Research Article

Fatigue resistance of modified cold reclaimed mixes with 100% content of recycled asphalt pavement (RAP)

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Abstract

This study is devoted to finding a solution to an important problem of increasing the accuracy of assessing the fatigue stability of composites based on recycled asphalt concrete. Another problem for solving was a selecting optimal and effective ways to improve their physical–mechanical properties during modification by polymers. For experimental work, a new indicator reflecting the strength of elastic structural bonds and the specific number of viscoplastic bonds was used as a criterion for fatigue stability of bituminous-cement composites. As shown by the results of the research, fatigue (cyclic) stability has an increasing trend with the growth of these parameters. As a result of processing data from experimental studies of the structural characteristics of composites, a comparative analysis of the effectiveness of modification of cold recycled mixes by styrene acrylate and epoxy resin was performed. It was established that the composites modified with styrene acrylates have a higher relaxation ability, which is reflected in the increase in the number of cycles to failure when testing for cyclic stability. It is also noted that with an increase in the content of epoxy resin in the composition of mixes, the increase in stiffness occurs much more strongly in comparison with an increase in their relaxation ability. At the same time, the efficiency of modification of cold recycled mixes with epoxy resins is significantly increased with the preliminary preparation of asphalt granulate (RAP), for example, during its plasticization with soy epoxidized oil. This work also allowed us to outline some areas of development of the methodological foundations for assessing the cyclic and fatigue stability of composites based on cold recycled mixes.

Keywords Fatigue resistance · Recycled asphalt pavement (RAP) · Modified cold reclaimed mixes · Styrene-acrylic water dispersion · Water dispersion of epoxy resin · Epoxidized soybean oil

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1 Introduction

In the practice of road construction, asphalt-cement composites of various constitution and preparation technologies are widely used. Today, more and more widely, for their preparation, reclaimed asphalt concrete from spent road structures is used, and the preparation takes place at ambient temperature without additional heating. This is clearly of great interest from the environmental safety of road repair works point of view and leads to a decrease in the costs of their implementation.

Concrete of this kind, based on organo-hydraulic binders (OHBC)—is an artificial building material based on reclaimed asphalt concrete at ambient temperature, and combines the properties of thermodynamically incompatible organic (for example, bitumen emulsion) and hydraulic (for example, cement) binders in its structure.

New materials require the study of their behavior in a temperature–time field to develop objective technical requirements for their physical and mechanical characteristics, which would provide the required values of strength and reliability. The issues of obtaining, optimization of the composition and structure of OHBC are dealt with in many countries in the world. The main technological parameters of concrete production have been established, studies of the effect of composition on strength have been carried out, durability in operation has been researched. The importance of cement in the processes of structure formation is noted. It was found that at low cement contents, or its absence, the durability of the material in road pavements is extremely low. However, the behavior of these materials has not been sufficiently studied. This is especially true for cyclic (fatigue) stability.

By introducing cement into the structure of concrete, resistance to plastic deformation at high temperatures increases. However, brittleness increases, and fatigue resistance may decrease. Currently, there is no reliable solution to the problem of standardization and assessment of fatigue and cyclic stability of road monolithic materials (asphalt concrete and other composite materials, including OHBC). The reason for this situation is the lack of correlation between the calculated characteristics of materials and the process of development of the corresponding deformations in real road structures. A complex experiment is required, the result of which depends on numerous factors that determine the impact of transport, climate, technological features of construction (repair), etc. The results of calculating the limiting number of cycles before destruction can often differ by tens or hundreds of times. In most cases, long-term tests

are required, which makes it difficult to perform operational quality control, for example, in a production environment, and expensive equipment is required. Thus, it becomes difficult to unify the criterion and its use when standardizing indicators of the properties of road composites, incl. OHBC, in technical specifications. It is not always possible to use the test results for practical purposes of designing and calculating road pavements, but the fatigue resistance criterion is the main one in the system for assessing the reliability of the work of materials in road structures during the designed service life and requires constant improvement.

Multiple repeated loads lead to the appearance of specific deformations and destruction of road pavements materials. Those are cracks of narrow opening in the longitudinal and transverse directions, networks of cracks, pot-holes, and spalling (along with the weather and climatic factors).

In theory and practice, they operate with the concepts: long-term strength, cyclic stability, fatigue resistance per se. These concepts differ not only in terminology but also in the essence of the processes of deformation and destruction of materials.

