assumed to be equal to 1; $\sum N_p$ – the total number of passages of vehicles during the service life of the coating on bridges; σ_{TP} – tensile stresses that occur in the asphalt pavement when bending depending on the action of the calculated transport load; t_p – time to destruction; t_H – load time.

The limit state of the residual coating resource on bridges is as follows [1]:

$$Z_p(t) \geq [Z], \qquad (5)$$

where $[Z]$ is the maximum permissible value of the residual resource, obtained from the results of numerical analysis of the studied asphalt concrete; it is 0.3.

Taking into account the above dependences, for the established estimation schemes (Fig. 1, 2), we get:

$$Z_{pi}(t,T) = C_T\ K_y - K_{vid}\left(\begin{array}{l} n_{i(l)}\int\limits_0^{t_i}\dfrac{\left(\sigma^p_l+\sigma^\partial_l\right)^{b\tau_k}}{B_l}\mathrm{d}t+ \\ +\,n_{i(>v)}\int\limits_0^{t_i}\dfrac{\left(\sigma^p_{o,v}+\sigma^\partial_{o,v}\right)^{b\tau_{o,v}}}{B_{o,v}}\mathrm{d}t+ \\ +\,n_{i(z)}\int\limits_0^{t_i}\dfrac{\left(\sigma^p_z+\sigma^\partial_z\right)^{-b\tau_z}}{B_z}\mathrm{d}t\end{array}\right)+$$

$$+\sum N_p\int\limits_0^{t_H}\frac{\mathrm{d}t}{B\cdot\left(\sigma_r\left(R(t,T),h_1/D\right)\cdot p\cdot K_s\right)^{-b}} \geq [Z], \qquad (6)$$

where $n_{i(l)}$, $n_{i(o,v)}$, $n_{i(z)}$ is the season period: summer, autumn-spring, and winter, respectively; B_l, $B_{o,v}$, B_l, $b\tau_l$, $b\tau_{o,v}$, $b\tau_z$ – parameters of the function of durability of asphalt concrete using an SBR-type polymer depending on the season. Taking into account the formulas (4) to (6), it is proposed to estimate the estimated service life T_P (in years) of asphalt pavement on bridges, according to the following analytical dependence:

$$T_P=\frac{Z_p(t,T)}{[Z]}\cdot T_n \geq T_n, \qquad (7)$$

where T_n is the normative service life of the carriageway coating of reinforced concrete transport structures.

Our formulas (1) to (7) make it possible to comprehensively take into account different amounts of an SBR-type polymer for the service life of asphalt concrete pavement on road bridges due to the determined parameters of the asphalt concrete durability function.

5. 2. Results of calculating the strength of asphalt pavement on transport structures

Verification of the adequacy of theoretical solutions, the results of which are given in Tables 1, 2, was conducted based on the theoretical and experimental studies reported in [1].

Theoretical calculations correlate well with experimental data. The error ranges from 3.8 % to 9.2 % in determining the tensile strength of samples at bending. To determine the number of load cycles before destruction – from 14.1 % to 18.8 %, with a confidence level of 0.95. This proves the practical feasibility of using the dependences in order to ensure or predict the required residual resource of asphalt pavement on bridges. This allows calculating the service life of asphalt pavement under the influence of temperature and transport.

5. 3. Calculation of the residual life of asphalt concrete pavement in terms of crack resistance

Numerical analysis of the regularities of influential factors on the residual life of asphalt pavement on structures was carried out on the Pechersk overpass in Kyiv, operated on Lesia Ukrainka Boulevard.

For analysis, we took the estimation scheme in Fig. 1, *a*. The assessment of the residual resource of the coating on the overpass involved calculating the degree of damage to the coating under the influence of temperature and vehicles.

The results of the assessment of the residual resource (Z_p) and the estimated period (T_P) of service using an example of the asphalt concrete ASG.Dr.Sh.B.NP.I.BND 50/70 (type B-20) depending on different amounts of an SBR-type polymer, introduced into the bitumen binder and asphalt concrete mixture, are shown in Fig. 3, 4.

