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FATIGUE RESISTANCE OF ASPHALT CONCRETE PAVEMENTS. PECULIARITY AND ASSESSMENTS OF POTENTIALS

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Abstract. This article presents the results of research of processes of deformation and destruction of asphalt concrete pavements under cyclic loads. As the ground for such approach to estimation of the asphalt concrete properties served the proof that regardless of the composition and structure of asphalt concrete with an equal amount of elastic (visco-plastic) bonds possess the same relaxation ability. This situation is a significant feature of the behaviour of asphalt concrete, which opens the way for the development of certain approaches to the analysis of their properties, evaluation of reliability and durability. The promising methodology for the comparative assessment of fatigue and cyclic durability of asphalt concrete by exploring the complex set of elastic and viscoplastic bonds in their structure depending on the temperature, magnitude, and modes of action of the loads is proposed in the presented work. In the future, the establishment of patterns of behaviour of asphalt concretes with the same set of elastic bonds is allows to optimize compositions based on the principles of temperature-structural analogythat is relevant in studying fatigue and cyclic durability as well as low-temperature crack resistance and shear stability.

Keywords: asphalt concrete, cyclic life, elastic bonds, energy of rupture, fatigue, strain, stress, toughness, viscoelasticity.

1. Introduction

Fatigue life of asphalt concrete is one of the most important criteria, ensuring reliable and durable work of the road structures, particularly subjected to repeated loads under a wide temperature-time range. When choosing the type of asphalt concretes for road pavements it is decisive to have a methodology for comparative evaluation of their fatigue properties.

Material fatigue is the accumulation of damageability due to the impact of variable (cyclic) loadings, resulting in its destruction over a specified period.

In world practice there are many types of tests with subsequent definitions of the fatigue properties under constant value of stress or deformation (Kennedy 1977; Maggiore *et al.* 2014; Pell, Cooper 1975; Picado-Santos *et al.* 2009; Pronk 2009; Raithby, Sterling 1972; Van Dijk 1975), for example:

- 2-point bending;
- 3-point bending;
- 4-point bending;
- torsional bending;
- direct test with axial loading (tension/compression, tension);
- split test (indirect tensile test).

All of these test methods have both advantages and disadvantages from assessing the asphalt concrete resist to cyclic stress as part of road constructions (Di Benedetto *et al.* 2004; Li *et al.* 2015; Molenaar 2007). There are numerous methodologies of asphalt concrete fatigue evaluation (Cao *et al.* 2016; Carpenter, Jansen 1997; Dondi *et al.* 2013; Finn *et al.* 1977; Georgouli *et al.* 2016; Griffith 1921; Irwin 1977; Kim, Buttlar 2009; Kim, Little 1990; Lucas *et al.* 2016; Pronk, Hopman 1991; Roque *et al.* 1999; Walubita *et al.* 2005; Yuan *et al.* 2013), for example:

- methodologies based on the study of stress and strain;
- distortion energy methodologies;
- methodologies based on fracture mechanics.

At the same time unambiguous solution of the problem of the rate setting and the asphalt concrete pavements fatigue assessment is still lacking due to the complicated correlation between appropriate deformations

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development and the real road structures. A long experiment is required and result depends on numerous factors, determining the impact of transport, climate, particularities of construction (repairs) technology. Results of the fatigue life calculations often differ by tens and hundreds of times. In most cases, the necessary long-term testing is required, and that hampers operational quality control of the asphalt concrete, for example, in a production environment and requires expensive equipment. Thus, the unification of criterion and its use for the rate setting indicators of the asphalt concrete properties in the technical specifications is hampered. Very often it is difficult to use the tests results for the practical purposes of designing and calculation of road pavements the criteria of the fatigue life is major factor in the assessment of the reliability of the asphalt concrete in the design of the road constructions and requires constant improvement.

2. Peculiarity and prospects for the assessment of the asphalt concrete fatigue life

Complexity of asphalt concrete fatigue life evaluation lies in the fact it combines the properties of coagulation, condensation, and crystallization structures. In such systems the location of the various bounds, the binder matrix and the secondary structure of the uneven volume distribution of material, the strength and stress-related characteristics of structural units and clusters are also highly heterogeneous. From the point of view of deformation and fracture mechanics, the structure of such materials is represented in the form of a phenomenological model with a complex set of elastic, viscous and plastic bounds, alternating series and parallel patterns (Fig. 1).