Long-term strength is interpreted as the time until the material breaks down under a constant load. This criterion is used in assessing temperature crack resistance and other strength criteria. It almost unambiguously depends on the ratio of the strength of the material to the effective stress. The higher the ratio, the higher the long-term strength.

Fatigue is associated with the accumulation of infrastructural damage and the avalanche-like destruction of the material in a fragile pattern. Classically, one can speak of fatigue failure only for elastic materials or its work in the elastic stage. For road composites, such conditions are likely at low temperatures and high deformation rates.

Fracture of materials during fatigue processes occurs according to the theory of Griffiths, according to which the shape, number, and size of structural defects are decisive.

Fatigue failure in its pure form is typical for materials of crystallization structure (cement concrete, metals), and for road composites and their varieties (including OHBC) it is not always decisive. The most suitable term for assessing their reliability and durability under the influence of heavy, repetitive loads should be considered the concept of cyclic durability, which is understood as durability under the action of repeated loads in a wide temperature–time field when the road composite exhibits the entire complex of rheological properties.

In world practice, there are a large number of types of tests with the subsequent establishment of the characteristics of the cyclic stability of OHBC (at a constant value of stresses or deformation), for example: two-point bending; three-point bending; four-point bending; torsional

bending; direct testing with axial load application (compression, tension); splitting test (indirect tensile test), etc.

All these test methods have their advantages and disadvantages in terms of assessing the ability of composites to resist cyclic stress in road structures.

In general, experimental methods for assessing fatigue or cyclic resistance can be divided into three groups:

- Methods, based on measuring the number of cycles until material failure under constant load;
- Methods based on measuring the number of cycles before material failure under constant deformation;
- Sophisticated combined methods evaluating multiple destruction mechanisms.

Most often, the criterion for the cyclic durability of a material is the number of cycles of exposure to constant load before the destruction of a material sample. In this case, the load application scheme and the type of samples are significantly different.

The scheme is useful when evaluating materials operating in the elastic stage when it is possible to speak about classical fatigue. When the material is operating in the viscoelastic stage, the durability of the composite usually does not exceed 100–200 cycles and cannot serve as an objective criterion for the work in the pavement. This testing scheme almost always gives superiority to materials with higher strength (under constant load).

The second loading scheme is an estimate of the number of cycles to failure at constant deformation. This kind of approach is closer to the real work of the material in the road structure. However, the devices used for assessing the durability are aimed at the accumulation of permanent residual deformation during the viscoelastic work of the material.

More complex schemes for assessing the cyclic durability of materials are also used.

That being said, as of now, in Europe, the study of fatigue of organic mineral composites at low temperatures is widely used, which consists in applying cyclic loads of a certain magnitude to a prestressed sample (prestressing corresponds to the voltage value from exposure to low temperatures of -5°C and/or -15°C) [1].

Until now, a large amount of research on the fatigue and cyclic stability of composites based on cold reclaimed mixes has been carried out; similar studies are being carried out today [2–10] but the results require significant post-processing and are not always adequately interpreted.

In this regard, the question of assessing the fatigue resistance of composites prepared based on RAP by cold method is still open. This direction requires development and improvement. This study attempted to evaluate the

fatigue properties of such materials based on the features of their structural changes (replacing elastic bonds with viscous ones and vice versa) when varying the temperature, load size, and loading modes.

Among other things, there is currently no clear understanding of the effect of various modifiers on the properties of cold recycled mixes. In this paper, considering the proposed methodology for assessing fatigue resistance, primary studies of the effect of epoxy resin and styrene acrylate are presented.

This type of research allowed us not only to suggest a direction for improving the methodology for evaluating the properties of such composites, but also to assess the prospects for improving their component compositions.

