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asphalt concrete; the modifier; modifying agent; rubber; thermoelastolayer

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THE FATIGUE DURABILITY OF THE MODIFIED ASPHALT CONCRETE UNDER THE EFFECT OF INTENSIVE TRAFFIC LOADS

Summary. The problem of prediction of the service life of asphalt concrete surface constructed with modified asphalt concrete application onto a traffic lane is examined. Asphalt concrete behaviour in road surface under the traffic loads was analysed. There were shown The results of experiments and their mathematical analysis of the assessment of standard and modified cold asphalt concrete fatigue life on road surface were shown. The service life of an asphalt concrete surface covered with standard and modified cold asphalt concrete is examined. The prediction has been received with an account of stress relaxation processes in asphalt concrete pavement and unevenness of traffic load application.

УСТАЛОСТНАЯ ДОЛГОВЕЧНОСТЬ МОДИФИЦИРОВАННОГО АСФАЛЬТОБЕТОНА ПРИ ВОЗДЕЙСТВИИ ИНТЕНСИВНЫХ ТРАНСПОРТНЫХ НАГРУЗОК

Аннотация. Рассматривается задача прогнозирования срока службы асфальтобетонного покрытия, отремонтированного с применением модифицированного холодного асфальтобетона. Проведён анализ работы асфальтобетона в дорожном покрытии при воздействии транспортных нагрузок. Показаны результаты эксперимента и их математический анализ по оценке усталостной долговечности традиционного и модифицированного холодного асфальтобетона в дорожном покрытии. Определены сроки службы отремонтированных асфальтобетонных покрытий традиционным и модифицированным холодным асфальтобетоном. Прогноз получен на основе учета процессов релаксации напряжений в асфальтобетонном покрытии и неравномерности приложения транспортной нагрузки.

1. INTRODUCTION

Extending the time between asphalt concrete surface repairs is an important problem of the road industry in Russia. Expert assessments show that nowadays only 37% of federal and 24% of regional roads satisfy the standard requirements [6].

The service life and traffic performance criteria of highways can be considerably enhanced at the expense of modern material and technology application during their repair. Their choice should be based on the results of predictions of road surface state changes and its deterioration process.

The asphalt-concrete deterioration processes affected by repeated vehicle influence are determined by fatigue, that is, gradual material strength reduction over time [2, 3, 11-13, 15]. The significant increase of the load application number per unit time takes place under the heavy traffic effect. It is one of the main causes of road surface failure.

There is a strong opinion in global experience that the application of road concrete mixes based on modified bitumen is the radical technique of pavement construction and repair improvement [2, 3, 5, 7-9]. The use of materials based on bitumen modified with polymers refers to one of the most advanced technologies in road building. The technology of pavement repair with the help of cold modified road concrete mix is another one of them.

The well-known technique of static load single application tests does not allow the giving of an assessment of asphalt concrete fatigue resistance processes caused by repeated fatigue cyclic loadings acting for a long period. Cycle dynamic deflection is the asphalt concrete test profile most closely simulating the real conditions of material behaviour under traffic load effect on a bituminous surface [4, 5]. The fatigue characterises gradual material performance degradation in the pavement under repeatedly applied loads; then according to the above-mentioned technique, it is determined by the number of load cycles that asphalt concrete sample can carry before deterioration. The design time of one cycle of load effect is 0,02 sec, which corresponds to surface loading condition at a vehicle speed of 60 km/h [1, 4].

The higher the vehicle speed, the later the retroaction in road pavement appears.

Investigations [1, 4, 6] of non-rigid road type of pavement deformation determine the following behaviour of asphalt-concrete in pavement:

- amplitude of road base deflection of a permanent type of pavement (thickness of bituminous concrete surface is 18-25 cm) under the load of 100-130 kg is not more than 0,1-0,15 mm;
- maximal amplitude of road pavement deflection is 0,35 mm at the truck speed of 60 km/h, and it is 0,1-0,15 mm at 120 km/h, respectively;
- the complex deflection cup with amplitude up to 0,4 mm appears when two adjacent traffic lanes of road permanent type of pavement are full of trucks with design load of 100 kN;
- frequency of pavement loading at two-axle vehicle traffic is 20-35 hertz, at five-axle articulated lorry traffic it is 15- 65 Hz.