Each model bound (elastic, viscous, plastic) has its own mechanical characteristics, resulting in asphalt concrete range of elastic-viscose-plastic properties. Variation of temperature, load and/or mode of loading causes replacement of some bounds (e.g. elastic by viscous).

Depending on temperature, mode of loading, the composition of asphalt concrete, the process of forming involves different numbers of elastic and viscoplastic bounds. Accordingly, the asphalt concrete exhibits varying degrees of elastic or viscous properties.

In case if only elastic bounds are deformed, full reversibility of the deformation is observed; failure occurs according to the brittle mechanism without influence of load action duration. Conversely, viscose-plastic bounds are responsible for residual strains, which are affected by temperature and loading time.

The accumulation of damage in the structure of asphalt concrete occurs in two ways:

- breaking of elastic bonds;
- achieving limit deformation of viscoplastic bounds.

Regardless of the composition and structure, asphalt concrete with an equal amount of elastic (viscoplastic) bounds has the same relaxation ability, relaxation rate, ratio of the transverse deformation and balance between the amounts of dissipated and stored energy. The reason is that with the same amount of bounds, relaxation rate inhibition causes a decrease of the relaxation constants by the same amount. This situation is the valued feature of the studied materials behaviour, which allows developing some approaches to their properties analysis, of such as fatigue life.

In the development of methodological grounds of assessment of the reliability and durability of asphalt concrete structural layers of road pavements in Henan province (China) the research was based on the fact that accumulation of damageability in the asphalt concrete structure caused by cyclic actions would be determined by the following factors:

- amount of elastic bounds involved in the process of deformation;
- maximum asphalt concrete strength in the whole range of temperature (load action duration);
- maximal deformation in the whole range of temperature (load action duration).

In case if to denote the proportion of elastic bounds responsible for the asphalt concrete condition by some scalar n_r and viscoplastic by n_v, then meets the following condition Eq (1) (the subject is still missing):

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

Since as the result of viscoplastic bounds deformation complete dissipation of applied energy occurs, it is theoretically possible to accept that the ratio n_r is n_v determined by the ratio of the dissipative energy to the applied energy. In this case, the number n_r and n_v depends ultimately on the relaxation properties of the asphalt concrete and the time of load action; the number of elastic bounds involved in the deformation process determined from the following dependencies Eq (2):

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

where E_t and R_t – relaxation modulus and strength of asphalt concrete under specific conditions of load and temperature, MPa; E_c and R_c – maximum values of the relaxation modulus and strength throughout the whole temperature and speed (time) of load action range, MPa; m – coefficient depending on the properties (type) of asphalt concrete.

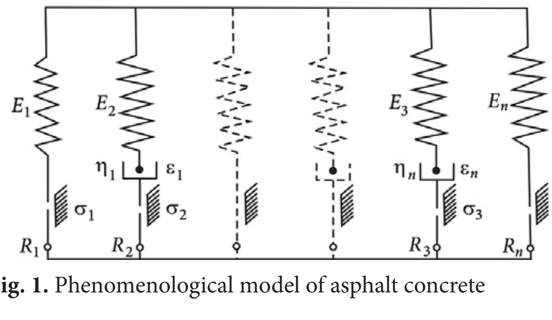

Fig. 1. Phenomenological model of asphalt concrete

The value of the coefficient m for asphalt concrete is in the range of 0.75–0.90 and determined first by its modulus of elasticity (stiffness). The higher the modulus of elasticity (stiffness), the higher the ratio m, and for simply calculations is equal to 0.8.

The value n_r changes in the process of creeping and relaxation as a function of E_t stress and load action time and causes the complex influence on the properties of asphalt concrete, and the mechanics of its destruction.

The Boltzmann-Volterra equation is presented in the next form for the core $T(\tau)$ that determines the stress relaxation process Eq (3)–(4):

$$\frac{\sigma_t}{\sigma_0} = 1 - \int_0^t T(\tau)d\tau\,, \tag{3}$$

$$\frac{E_t}{E_0} = 1 - \int_0^t T(\tau)d\tau\,, \tag{4}$$

where σ_0, E_0 – stress and relaxation module in the initial moment of the loading time action, MPa; σ_t, E_t – stress and relaxation module in the moment t of the loading time action, MPa.