As a result of research, the residual life of the ASG. Dr.Sh.B.NP.I.BND 50/70 asphalt concrete (type B-20), 10 cm thick on traditional bitumen binder, without modification by polymer (standard) was 0.335.

When modifying the bitumen with 2 % of the polymer, the coating life increased 1.67 times, with 4 % of the polymer – 2.23 times, and with 6 % of the polymer – 2.49 times compared to the standard.

Our results of the residual resource depending on the introduction of polymer into asphalt concrete indicate the effective effect of the polymer on increasing the coating life.

In the case of modification of asphalt concrete mix with 3 % of the polymer, it increases by 1.8 times; with 6 % of the polymer – 2.36 times compared to the standard.

Research results indicate that the residual resource increases with an increase in the polymer modifier.

Table 1

Results of comparison of experimental and theoretical data for determining the tensile strength of samples at bending with a constant loading rate using an example of the asphalt concrete grade ASG.Dr.Sh.B.NP.I.BND 50/70 with a maximum size of crushed stone of 20 mm, at the amount of bitumen binder (BND 5 0/70) of 6.3 %, and crushed stone mastic asphalt concrete with a maximum size of crushed stone of 10 mm (SMA-10) at the amount of bitumen binder (BND 50/70) of 6.8 %

Material	Amount of an SBR-type polymer, %	Number of cycles	V_σ, MPa/s	Durability function parameters		σ_c, MPa		
				$b\tau$	lg$B\tau$, s·MPa	theory	experi-ment	Δ, %
Test temperature: T=+20 °C								
ASG.Dr.Sh.B.NP.I.BND 50/70	2	0	0.28	2.62	3.41	6.83	6.56	3.8
SMA-10	4		0.33	3.69	4.47	7.07	7.72	–9.2
ASG.Dr.Sh.B.NP.I.BND 50/70	2	10	0.28	2.03	2.73	5.16	5.38	–4.2
SMA-10	4		0.33	3.25	4.00	6.94	7.21	–3.8

Table 2

Results of comparison of experimental and theoretical data determining the number of load cycles before destruction of samples using an example of the asphalt concrete grade ASG.Dr.Sh.B.NP.I.BND 50/70 with a maximum size of crushed stone of 20 mm, at the amount of bitumen binder (BND 50/70) of 6.3 %, and crushed stone mastic asphalt concrete with a maximum size of crushed stone of 10 mm (SMA-10) at the amount of bitumen binder (BND 5 0/70) of 6.8 %

Asphalt concrete cipher	Amount of an SBR-type polymer, 5 %	Number of cycles to destruction N_m, (theoretical)	Number of cycles before destruction N_e, (experimental)	Δ, %
Test temperature: T=+20 °C				
ASG.Dr.Sh.B.NP.I.BND 50/70	0	963	807	16.2
ASG.Dr.Sh.B.NP.I.BND 50/70	4	3 194	3 695	15.7
SMA-10	0	2 268	1 841	18.8
SMA-10	4	19 437	16 696	14.1

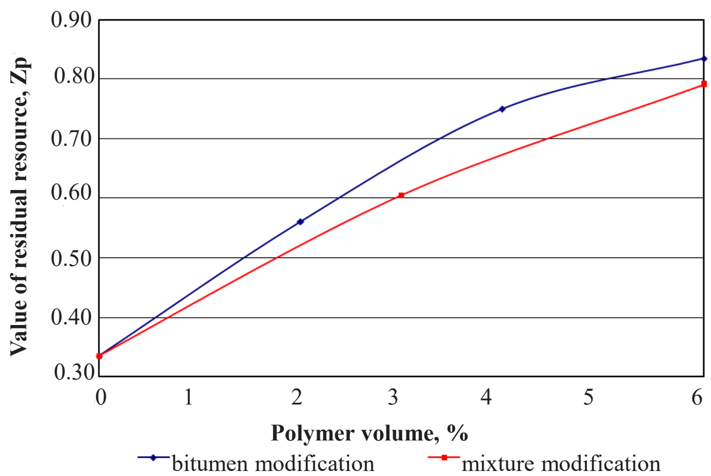


Fig. 3. Dependence of the residual resource of the ASG.Dr.Sh.B.NP.I.BND 50/70 asphalt concrete (type B-20) on an SBR-type polymer