Test conditions simulating operating regimes of pavement behaviour were defined on laboratory plant of cyclic loading for experimental investigation of cold modified asphalt concrete fatigue life: temperature is +200 C, loading frequency is 50 Hz, sample loading down to failure from minimal up to maximal load rate is 0,23; 0,35; 0,50 mm in the mode of constant deflection amplitude.

According to the mentioned conditions, there were tested asphalt concrete samples of 16x4x2,5 cm size under the cyclic load effect. Three samples of cold asphalt concrete with the application of sand from fragmentation siftings of the same size distribution based on different binding agents were prepared. The control one was prepared on standard liquid oil bitumen obtained from viscous bitumen fluidized by kerosene (road petroleum asphalt 60-90 (0,1 mm). The other cold road concrete mixes were based on liquid strongly thickening modified bitumen (SG 130/200 Russian standard). Synthetic styrene rubber and divinyl-styrene thermoelastolayer are used as polymer modifying agents. Polymers were before diluted in kerosene and then viscous bitumen was fluidized by the derived solution with a penetration depth of 60-90 (0,1 mm). The test data of the above-mentioned cold asphalt concrete mix proportion under cyclic loading down to failure are given in table 1.

As follows from the test data, the number of cycles up to modified cold asphalt concrete deterioration increases the mentioned data of standard cold concrete more than 1,30-1,40 times in a dry state and relatively 1,30-1,35 times in a water-saturated state. In toto, a small cycle life of cold asphalt concrete under constant loading was specified.

According to findings describing six test series (table 1), the unified quantitative characteristic of cold asphalt concrete fatigue life under the traffic load effect in road surface is suggested.

Thus, we proceed from the proposition about the destructive fracture energy accumulation (leading to residual strain generation) of the material under test: in the series of N-one-type loadings, this energy is N times more than the similar one, connecting with a single loading. In the frame of such a proposition, the sample deterioration takes place when the energy accumulation exceeds some critical value, which we call durability.

Table 1

Fatigue life of cold asphalt concrete

#	Applied binding agent (name of modifying agent)	Number of sample fatigue cycles at deflection amplitude, mm					
		0,50		0,35		0,23	
		dry	water saturated	dry	water saturated	dry	water saturated
1	Strongly thickening bitumen 130/200	8034	4558	21874	12567	61510	35611
2	Cutback modified bitumen (divinyl – styrene thermoelastolayer)	10782	6180	29078	16164	81707	47502
3	Cutback modified bitumen (synthetic styrene rubber)	11312	6086	32116	17828	80695	45883

Examination of experimental findings [actually rectilinear disposition of experimental points for logarithm of loading number N in all six series (Fig. 1)] suggests the following dependence

$$R = N\exp(\alpha M) \quad , \tag{1}$$

where α is a certain numerical parameter assignable by the behaviour of the material of interest.

While examining the experimental data there were also considered some other model dependencies of durability R on N and M, for example, such dependence as

$$R = (N + N_0)\cdot M^{\alpha} \quad . \tag{2}$$

with some parameters N_0, α. But the dependence (1) is the most adequate.

It is convenient to write it down in logarithmical form as

$$\ln R = \ln N + \alpha \cdot M \quad . \tag{3}$$

For each of the six series under consideration, we have three experimental points, for example (for dry state from the first sample, where N is a number of loadings times 10^{-3})

$$M_1 = 0.23,\ M_2 = 0.35 = 0.35,\ M_3 = 0.5,$$

$$\ln N_1 = \ln(80.7) = 4.39,\ \ln N_2 = \ln(32.1) = 3.468,\ \ln N_3 = \ln(11.3) = 2.42.$$

By the standard formulas of statistics [6], it is easy to construct a straight regression line by the data of such a type. As an example, we have a straight line

$$\ln N = -7.27M + 6.045 \quad . \tag{4}$$

It means that for the given sample, $\alpha = 7.27$ and its durability is $e^{6.045} = 421.8$ thousand standard units.