2 Theoretical background and research methodology

If we designate the fraction of elastic bonds responsible for the state of the composite by the n_r scalar, and viscoplastic by the n_v scalar, then the following condition should be valid:

$$n_r + n_v = 1. \quad (1)$$

Since the deformation of viscoplastic bonds results in the complete dissipation of the energy applied, it can theoretically be assumed that the n_r and n_v ratio is determined by the ratio of the dissipative energy to the applied energy. In this case, the amount of n_r and n_v depends, first of all, on the relaxation properties of asphalt concrete and the duration of the load, and the number of elastic bonds involved in the deformation process can be determined from the following relationship [11–13]:

$$n_r = \frac{E_t}{E_c} = \left(\frac{R_t}{R_c} \right)^{\frac{1}{m}}, \quad (2)$$

where E_t and R_t are the relaxation modulus and strength under specific conditions of load and temperature, MPa; E_c and R_c are maximum values of the relaxation modulus and strength in the entire range of temperature and rate (time) of the load, MPa; m is the coefficient that depends on the properties (type) of the composite.

The value of the m coefficient for OHBC is in the 0.80–0.95 range and, first of all, is determined by its modulus of elasticity (stiffness). The higher the modulus of elasticity (stiffness), the higher the coefficient, which for comparative calculations can be taken equal to 0.9.

When the composites work in the elastic stage ($n_r \rightarrow 1$) their strength will be equal to the maximum in the entire temperature range (load time) and correspond to R_c [5]. Since the number of cycles to failure depends on the ratio

of effective stresses to strength, the higher, the higher R_c is, the greater will be the cyclic stability of asphalt concrete in the elastic stage of operation, and the greater the level of damage in the material can be achieved at the moment of failure. Therefore, the value of R_c can serve as a criterion for the cyclic stability at constant stress in the elastic stage of work [11–14].

If the loading mode corresponds to the operation of asphalt concrete in the viscous stage ($n_r \rightarrow 0$), then asphalt concrete has higher cyclic durability, which can dissipate a greater amount of energy before dissolution W_d , which correlates with the value of the maximum deformation ε_m realized in a wide range of temperature and load duration. The work of asphalt concrete in the viscous stage is observed during relaxation processes, creep, etc.

Since an increase in R_c raises the likelihood of an increase in durability in the elastic stage of work, and an increase in ε_m in a viscous stage, then in the general case ($0 < n_r < 1$), the maximum cyclic durability will be possessed by materials having the maximum value of $R_c \varepsilon_m$ product [11].

A somewhat different situation is observed when the composite is periodically subjected to a constant level of deformation (deformation fatigue). In this case, the dependence connecting the limiting number of cycles to failure N_m from n_r will have the form of an extreme curve. This is due to the fact that, under the action of constant deformation, stresses increase with the amplification of n_r , since the E_t relaxation modulus increases, which depends on the maximum E_c elastic modulus (uniquely determined from the value of R_c [12]) and the fraction of elastic bonds ($E_t = n_r \cdot E_c$). Therefore, the higher n_r , the fewer cycles to failure the elastic bonds withstand. And, conversely, viscoplastic bonds with an increase in n_r

taking on a smaller proportion of the total deformation and their durability increases. As a result, the maximum durability of the material will be observed at a certain optimal ratio of elastic and viscoplastic bonds.

Taking the above into account, it is unambiguous that the assessment of the cyclic durability of material must be made only based on a comprehensive account of its rheological properties and the features of work in a road structure, and when studying the situation only from a materials science point of view, serious errors can be made in the forecasts of cyclic durability.

The work of the material in the structure and its cyclic durability, in this case, are determined by the amount of deformation during the design period, rheological (the number of elastic bonds involved in the deformation process) properties, and constants of strength properties (maximum structural strength and deformation) of the material, as well as the parameters and conditions of the transport load.

When testing OHBC samples with a constant load ($\sigma = \text{const}$), the cyclic stability decreases with a decrease in the loading rate and an increase in temperature (decrease in n_r) according to the pattern shown in Fig. 1a.

When testing an OHBC specimen with constant deformation ($\varepsilon = \text{const}$) an extreme dependence of the cyclic stability on temperature and the n_r parameter can be observed, as shown in Fig. 1b.

This is due to the fact that the stress level depends on the amount of deformation and the modulus of elasticity, which increases with the amplification of n_r . At the same time, the strength decreases with a decrease in the value of the proportion of elastic bonds, thus leading to the appearance of an extremum.

Fig. 1 Cyclic durability under constant load and deformation

Both the first and the second schemes do not reflect the external picture of fatigue fracture of the material since the fracture occurs not only due to elastic bonds but also due to dislocation (separation) of structural components.