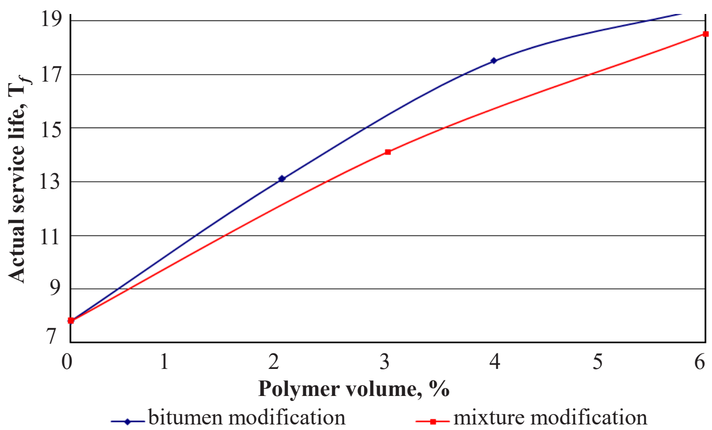


Fig. 4. Dependence of the estimated service life of the ASG.Dr.Sh.B.NP.I.BND 50/70 asphalt concrete (type B-20) on the amount of an SBR-type polymer

Thus, as a result of research, the actual service life of SMA-10 (Fig. 5), 10 cm thick, on a traditional bitumen binder, without modification by polymer (standard) was 16.1 years. With the modification of bitumen with 2 % of the polymer, it increased 1.21 times; with 4 % of the polymer – 1.29 times; and with 6 % of the polymer – 1.37 times compared to the standard.

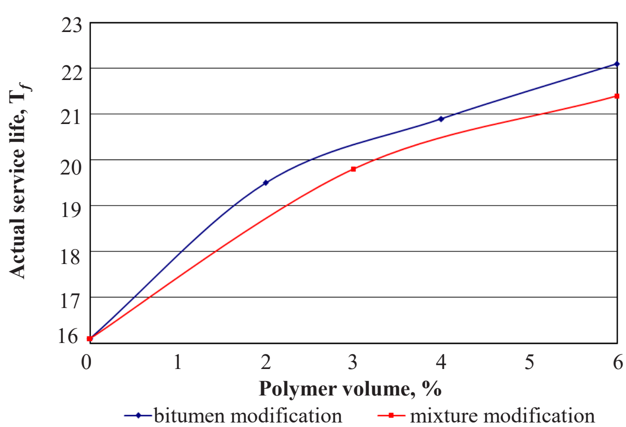


Fig. 5. Dependence of the actual service life of SMA-10 on the amount of polymer

The results of the actual service life depending on the introduction of the polymer into the asphalt concrete mixture indicate an increase in the coating life. When modifying asphalt concrete mix with 3 % of the polymer, it increases by 1.22 times; and with 6 % of the polymer – 1.32 times compared to the standard.

The results of the actual service life of SMA-10, depending on the amount of polymer, showed that the addition of polymer leads to an increase in the service life of asphalt concrete. The method of interpolation found that with the modification of bitumen with 2 % of the polymer, the service life of asphalt concrete increases by 5 % compared to the modification of asphalt concrete mix. In the case of modification of bitumen with 3 % of the polymer – by 3 %, with modification of bitumen with 4 % of the polymer – by 3 %, and with modification of bitumen with 6 % of the polymer, service life is increased by 4 times. With an increase in the polymer, both an increase in service life and the difference between the modification of bitumen and asphalt concrete mix stabilize.