For the asphalt concretes with the same relaxation cores $T(\tau)$ condition Eq (5):

$$\frac{E_{t_1}}{E_{0_1}} = \frac{E_{t_2}}{E_{0_2}}\,, \tag{5}$$

automatically ensures the fulfilment of the condition Eq (6):

$$\frac{\sigma_{t_1}}{\sigma_{0_1}} = \frac{\sigma_{t_2}}{\sigma_{0_2}}\,. \tag{6}$$

In fact, if the two different properties of asphalt concrete (for example, maximum relaxation modulus E_c) with equal n_r (with equal relaxation ability) are subjected to an instantaneous strain ε, the stress values in each of them are (Eq (7)):

$$\sigma_{0_1} = \varepsilon E_{c_1}\,,\ \ \sigma_{0_2} = \varepsilon E_{c_2}\,. \tag{7}$$

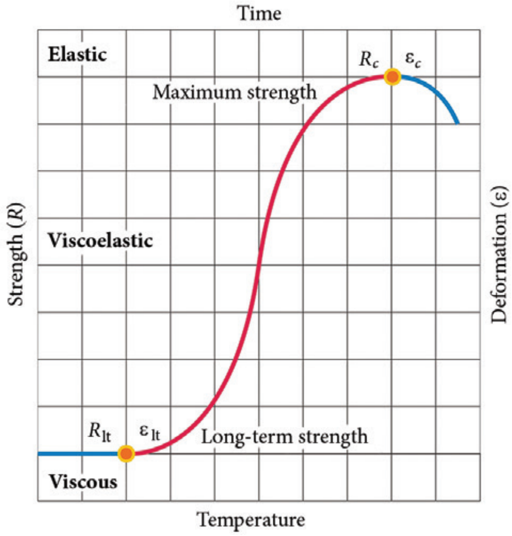

Fig.2. Characteristics of asphalt concrete depending on the temperature (time of loading)

After a certain period t the stress in each asphalt concrete reaches the level Eq (8):

$$\sigma_{t_1} = \varepsilon E_{t_1}\,,\ \ \sigma_{t_2} = \varepsilon E_{t_2}\,. \tag{8}$$

Accepting as the factor of relaxation ability rations of initial stress to the current one, get Eq (9):

$$\frac{\sigma_{t_1}}{\sigma_{0_1}} = \frac{E_{t_1}}{E_{0_1}}\,,\ \ \frac{\sigma_{t_2}}{\sigma_{0_2}} = \frac{E_{t_2}}{E_{0_2}}\,. \tag{9}$$

Hence, the equality of the right sides of expressions Eq (5) and, consequently, the equality of the stress ratio, theoretically confirms the proposition about equal relaxation ability of materials with the same n_r.

When the asphalt concrete works in the elastic mode ($n_r \to 1$), its strength R_c is equal to the maximum in the whole temperature range (load action time). Since the number of cycles to fracture depends on the ratio of stresses to strength, then the higher R_c, the higher is the cyclic stability of asphalt concrete in elastic work stage, and the higher level of the damage in the material is achieved at the time of destruction. Therefore, the value R_c serves as a criterion of cyclic durability under constant stress in the elastic work stage (Fig. 2).

The maximum strength of asphalt concrete in the entire temperature range (duration of load) is calculated by the split test results (indirect strain) of standard cylindrical samples according to the following dependencies Eq (10):

$$R_c = \frac{\dfrac{R_{t_1}^T + R_{t_2}^T}{2}}{1 + k_1 \log\left(\dfrac{R_{t_1}^T}{R_{t_2}^T}\right)}\,, \tag{10}$$

where $R_{t_1}^T$ – the strength of asphalt concrete at a rate of load action t_1 and test temperature T, MPa; $R_{t_2}^T$ – the strength of asphalt concrete at a rate of load action t_2 and test temperature T, MPa; k_1 – coefficient depending on the test conditions (rate of load action, temperature).

For example, the value of the coefficient k_1 is:

- for temperature −10 °C, for the rate of load action t_1 = 1 mm/min and t_2 = 10 mm/min – is 2.64;
- for temperature −15 °C, for the rate of load action t_1 = 3 mm/min and t_2 = 10 mm/min – is 1.92.