The resultant values of the asphalt concrete sample compositions limiting stress for all six series (the first three, dry state; the last three, water-saturated state) are given below:

$$R_{1C} = 421.8483208,\ R_{2C} = 432.4110710,\ R_{3C} = 329.6867601,$$

$$R_{1B} = 251.0496790,\ R_{2B} = 250.8649025,\ R_{2B} = 194.1880971.$$

The number of loadings – load amplitude diagrams of dependence or cold asphalt concrete based on a modified agent, constructed by formula (1) – is presented in fig. 2.

The experiments carried out allow for judging about limiting the stress of cold standard and modified asphalt concrete under the cyclic effect of traffic loadings, but the obtained results are not enough for determining the life cycle of repaired surface section.

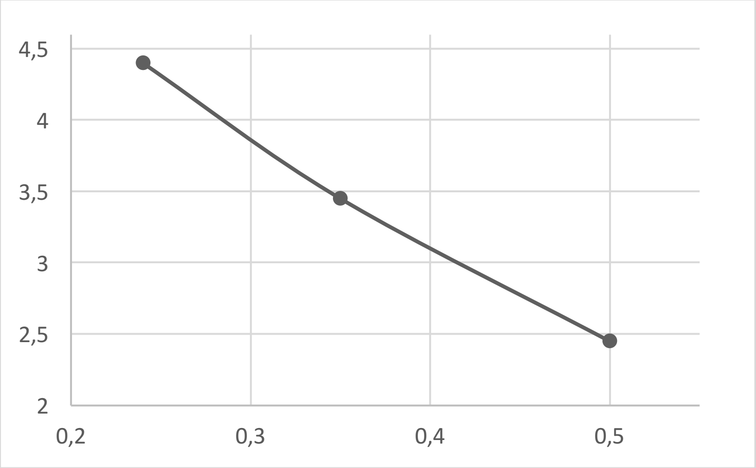

Fig. 1. Loadings number logarithm dependence (down to sample failure) on loading amplitude for cold asphalt concrete based on the modifying agent of synthetic styrene rubber in dry state (point values – experimental findings, diagram of straight line – theoretic dependence, constructed by the least-squares method)

Рис. 1. Логарифмическая зависимость количества нагружений (вплоть до разрушения образца) от амплитуды нагрузки для холодного асфальтобетона, полученного на модификаторе СКС в сухом состоянии, в сухом состоянии (точки на графике – экспериментальные данные, непрерывная кривая – теоретическая зависимость, построенная по методу наименьших квадратов)

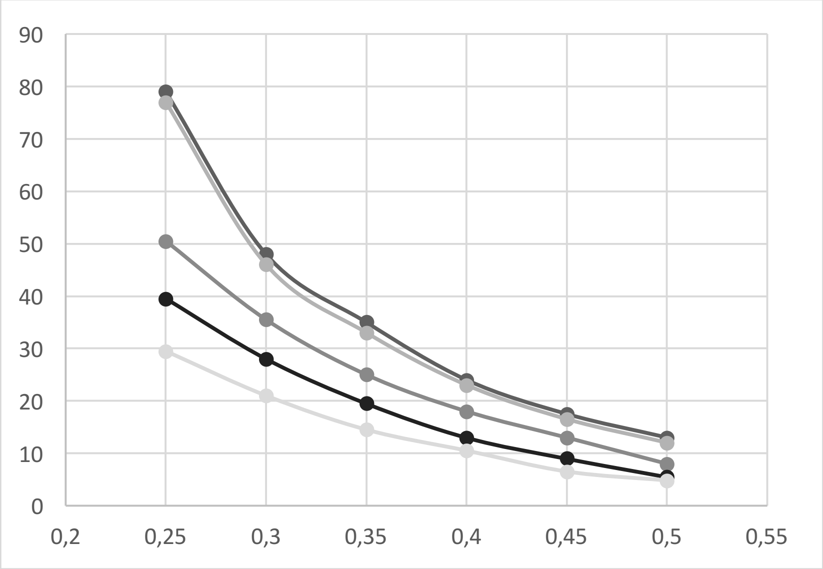

Fig. 2. Loading number dependence diagram (down to sample deterioration) on loading amplitude for three tested asphalt concrete compositions (top-down: the 1st diagram – (divinyl styrene elastolayer), dry state; 2nd diagram – (synthetic styrene rubber) dry state; 3rd diagram – standard liquid oil bitumen, dry state; 4th diagram – divinyl styrene thermoelastolayer, water-saturated state, 5th diagram – synthetic styrene rubber, water-saturated state; 6th diagram – standard liquid oil bitumen, water-saturated state). 4th and 5th diagrams coincide