As a result of research, the residual resource of SMA-10 (Fig. 6), 10 cm thick, on traditional bitumen binder, without modification by polymer (standard) was 0.691. And with the modification of bitumen with 2 % of the polymer, it increased by 1.20 times, with 4 % of the polymer – 1.29 times, and with 6 % of the polymer – 1.37 times compared to the standard. Our results of the residual resource depending on the introduction of the polymer into the asphalt concrete mixture indicate the following: when modifying the asphalt concrete mixture with 3 % of the polymer, it increases by 1.23 times, with 6 % of the polymer – 1.32 times compared to the standard.

The results of the residual life of SMA-10 depending on the amount of polymer indicate the following: the residual resource is directly proportional to the service life of asphalt concrete; with an increase in the polymer modifier, it increases.

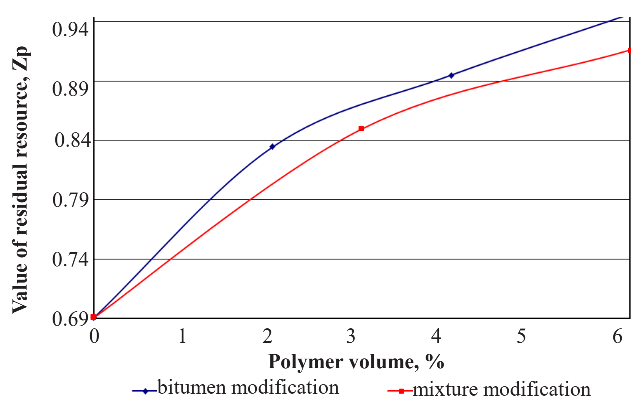


Fig. 6. Dependence of the residual resource of SMA-10 on the amount of polymer

Our results of the residual resource depending on the introduction of the polymer into the asphalt concrete mixture indicate the following: when modifying the asphalt concrete mixture with 3 % of the polymer, it increases by 1.21 times, with 6 % of the polymer – 1.28 times compared with the standard.

The obtained values of the residual life of asphalt concrete pavement showed that the service life depends on the amount of crushed stone in asphalt concrete. The research results are shown in Fig. 7.

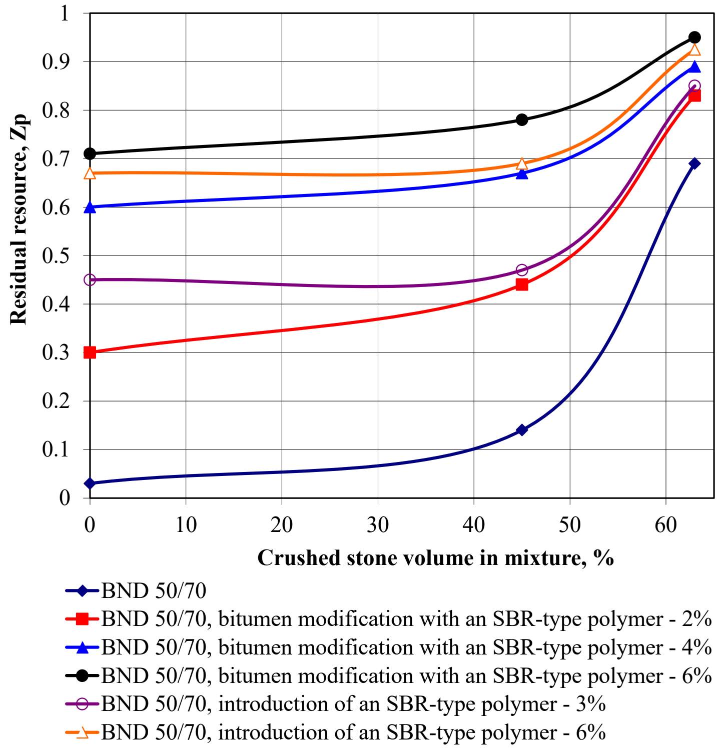


Fig. 7. Dependence of the residual resource on the content of crushed stone in asphalt concrete and on the amount of an SBR-type polymer

Thus, as a result of research, the residual life of asphalt concrete, depending on the content of crushed stone (Fig. 7), 10 cm thick, on traditional bitumen binder, without modification by polymer (standard) was 0.025 for sand mixtures. The service life for asphalt mixes containing 45 % crushed stone is 5.6 times, and for mixtures of 65 % crushed stone is 27.6 times longer compared to the standard.