As noted above, as a criterion for the fatigue resistance of mixes of experimental compositions under working conditions in the road pavements, the value $R_c \cdot (1 - n_r)$ can be assumed. And since the deformation resistance of complex composite materials is determined not only by the strength of the secondary structure (coagulation–crystallization structure) but also by the viscoplastic component, the higher the temperature and the amount of organic binder, the higher the fatigue resistance can be. Such a position concerning this criterion also requires experimental verification in relation to OHBC.

To assess the fatigue resistance of modified cold reclaimed mixes based on asphalt granulates and the effectiveness of the considered modification methods in terms of changes in structural features in the entire temperature–time range, the following mechanical parameters of the composites were determined:

- Indirect tensile strength during fracture at a temperature of 5 °C and a strain rate of 10 mm/min, ITS_{10}^5 , MPa;
- Indirect tensile strength during fracture at a temperature of 5 °C and a strain rate of 60 mm/min, ITS_{60}^5 , MPa;
- Marshall flow at a temperature of 60 °C and a strain rate of 50 mm/min, MF_{50}^{60} , kN;
- Marshall stability at a temperature of 60 °C and a strain rate of 50 mm/min, MS_{50}^{60} , kN;
- Alteration in the flexural strength of a beam on an elastic foundation upon cyclic application of a constant deformation of 0.2 mm at a rate of 10 mm/min at a temperature of 5 °C with the determination of the number of cycles to failure, N_m .

The maximum strength of modified concretes based on organo-hydraulic binders in the entire temperature range (load time) was calculated based on the results of a split test according to the following relationship [15, 16]:

$$R_c = \frac{\bar{R} \cdot \lg \frac{10}{60}}{\lg \frac{10}{60} - \lg \frac{ITS_{10}^5}{ITS_{60}^5}}, \quad (3)$$

where 10 and 60 are the strain rates in two tests, mm/min.

$$\bar{R} = \frac{ITS_{10}^5 + ITS_{60}^5}{2}. \quad (4)$$

The number of elastic bonds involved in the deformation process at a design temperature of 5 °C and a deformation rate of 10 mm/min was determined by the following formula:

$$n_r = \left(\frac{ITS_{10}^5}{R_c} \right)^{\frac{1}{0.9}}. \quad (5)$$

Taking the noted provisions and indicators into account, an experimental check was carried out.

The establishment of the features of the change in the bending strength of a beam on an elastic foundation upon cyclic application of a constant deformation of 0.2 mm at a rate of 10 mm/min at a temperature of 5 °C with the determination of the number of cycles to failure (N_m) was carried out in relation to the test scheme shown in Fig. 2.

To simulate the elastic reaction of the base, the beam during the test was placed on a rubber plate 60 mm thick with a modulus $\left(\frac{\Delta h}{S, \text{mm}^2} \right)$ of 20% deformation at a temperature of 5 °C equal to 190. The free movement of the beam ends was limited by special shape.

3 Initial materials and experimental compositions accepted for research

Asphalt granulate from milling road asphalt pavement with a grain composition was used for research, according to Table 1. The content of bitumen in asphalt granulate is 4.63% of the mass of the mineral part.

At present, a rather great interest of researches of cold reclaimed mixes is riveted to modifiers based on epoxy resins [17–26] and styrene-acrylates [27–32].

In this regard, as modifiers adopted for research, the following have been used:

- Water dispersion of epoxy resin + hardener (WERD + H);
- Styrene-acrylic water dispersion (WSAD).

As a result of the earlier work, it was found [33], that for practical use the most acceptable aqueous dispersion of NPEL 127 resin (NANYA, Taiwan) with a ratio of “resin/water” = 3:1 with an emulsifier content of 2% of wt. of high molecular weight block copolymer butyldiglycol from the mass of resin, which was used for research. An aqueous solution of an amine adduct marketed under the trademark Telalit 180 (SPOLCHEMIE, Czech Republic), additionally diluted with water in a 1:1 ratio, was used as a hardener. The characteristics of the hardener are presented in Table 2.

For a comparative analysis of the effect of modifiers on the properties of BCCRM, we also used a ready-made styrene-acrylic aqueous dispersion WANOL (rub Berlin GmbH, Germany) with the properties presented in Table 3.