Figure 3 presents the data, correlating experimental results with the results of calculation R_c by formula (10) for the coefficient values k_1 = 2.64, obtained for asphalt concrete structural layers of road pavements in Henan province (China).

In China and Belarus to assess the ability of asphalt concrete to resist the fatigue strain. an indicator of their maximum strength in the entire temperature range (duration of load) R_c is used, because regardless of the asphalt concrete work schemes in a road construction. the fatigue build-up is determined by rupture and damage to elastic bounds. Also, the value R_c reflects the potential of the asphalt concrete to resist the fatigue deformation show and damage caused by cyclic loads but needs refinement as a characteristic uniquely determining the fatigue life when used in road construction.

In case if loading regime corresponds to the asphalt concrete work in a viscous stage ($n_r \to 0$), then the longer cyclic fatigue life demonstrates the asphalt concrete capable of dispersing a greater amount of energy before destruction W_d, which is correlated with the maximum deformation ε_m, in a wide range of temperature and the load action duration. Asphalt concrete performance in a viscous state is observed in the course of relaxation processes, creep.

Since the increase of R_c enhancing the likelihood of increased fatigue life in the elastic work stage and the increase of ε_m in the viscous stage, in general case ($0 < n_r < 1$) the materials with the maximum value of $R_c\varepsilon_m$ are maximum fatigue cyclic life.

Figures 4–5 presents the analytical processing of definition dependence of the cycles number limit of rapture at constant acting stresses and deformations from the estimated traffic load, defined by finite element method applied to three-layer pavement. Asphalt concrete under investigation was specified as stone matrix asphalt. From the dependences described herein, it follows that the increase in cycles number up to fracture under continues stress with increasing values of maximum asphalt concrete strength R_c is definite.

The situation is somewhat different when the material is subjected to continuous strain level (Fig. 5). In this case, the dependence of a maximum number of cycles until rapture n_r would be presented by the extreme curve, because under continuous strain, stress increases with the increase of n_r, due to the increased module $E_t = f(n_r \cdot E_c)$. Therefore, the higher n_r, the fewer cycles elastic bounds survive before the rapture. Conversely, viscoplastic bounds n_v with n_r increase carry a smaller portion of the total deformation and their fatigue life increases.

As a result, maximum material durability is observed at defined optimal ratio of the elastic and viscoplastic bounds.

Figure 6 presents dependence of determining the maximum number of cycles to rapture (cyclic durability) under the estimated traffic load of 130 kN.

As Fig. 6 shows, the asphalt concretes with a high value of maximum strength R_c have a higher potential to resist cyclic stresses. At the same time for such asphalt concrete, it is essential to control some elastic deformation bounds n_r involved under the appropriate temperature, load and loading conditions.