Рис. 2. График зависимости числа нагружений (до износа образца) от амплитуды нагружения для трех исследованных составов асфальтобетона (сверху вниз: 1-й график – (ДСТ), сухое состояние; 2-й график – (СКС), сухое состояние; 3-й график – традиционный жидкий битум, сухое состояние; 4-й график – (ДСТ), водонасыщенное состояние; 5-й график - (СКС), водонасыщенное состояние; 6-й график – традиционный жидкий битум, водонасыщенное состояние). 4-й и 5-й графики совпадают

2. PREDICTION CALCULATION OF ASPHALT CONCRETE PAVEMENT SERVICE LIFE WITH ACCOUNT OF UNEVEN TRAFFIC LOAD APPLICATION ONTO THE LANE

Examine the situation of the fracture energy application with the consequential residual strain accumulation in the pavement material of repaired road surface in the following example.

Let the lane width be equal to L= 3m. Every wheel of an average (simulated) vehicle dint on the highway, the width of which takes equal to $2d$ = 0,22m. Let the distance between vehicle wheel axles (left and right) be equal to $2l = 1.7m$. We consider the vehicle travelling on the lane sticks to the lane central line. At the same time, the vehicle axle's deviation from the central line is possible. Take this deviation for variate and designate it by X. We place the possible values of this variate between spaces.

$$[-(L-l-d),(L-l-d)] \quad (5)$$

The situation $X+l+d<L$ means that a vehicle does not cross the right margin traffic lane markings and the same situation characterises the left margin of the mentioned lane. In our example, the interval has the extent of [-0.54, 0.54] m.

The loading of every surface section and sustaining the wheel load take place while the vehicle is travelling on it. Take one section of the repaired pavement and connect the real road situation with the laboratory experiments described at the beginning of the article. The observable section is considered geometrically equal to the rectangular laboratory sample of (0.04 x 0.16) m size. Locate a rectangle longitudinal axis parallel to the roadway axis, which is at l distance from the last one.

It is better to conduct the further discussion in simplified form, connecting the reference system with the centre of the rectangle under study. Deviation vehicle X-axis from road lane axis coincides with wheel deviation from the rectangular longitudinal axis.

At deviation X, which has a nonzero value, the wheel track cannot cover the repaired pavement rectangle completely. We consider the complete loading amplitude equal to $M = 0.15$ mm $= 1.5 \cdot 10^{-4}$ m.

The cases of partial loading can be a substitute for the complete ones, taking into account correction factors. While calculating the fracture energy, it is not necessary to take into consideration the situations in which $|X|>(d+b)$ (a wheel track does not touch the rectangle under test).

After such refining, it is possible to calculate the energy value that the repaired pavement section obtains during the twenty-four hour period. Comparing this daily value with the calculated residual (long-term) durability, we can give an assessment of the life duration of the repaired pavement section.

So we consider that $n=30000$ vehicles travel on the repaired section of the pavement for twenty-four hours.

Let us divide the space $[-(d+b),(d+b)]$ into small sections and estimate the number n_k from the traffic flow vehicles whose deviation X gets on one of such sections $[x_k, x_k+\Delta x_k]$. The number n_k can be determined by the given partition law of the variate X. As is known, the probability of a continuous variate hits into a small interval Δx_k approximately equal to the product of this variate density and the length of the interval under discussion:

$$P(X \in \Delta x_k) \approx f(x_k)\Delta x_k. \quad (6)$$

In its turn, the number of certain variate tests X (in a big series) makes X hit into given intervals approximately equal to

$$n_k = n \cdot P(X \in \Delta x_k). \quad (7)$$

Taking into account the above-mentioned exponential formula for fracture energy, the total energy obtained by the section during a twenty-four hour period can be estimated equal to

$$E=\sum_k n_k \exp(\alpha m(x_k)) = n \cdot \sum_k P(X \in \Delta x_k) \cdot \exp(\alpha m(x_k)) = n \cdot \sum_k \exp(\alpha m(x_k)) \cdot f(x_k) \cdot \Delta x_k \quad (8)$$

Passing from the sum to the integral, we have the formula

$$E = n \cdot \int_{-(d+b)}^{d+b} \exp(\alpha m(x)) \cdot f(x) dx \quad . \tag{9}$$

Now we should calculate this integral (exactly or approximately) and put all the parameter points and functions in it.