Epoxidized soybean oil (ESBO) (Table 4) produced by INTERFAT (Spain) was used as a regenerator of asphalt

Fig. 2 Beam samples testing scheme **Table 1** Grain composition of asphalt granulate

Full passage through the sieve, mm, as %											
19	16	13.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
100	98.0	94.7	81.6	48.9	26.9	14.2	8.4	4.4	3.4	1.9	

Table 2 Telalit 180 hardener specifications

Viscosity (23 °C, Pa·s)	Amine number (mg KOH/g)	Hydrogen adequation (g/mol)
0.75–1.1	130–150	243

Table 3 Characteristics of WANYL styrene-acrylic dispersion

Glass transition temperature (T_g), °C	Dry residue, %	pH	Viscosity, cP
–6	50	7.0	425

Table 4 Specifications of soybean epoxidized oil

Indicator name	Measurement unit	Indicator value
Acid value	mg KOH/g	< 1
Viscosity	cPoise (20 °C)	350–600
Color	Gardner	< 2
Refractive index	(20 °C)	1.472–1.478
Epoxide value	%	> 6.4
Iodine value	g I ₂ /100 g	< 3
Density	g/cm ³ (20 °C)	0.99–1.01

granulate. Today, more and more attention is paid to this type of bio-oil, which, under certain conditions, exhibits the properties of not only a plasticizer (regenerator) but also an effective modifying agent, incl. for cold mixes based on bituminous binders [34–36].

The addition of bitumen emulsion (including the case with water dispersions) was carried out after the preliminary mixing of asphalt granulate with cement and water. Aqueous dispersions (including epoxy resin together with

an aqueous solution of a hardener) were manually mixed with a bitumen emulsion before being fed into the mixer until a uniform consistency was obtained. The addition of epoxidized soybean oil to the asphalt granulate was carried out 3 days before the preparation of the samples, mixing was carried out until visual homogenization. The RAP processed in this way was stored at room temperature.

The final matrix of BCCRM formulations accepted for research is presented in Table 5.

The production of cylinder samples was carried out according to the Marshall method with 75 impacts on each

side of the sample, and sample beams with dimensions of $40 \times 40 \times 160$ mm—by static pressing for 3 min in special molds under a pressure of 10 MPa after vibration for 3 min with an applied load of 0.03 MPa. After that, the samples, without removal from the molds, were stored at room temperature for 1 day, after their removal from the molds, they were placed in an oven with a temperature of 60°C for 3 days. The samples prepared in this way were stored at room temperature for another 3 days before testing.

4 Test results

As mentioned above, the maximum durability of the material will be observed at a certain optimal ratio of elastic and viscoplastic bonds, i.e. with the optimal ratio of the value of the maximum structural strength R_c (formula 3) and the proportion of elastic bonds n_r (formula 5).

As the calculated boundary conditions, the deformation rate of the samples is 10 mm/min and the temperature is 5°C , which corresponds to the conditions for the maximum accumulation of damage in the structure of the composite (operating under compression tension, not elastic deflection) when it operates under the wheel of the design vehicle at low speed of movement.

Table 6 shows the results of testing concretes of experimental compositions based on organo-hydraulic binders.

The calculated values of the indicators, which characterizing the fatigue resistance and structural strength of composites prepared from experimental mixes are presented in Table 7.

The results of the studies carried out on the above scheme of the properties of composites based on cold reclaimed mixes unambiguously indicate the efficiency of using epoxy and styrene-acrylic aqueous dispersions to increase their cyclic durability. So, the number of cycles

Table 5 Component compositions of experimental mixes

Mix no.	Component composition of the mix, %						
	RAP	Over 100% RAP					
		Cement (CEM)	Bituminous emulsion (BE)	Water epoxy resin dispersion + hardener (WERD + H)	Water styrene-acrylic dispersion (WSAD)	Epoxidized soy-bean oil (ESBO)	Water (W)
1	100	2.5	5.0	–	–	–	5.0
2	100	2.5	3.5	1.5	–	–	4.9
3	100	2.5	1.5	3.5	–	–	4.7
4	100	2.5	3.5	–	1.5	–	4.9
5	100	2.5	1.5	–	3.5	–	4.7
6	100	–	2.5	2.5	–	0.5	–