With the modification of bitumen by the polymer in the amount of 2 %, the residual resource is 0.311 for sand mixtures. For asphalt mixes with 45 % crushed stone content, the residual resource is 1.44 times, and for mixtures with 65 % crushed stone, 2.68 times higher compared to the standard.

With the modification of bitumen with the polymer in the amount of 4 %, the residual resource is 0.608, for sand mixtures. The residual resource for asphalt mixes with 45 % crushed stone content is 1.08 times, and for mixtures with 65 % of aggregates is 1.47 times more compared to the standard.

With the modification of bitumen by the polymer in the amount of 6 %, the residual resource is 0.71 for sand mixtures. At the same time, the residual resource for asphalt mixes with 45 % crushed stone content is 1.11 times, and for mixtures with 65 % of crushed stone – 1.33 times more compared to the standard.

With the modification of asphalt concrete mix with the polymer in the amount of 3 %, the residual resource is 0.444 for sand mixtures. At the same time, the residual resource for asphalt mixes with 45 % crushed stone content is 1.05 times, and for mixtures containing 65 % crushed stone is 1.91 times more compared to the standard.

With the modification of asphalt concrete mix with the polymer in the amount of 6 %, the residual resource is 0.676 for sand mixtures. At the same time, the residual resource for mixtures with 45 % crushed stone content practically does not change from the standard. For asphalt mixes with 65 % crushed stone, the residual resource increased 1.35 times compared to the standard.

The value of the actual service life depending on the amount of crushed stone is shown in Fig. 8.

The service life of asphalt concrete, depending on the content of crushed stone (Fig. 8) with a thickness of 10 cm was 6 months, for mixtures without crushed stones. The service life of asphalt concrete for mixtures with 45 % crushed stone content is 5.5 times, and for mixtures with 65 % crushed stone content is 26.8 times higher than asphalt concrete on traditional bitumen binder, without polymer modification.

With modification of bitumen with 2 % polymer (for crushed stone mixtures), the service life of asphalt concrete is 7 years and two months. For mixtures with 45 % aggregates content, the service life is 1.45 times, and for mixtures with 65 % crushed stone, 2.7 times longer compared to the standard.

With the modification of bitumen with 4 % polymer (for crushed stone mixtures), the service life of asphalt mixes is 14.2 years. For mixtures with 45 % crushed stone content, the service life is 1.08 times, and for mixtures with 65 % crushed stone – 1.47 times more compared to the standard.

With modification of bitumen with 6 % polymer (for crushed stone mixtures), the service life of asphalt concrete is 16 years and six months. For mixtures with 45 % crushed stone content, the service life is 1.10 times, and for mixtures with 65 % aggregates content – 1.33 times more than the standard.

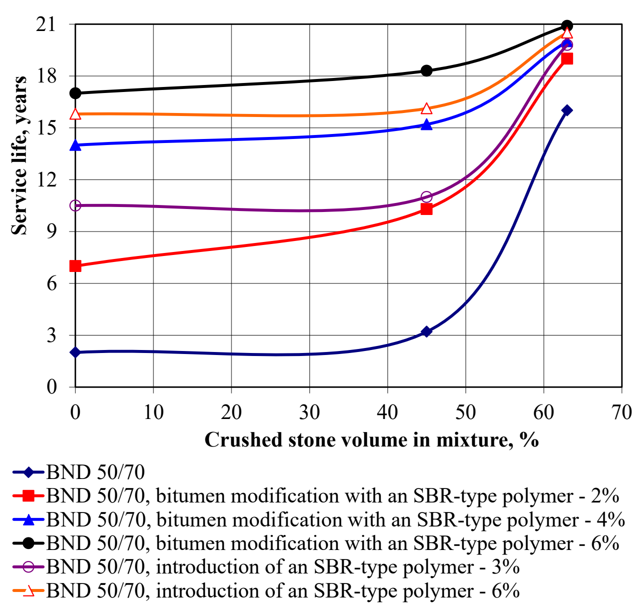


Fig. 8. Dependence of the actual service life on the content of crushed stone in asphalt concrete and on the amount of an SBR-type polymer