We made calculations for two distributions of variety *X*: normal and even. Let *X* initially be distributed by Gauss law with probability density

$$f(x) = f_{(a,\sigma)}(x) = \frac{1}{\sqrt{2\pi}\sigma} \cdot \exp\left(-\frac{(x-a)^2}{2\sigma^2} \right) \quad . \tag{10}$$

Let us assume that the mean value of such deviation is equal to zero and specify the dispersion proceeding from the known three-sigma rule assigned by ratio

$$3\sigma = L - l - d \quad , \tag{11}$$

where $\sigma = 0.18$ m.

We will make calculations for a rectangular fragment of the repaired pavement section located on “the most susceptible” place of the lane. It means that the integral (12) in its range is compared with the analogical integral in its interval $[-(d-b),(d-b)]$ of the “big” values of the integral function. On the mentioned interval, this function is equal to $\exp(\alpha M) \cdot f(x)$. Thus, the integral $\int_{-(d-b)}^{d-b} e^{\alpha M} \cdot f(x) dx$ which is the estimation for integral from (12), is equal to $e^{\alpha M} \cdot 2 \cdot F\left(\frac{d-b}{\sigma}\right)$, where *F* denotes Laplace's function. Its value is possible to find in the table (see as an example [8, p. 462]). With the values of parameters d, b, σ, we receive

$$F\left(\frac{d-b}{\sigma}\right) = F\left(\frac{0.11-0.02}{0.18}\right) = F(0.5) = 0.1915. \tag{12}$$

Take into consideration the value *M*=0.15 mm and the coefficient $\alpha = 7.27$ for one of cold asphalt concrete proportions examined above (underline that in formulas based on experiments the amplitude is measured in millimetres). Then the integral from (12) is compared with the value:

$$\exp(7.27 \cdot 0.15) \cdot 2 \cdot 0.1915 \approx 3 \cdot 2 \cdot 0.1915 \approx 1{,}15 \tag{13}$$

All the fracture energy described by formula 12 has the value of about 3400 reference units. Since the sample durability is 421,8 thousand of the same units, we formally receive only (approximately) two weeks period of repaired section operation.

In the case of variate X, even distribution in the interval [-0.54, 0.54] m, the complete loading of the control rectangle takes place while a wheel axis gets in the length interval $2(d-b) = 0.18$. So the probability of the loading can be calculated as $0.18/1.08 = 1/6 \approx 0.17$ (instead of $2 \cdot 0.1915 = 0.383$ in the case of normal distribution, examined before). So the control sample lifecycle increases approximately 2,0-2,5 times.

3. ACCOUNTING OF STRESS RELAXATION PROCESS IN ASPHALT CONCRETE

Pavement lifecycle prediction is not right a fortiori without accounting for the well-known asphalt concrete’s ability to its structure and strength properties recovery in extend of stress relaxation during “the rest”, e.g. the interval between the traffic load applications [8, 10, 12, 14 - 16]. Assume that the traffic load of the corresponding design durability of road base and single load does not lead to the formation of residual plastic deformation.

For example, enter the function of recovery intensity of asphalt concrete strength characteristics as

$$f(t) = \lambda \exp(-\lambda t),\ t \geq 0, \tag{14}$$

where λ is a certain numerical parameter (“rate” of rehabilitation).