Table 6 Test results of OHBC experimental composites

Mix no.	ITS ₁₀ ⁵ , MPa	ITS ₆₀ ⁵ , MPa	MS ₅₀ ⁶⁰ , kN	MF ₅₀ ⁶⁰ , mm	N_m	CV (N_m), %	SD (N_m)
1	1.18	1.59	11.23	4.02	76	8.63	6.56
2	1.41	2.01	18.44	3.98	88	8.58	7.55
3	2.01	3.32	26.14	3.72	225	6.55	14.73
4	1.10	1.74	16.17	4.44	133	7.25	9.64
5	1.17	2.24	20.32	5.69	355	5.17	18.36
6	0.56	1.17	6.43	6.84	572	6.22	35.55

CV coefficient of variation; SD standard deviation

Table 7 Calculated properties of the composites

Indicator name	Indicator value for mix No					
	1	2	3	4	5	6
R_c , MPa	1.66	2.13	3.70	1.91	2.67	1.47
n_r	0.69	0.63	0.51	0.55	0.40	0.35
$R_c \cdot (1 - n_r)$, MPa	0.52	0.78	1.81	0.87	1.60	0.96
MQ_{50}^{60*} , kN·mm	22.57	36.70	48.62	35.90	57.81	21.99

*Marshall quotient- $MQ_{50}^{60} = MS_{50}^{60} \cdot MF_{50}^{60} \cdot 0,5$

to destruction (Fig. 3) when using epoxy dispersion in the amount of 30% of the total mass of the bitumen emulsion modified in this way increases by 15.8% in comparison with the composition based on a pure binder, and in the amount of 70%—by three times, when using styrene-acrylic dispersion, by 75% or 4.7 times respectively.

At the same time, the standard index of the composite fracture strength at a temperature of +5 °C and a deformation rate of 10 mm/min increases for the above concentrations of epoxy dispersion by 19.5% and 70%, respectively, and for styrene-acrylic dispersion it practically does not change; at a temperature of +5 °C and a deformation rate of 60 mm/min, it increases for the above concentrations of epoxy dispersion by 26.4% and 108.8%, respectively; styrene-acrylic dispersion—by 9.4% and 40.9%. The maximum structural strength R_c of composites prepared with the use of binders modified with epoxy resin also increases more significantly. This indicator unambiguously determines the ability of the material to resist the accumulation of fatigue directly in the structure. For the accepted concentrations, the R_c growth is 28.3% and 122.9%, and when modified with styrene-acrylic dispersion—15.1% and 60.8%.

However, with all the advantages in terms of increasing strength indicators, as shown the performed cyclic durability tests, modification with styrene-acrylic dispersion looks more promising. This is because composites, modified with copolymers of styrene with acrylates, exhibit better relaxation ability, which is expressed in a decrease in the proportion of elastic bonds (n_r) involved in the deformation process. This unambiguously depends both on the nature and properties of the modifier and on the features of the intercontact

interaction between asphalt granulate particles in the structure of the modified composite. In any case, for all batches of mixes, one can note an increase in the cyclic durability index N_m , which depends on the growth of the conditional proportion of the structural strength of the composite, provided by viscoplastic bonds— $R_c \cdot (1 - n_r)$. Figure 4 shows only the features of the material behavior (the growth of the characteristic N_m from the parameter $R_c \cdot (1 - n_r)$), and not the regression dependencies connecting them.

Of particular interest are the results obtained for the composition of mix No.6, in which there was no cement binder, while preliminary plasticization of RAP particles was carried out. The absence of cement is due to its effectiveness in the presence of epoxidized soybean oil in connection with which an attempt was made to structure the composite due to epoxy resin, which, in principle, to one degree or another was achieved (Figs. 3, 4). For a composite based on this kind of modified cold reclaimed mix, the cyclic durability index increased significantly in relation to the accepted test scheme ($N_m = 572$). At the same time, in comparison with the unmodified composition No. 1, there was a non-critical drop in the maximum structural strength indicator R_c by 11.5%, the value of tensile strength during splitting along the generatrix (ITS), by 52.5% and 26.4%, respectively, at a deformation rate of 10 and 60 mm/min. In connection with the results obtained, it can be concluded that when modifying cold reclaimed mixes with epoxy resin through its aqueous dispersion, it is necessary, to achieve greater efficiency, for the preliminary preparation of asphalt granulate for improved

Fig. 3 Test results of composites based on cold reclaimed mixes

Fig. 4 Features of changes in the properties of modified composites, which determine their cyclic durability

homogeneity during mixing, increased adhesion with the surface of its polygranular particles and provided of plasticization of old bitumen to be performed.