When modifying an asphalt mix with 3 % polymer (for crushed stone mixtures), the service life is 10 years and four months. For mixtures with 45 % crushed stone content, the service life is 1.05 times, and for asphalt mixes with 65 % crushed stone content is 1.90 times longer compared to the standard.

6. Discussion of results of increasing the residual service life of asphalt pavement on road bridges

Taking into account the analysis of the working conditions of asphalt pavement on reinforced concrete road bridges, it was found that the pavement is under difficult operating conditions. This leads to premature destruction of the asphalt pavement and the structure of the transport structure as a whole. Previous studies into the work of asphalt pavement on reinforced concrete transport structures are fragmented. Therefore, there is a need to devise an integrated method for calculating the residual life of asphalt pavement on reinforced concrete road bridges. In this case, the calculation should be carried out taking into account the joint effect of temperature (seasonal, annual and daily temperatures) and vehicles.

Asphalt concrete pavements on road bridges using the SBR polymer have become extremely widespread in recent years in Ukrainian construction. But the use of asphalt concrete using SBR polymers is not supported by a sufficient theoretical base, and, as a rule, when designing road surfaces on bridges, they are assigned structurally, which does not allow determining the real service life of asphalt concrete pavement on road bridges at the design stage.

In order to achieve the main scientific result and establish a scientific idea, a working hypothesis has been put forward: the regularities of the action of external factors on the calculation of the residual resource of asphalt concrete pavement of reinforced concrete road bridges could be based on the application of the estimation model (Fig. 1, 2), regardless of the type of manifestation of internal factors.

The analytical dependences (1) to (7) were obtained on the basis of application of provisions from the theory of elasticity, thermoviscoelasticity, and the kinetic theory of strength of solids. They make it possible to assess the residual service life of asphalt pavement under the action of loads from vehicles and exposure to variable temperatures. This takes into account the thermoviscoelastic properties of asphalt concrete.

On the basis of experimentally established parameters of the durability and relaxation function for analytical dependence (6), the features of the coating operation with a certain type of manifestation of internal factors are evaluated.

The research results allowed us to put forward a scientific idea that the formation of cracks in the asphalt pavement on bridges occurs from the action of the vertical cyclic load of the pneumatic wheels of vehicles when the temperature changes according to the seasons. This is due to the accumulation of damage to the structure in the form of cracks in the coating, resting on a rigid reinforced concrete base. This is influenced by the complex action of internal (formulation-structural, structural, technological) and external (climatic, transport, operational) factors.

A conceptual method for assessing the residual life of asphalt pavement on road bridges has been proposed. It makes it possible to calculate asphalt pavement on bridges with different service life, taking into account internal, structural, technological, external climatic, transport, and operational factors. Internal factors include formulation-structural components: asphalt concrete of various granulometry, characteristics of asphalt concrete and road-building materials, physical and mechanical properties, parameters of the function of durability and relaxation, coefficient of linear thermal expansion, the amount of binder and the polymer SBR, asphalt concrete recovery coefficient. Structural – construction parameters, thickness of the corresponding layer, dimensions, etc. Technological – temperature, compaction coefficient. External climatic factors – changes in temperatures daily, annually, and during the season: summer, autumn-spring, and winter. Transport factors: pressure from the pneumatic wheel, different duration of the load of the pneumatic wheels of vehicles. Operational factors – vehicle speed, total number of passage of the estimated load over the service life.