It means that under a single load of the material with the subsequent interval of rest during t seconds the life duration damage is not $U_0 = e^{\alpha M}$, but a minor value

$$U_0^* = U_0 \cdot \left(1 - \int_0^t \lambda e^{-\lambda t} dt\right) = U_0 \cdot \left(1 - (1 - e^{-\lambda t})\right) = U_0 e^{-\lambda t}. \tag{15}$$

Specifically, at infinitely long rest ($t = \infty$), the damage from single pavement load (not having supercritical value by pavement deflection amplitude, which can be at specified overload), is compensated. In a real situation, to determine the intensity parameter of recovery, it is natural to discuss the period of partial recovery. Designate the section *T* by the term of “period of partial recovery”, for which $\exp(-\lambda T) = \frac{1}{2}$.

When this period is known, we can calculate the parameter [lambda] by the formula $\lambda = \frac{\ln 2}{T}$.

At the traffic volume of *n*=30 thousand vehicles for a twenty-four hour period, we sum not the energies U_k themselves but their variants U_k^*. Then for twenty-four hours, the total (with account of rest interval) energy, taken by the repaired pavement section, is equal not to nU_0, but to another value, that is

$$\sum_{k=1}^{n} U_k^* = \sum_{k=1}^{n} U_0 \exp(-\lambda t_k) = U_0 \cdot \sum_{k=1}^{n} \exp(-\lambda t_k) = (nU_0) \cdot \left(\frac{1}{n} \cdot \sum_{k=1}^{n} \exp(-\lambda t_k)\right), \tag{16}$$

where t_k is a time of “rest” of the pavement after *k* - vehicle travel.

The correction factor, discriminating the new value from the “old” value, is

$$\varepsilon = \left(\frac{1}{n} \cdot \sum_{k=1}^{n} \exp(-\lambda t_k)\right). \tag{17}$$

At a steady flow of vehicles (1 vehicle per time $\tau = t_k$) this factor is $\exp(-\lambda\tau)$. For example, at *t*=10 and the rate of recovery $\lambda = 0.7$ (corresponding to the interval of partial recovery *T*=1 sec) the correction factor is ≈ 0.001.

It is clear that the reduction factor 1000 is not real, even because the traffic flow is not strictly steady.

Let us account every time period t_k between two vehicle traffic in this flow to be an implementation of a variate τ. In this situation, formula 18 is a mean value of a function $Y = h(\tau) = \exp(-\lambda\tau)$ of variate τ.

Assume [tau] is distributed by exponential law with parameter $\mu > 0$. It means that density $g_\mu(t)$ of variety is described by the formula

$$g_\mu(t) = \begin{cases} 0, t \leq 0 \\ \mu \exp(-t\mu), t > 0, \end{cases} \tag{18}$$

Similar to (1), where μ is a mean flow, the density ($\mu = 0.1$ for averaged interval between vehicles is 10 sec).

By probability theory, the variate $Y = \exp(-\lambda\tau)$ a mean value or a mean of distribution is determined as an integral $\int_{-\infty}^{\infty} h(\xi) g_\mu(\xi) d\xi$

In our case

$$\varepsilon=\int_{-\infty}^{\infty} h(\xi)g_{\mu}(\xi)d\xi=\int_{0}^{\infty} e^{-\lambda\xi}\mu e^{-\mu\xi}d\xi=\mu\int_{0}^{\infty} e^{-(\lambda+\mu)\xi}d\xi=\frac{\mu}{\lambda+\mu}. \tag{19}$$

For example, at $\lambda=0.7, \mu=0.1$ the correction factor ε takes the value 1/8 = 0.125. Note that there is information about recovering of cold asphalt concrete strength performance for a fraction of a second (but not for one second). It means that the correction factor for this material has a smaller value (which increases the road pavement durability).

CONCLUSION

1) At the expense of traffic flow regulation along the strip of way, repaired surface service life increases 2,0-2,5 times in comparison with the variant of continuous loading.
2) A consideration of the process of asphalt-concrete relaxation between separate loadings allows for an increase in the predicted service life of material in road surface 10-50 times and in an ideal case up to 4 years.
3) A consideration of both factors leads to a two-week increase in the service life of cold modified asphalt concrete under continuous loading for the period from 4 years. It is an adequate assessment of the service life of a repaired surface of the road with a high traffic flow density when repair is implemented with the application of modified asphalt concrete with the presence of a qualitative drainage system.

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