In order to clarify the features of deformation of composites based on modified cold reclaimed mixes in the entire range of temperatures and loading rates, incl. clarification of the changes in their structural features in the zone where viscoplastic properties are largely manifested, stability studies were carried out according to the Marshall methodology at a temperature of 60 °C. The test results are shown in Fig. 5 and Tables 1, 2.

5 Discussion of the main research results

As it can be seen from the data presented in Fig. 5 and Tables 1, 2, the modification of composites with epoxy resin contributes to a sharper increase in their rigidity (MS growth by 1.64 and 2.33 times, depending on concentration, and a slight decrease in MF—by 1.01 and 1.08 times), which, in principle, absolutely agrees with the data obtained in the cyclic stability test. Due to this kind of modification, an additionally branched crystal lattice is formed in the structure, along with that formed by a mineral binder (cement). However, taking the impossibility of ensuring ideal homogenization due to relatively

Fig. 5 Results of an investigation of high-temperature properties of modified composites

short mixing time into account, as well as the peculiarities of the properties of epoxy resin in terms of adhesion to organic surfaces, incl. to those covered with dust, water, oils, etc., its activity decreases in the composition of cold reclaimed mixes based on asphalt granulates. We can say that to some extent the crystal lattice formed by the epoxy resin works independently, and that formed by the mineral binder works independently. At the same time, the ability of epoxy resin to involve polygranular particles of asphalt granulate in the general work is not high, and the number of weak contacts is quite large. This leads to a decrease in the relaxation ability of the modified composites, along with an increase in structural strength. To a certain extent, the effect of epoxy resin is similar to the effect of cement on the properties of concrete based on organo-hydraulic binders, when only a certain part of the cement interacts through bitumen films with aggregate particles, and at a certain concentration of mineral binder, the properties of asphalt granulate practically do not affect the properties of concrete. The properties of the composite determine the properties of the crystal lattice created by the mineral binder. Therefore, the modification of cold reclaimed mixes with epoxy resins should be approached with great caution, since an expensive procedure for increasing the design characteristics of the composites is sufficient, which may not give the desired technical and economic effect. In the future, it would be necessary to consider in more detail the features of the formation of the microstructure of such modified mixtures, depending on the conditions of homogenization of their components. The results of recent research by a number of scientists indicate that there are serious prospects for improving the physical and mechanical properties of composites taking into account a directional regulation of their preparation modes [37, 38].

Composites prepared on cold reclaimed mixes modified with styrene-acryl behave quite differently at high temperatures. With a slightly lower level of growth of Marshall stability (by 1.44 and 1.81 times) the Marshall flow, on the contrary, increases (by 1.1 and 1.42 times). In this regard, the work of destruction, assessed through the MQ index, also increases. In comparison with the modification with

epoxy resin at the maximum concentration adopted for research, this indicator increases by 19%. As noted above, the number of cycles to failure in the cyclic resistance test also increases. This suggests that the structure of the composite modified with an aqueous styrene-acrylic dispersion is more homogeneous in comparison with the modified epoxy resin, the polymer interacts more efficiently with the components of the cold reclaimed mix, polygranular particles of asphalt granulate are much better involved in joint work, the total force of intercontact interactions higher and is provided due to more significant involvement of viscoplastic bonds in the deformation process (the proportion of elastic bonds n_r is 0.40 at the maximum concentration adopted for research). Thereby, modified composites of this kind have a higher relaxation ability, which is reflected in an increase in the number of cycles to failure in the test for cyclic stability.

At the same time, as stated above, regeneration of the surface of asphalt granulate particles with epoxidized soybean oil made it possible to significantly increase the cyclic stability of composites modified with epoxy resin. Taking the absence of a mineral binder and plasticization of old bitumen into account, the indicators of high-temperature properties dropped in comparison with the unmodified composition No. 1. Thus, the Marshall stability index decreased by 1.75 times, and the Marshall flow increased by 1.7 times. In this case, the work of destruction, estimated through the MQ index, remained almost unchanged. With a slight decrease of 13% in the maximum structural strength, the cyclic stability increased by the number of cycles to failure by 7.53 times. As part of the experiment, in the summer of 2019, an experimental section of the street was arranged (Fig. 6), on which the top layer of the coating was laid from a cold reclaimed mix on bitumen emulsion and cement, 4 cm thick (1st lane) and from a cold, modified by the epoxy resin, reclaimed mix based on asphalt granulate treated with epoxidized soybean oil, 4 cm thick (2nd lane). The first 2 months of operation at high summer temperatures showed high reliability of the modified composite. The traffic was opened the next day, due to which there are some dents from