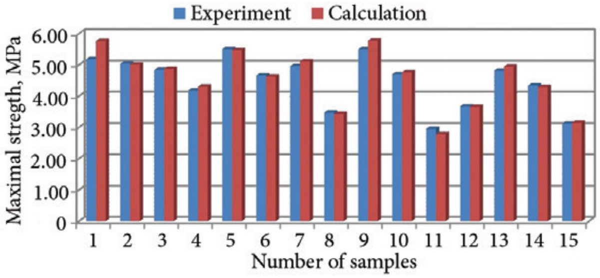

Fig. 3. Results of experimental and calculated definition data comparison R_c

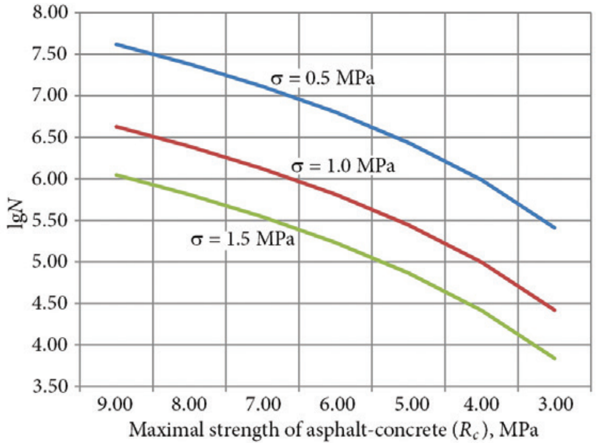

Fig. 4. Durability of asphalt concrete under cyclic continues stress

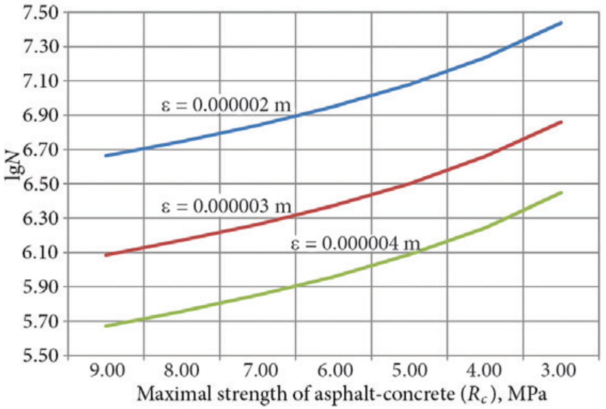

Fig. 5. Durability of asphalt concrete under cyclic continues deformations

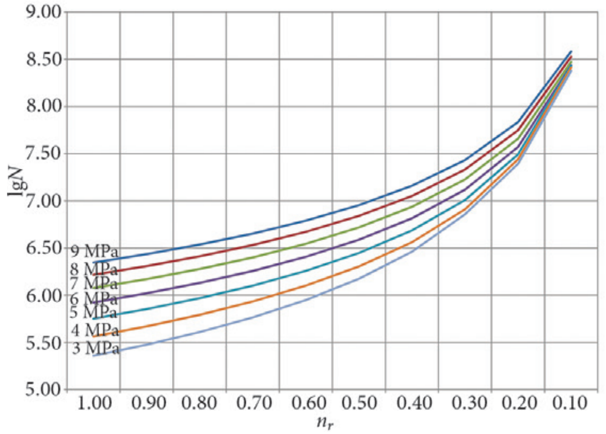

Fig. 6. Durability of asphalt concrete depending on the maximum strength and the amount elastic bounds, involved in the deformation process

The analysis of theoretical and practical results of the research proved that as a criterion for determining fatigue life of asphalt concrete, besides their maximum strength, is the number of elastic bounds n_r involved in the process of deformation. The tests were carried out under the following conditions: at a temperature of 0 °C (Belarus) or 15 °C (China, Henan Province) and the strain rate of 50 mm/min.

The maximum strength R_c of 6 MPa to 9 MPa and above is attainable mainly for asphalt concrete modified with polymers, from 3 MPa to 6 MPa for asphalt concrete on clean road bitumen. Some elastic bounds n_r at rated conditions for modified asphalt concrete used for paving on motorways of high technical categories is in the range of less than 0.55–0.85, of asphalt concrete on the pure bitumen – less than 0.40–0.55.

Thus, a rather simple and reliable way is presented for the optimization of the asphalt mixtures properties at the stage of mix design by the criteria of the fatigue and cyclic durability.

3. Conclusions

1. This article presents the results of a study of the asphalt concrete ability to resist the cyclic stress caused by transport.

2. It is established that the value of asphalt concretes maximum (structural) strength in the whole temperature range and modes of load action is suitable for their assessment of asphalt concrete ability to withstand the accumulation of fatigue leading to destruction.

3. Theoretically, confirmed prerequisites to the facts that asphalt concretes having the optimum ratio of the elastic and viscoplastic bounds ensure maximum cycle-life under the temperature range and the load modes. The less material brittle, the less its elastic bounds work, less the likelihood of fatigue deformation, ceteris paribus.

4. The maximum strength of 6 MPa to 9 MPa and above is attainable mainly for asphalt concrete modified with polymers, from 3 MPa to 6 MPa for asphalt concrete on road bitumen. Some elastic bounds at rated conditions for modified asphalt concrete used for paving on motorways of high technical categories are in the range of less than 0.55–0.85, for asphalt concrete on the pure bitumen – less than 0.40–0.55.

5. The direction for future research, associated with the implementation of complex experimental and theoretical studies, is set. This methodology for assessing the reliability and durability of asphalt concrete pavements under cyclical impact of transportation and climatic factors during the service life is urgent for optimizing the process of asphalt concretes mix design.

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