The estimation schemes (Fig. 1, 2) allow determining horizontal stresses in the asphalt pavement of reinforced concrete road bridges, taking into account seasonal annual and daily temperatures and taking into account the joint effect of the transport load, which causes tensile stresses.

The experimentally obtained values of the durability function parameter for the crushed stone mastic asphalt concrete SMA-10, both when using the polymer SBR ($b\tau=3.25$) and without the use of the polymer ($b\tau=2.73$), are consistent with the results of fatigue tests conducted by various scientists reported in [7, 8]. According to them, the following values of the parameter $b\tau$ were obtained: 2.76, 2.68, 2.79, and 3.39.

Taking into account the ability of asphalt concrete to partially restore its structure, [3] substantiated the choice of long-term strength condition and boundary state criterion for assessing the crack resistance of asphalt concrete pavement, taking into account the load mode characteristic of city conditions [4]. However, such approaches to assess the crack resistance of asphalt pavement should be taken into account only if tensile stresses appear in the upper asphalt layer. The current regulatory documents in Ukraine when calculating the pavement eliminate the possibility of determining tensile stresses in the upper layer of the surface. Therefore, we can conclude that the regulatory framework does not make it possible to use asphalt pavement on reinforced concrete transport structures as pavement. Assigning certain materials and their thickness in the coating occurs according to approximate procedures, based on the properties of the material without taking into account the thermal-rheological properties of asphalt concrete.

Theoretical calculations are consistent with experimental data. This indicates the possibility of practical application of our dependences in order to ensure or predict the required residual resource and the estimated service life of asphalt pavement on reinforced concrete road bridges. According to the above procedure, it is possible to calculate the service life of asphalt pavement under the influence of temperature and loads from vehicles.

The disadvantage of the experimental and theoretical studies into the residual life of asphalt pavement is determining the number of load cycles before destruction of samples using an example of the ASG.Dr.Sh.B.NP.I.BND 50/70 asphalt concrete (type B-20) and SMA-10 only at an ambient temperature of +20 °C.

One of the limitations of our studies is the assessment of the residual service life of asphalt concrete pavement only by taking into account the content of crushed stone in asphalt concrete and the amount of polymer without taking into account the combined effect of transport loads and ambient temperature. Therefore, the continuation of research work is to conduct comprehensive studies into the influence of variable values of ambient temperature and transport load on the residual life of asphalt pavement on bridges.

7. Conclusions

1. The concept of a method for assessing the residual resource of asphalt concrete pavement on road bridges has been developed. It provides for the possibility of calculating asphalt pavement on bridges with different service life. It also makes it possible to take into account formulation-structural, structural, and technological factors, and the effect of external climatic influences and transport loads on the service life of asphalt pavement. The peculiarity of this concept is the ability to comprehensively take into account different amounts of an SBR-type polymer for the service life of asphalt pavement on road bridges.

2. The results of our calculations showed that the theoretical calculations satisfactorily agree with the experimental data. The discrepancy between the obtained data is in the range from 3.8 % to 9.2 % in determining the tensile strength of the samples at bending. When determining the number of load cycles before destruction, the discrepancy between the obtained data is from 14.1 % to 18.8 %, with a confidence level of 0.95. This indicates the possibility of practical application of such dependences. Namely, ensuring or forecasting the necessary residual resource of asphalt pavement on reinforced concrete transport structures. It is also possible to predict changes in the time of the residual life of asphalt pavement under the influence of ambient temperature and vehicles.

3. Based on the results of numerical analysis, it was found that the estimated service life of asphalt concrete on the example of type B-20 with a thickness of 10 cm on a traditional bitumen binder (without modification by polymer) was 7.8 years, with a residual resource of 0.34. When modifying bitumen with 2 % polymer, the service life of asphalt concrete increased by 1.67 times. At the same time, the service life and residual life with the modification of bitumen with 4 % polymer increased by 2.24 times, with the modification of bitumen with 6 % polymer – 2.5 times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

The manuscript contains data included as additional electronic material.

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