Fig. 6 The layout of the experimental plots, arranged on modified reclaimed cold mixes: 1 – BE + CEM; 2 – BE, WDER + H, ESBO

individual wheels on the road surface in the courtyard entrance, which relates to insufficient strength gain. Nevertheless, the coating retained its texture hereafter, no excessive increase in density was noted on the reel strips. The monitoring continues.

Thus, the studies carried out show that through various modification methods, high indicators of the cyclic durability and structural strength of composites prepared on the bases of cold reclaimed mixes are achievable, which can be used and in the upper layers of road surfaces. However, currently, there is no highly specialized methodology for assessing their overall durability and reliability.

The work performed made it possible to outline some directions of development of the methodological foundations for assessing the cyclic and fatigue resistance of composites. So, the research results presented in Fig. 4 indicate an unambiguous relationship between the criterion of $R_c \cdot (1 - n_r)$ relaxation ability and the number of cycles to failure. At the same time, this trend is unique only for materials that are homogeneous in type and properties (the curves in Fig. 4 have different slopes to the abscissa axis). And the use of a constant value of the m coefficient in formula 2, even for comparative tests, affects the final calculated value of the indicators of cyclic stability too strongly. This situation requires additional research, which would make it possible to note the effect of creep, temperatures, and strain rates more reliably. For applied purposes, simple methodological principles are needed for the evaluation of the relaxation moduli of composites for various actual conditions of their operation in a road structure, which will be devoted to furthering research.

6 Conclusions

Based on the generalization of theoretical and experimental researches the issues of fatigue life of materials that are quite new in the practice of road construction—composites based on regenerated asphalt concrete from used road pavements obtained by cold method, are studied. A new indicator reflecting the strength of elastic structural bonds and the specific number of viscoplastic bonds was used as a criterion of fatigue stability for experimental work.

It has been found that in general, the level of fatigue (cyclic) stability increases both with increasing strength and the amount of secondary structure (content of cement, epoxy resin, polymers, etc.), and with an increase in the amount of organic binder (bituminous emulsion) and an increase in temperature. However, this leads to certain contradictions during mix design.

Experimental studies were performed based on mixes containing asphalt granulate, bitumen emulsion and

modifiers: cement, epoxy and styrene-acrylic dispersion, and epoxidized soybean oil.

Studies have shown that various modification methods can achieve sufficiently high indicators of cyclic durability and structural strength of composites prepared based on cold regenerated mixes, which can be used even in the upper layers of road pavements. However, now there is no narrowly specialized methodology for assessing their overall durability and reliability. Therefore, when choosing the most effective materials and compositions, it is necessary to additionally consider the indicators of resistance to plastic deformations at high temperatures (which was additionally carried out in the framework of this study).

Based on the test results, it can be clearly concluded that the modification of cold regenerated mixes with epoxy resin provides a significant increase in the design-level characteristics of composites. At the same time, a simple increase in content does not solve the problem of increasing cyclic (fatigue) stability cardinally. This is due to the fact that the increase in the stiffness of the composite (maximum structural strength R_c) occurs much more strongly in comparison with the increase in its relaxation ability (the proportion of viscoplastic bonds $1 - n_r$), which does not allow us to conclude that it is advisable to increase the concentration of epoxy resin during modification, both from a technical and economic point of view.

The efficiency of modification of cold regenerated mixes with epoxy resins is significantly increased during the preliminary preparation of asphalt granulate (RAP), for example, by plasticization of the surface of poly-grained particles, which covered with old bitumen. A more promising method for modifying such cold mixes is the use of water-based styrene-acrylic dispersions, the component composition of which can be directionally adjusted to optimize the elastic and viscoplastic properties of modified composites.

A promising direction for further research will be to obtain adequate reliable dependences that link the parameters of fatigue (cyclic) stability of bitumen-cement composites with the characteristics of their structural strength and deformability, which are described in this paper.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest

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