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Fatigue durability of asphalt-cement mixtures

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Abstract. This paper focuses on examinations of asphalt-cement mixtures (ACM). This is a recycled material which can be used in road pavement layers. In the article stiffness modulus tests and fatigue tests of asphalt-cement mixtures were shown. The authors decided to lead research on fatigue durability of asphalt-cement mixtures to set fatigue characteristics of these materials. So far in research or other works any adequate fatigue criterion for ACM mixtures has not been developed. As a result of the examinations a level of fatigue damage was suggested. For new fatigue damage a strain level in one million load cycle was estimated. Based on that a fatigue design criterion for asphalt-cement mixtures was estimated.

Key words: dynamic stiffness modulus, fatigue durability, asphalt-cement mixtures, fatigue criterions.

1. Introduction

The use of road materials which are taken from old and destroyed road pavements, leads to exploitation decreasing natural sources and to decreasing interference in a natural environment. These technologies are available in countries with highly developed road infrastructure such as: USA, Western Europe countries or China [1–3]. Rebuilding roads with the use of renewed materials is one of methods of road maintenance. Products which are reused in road building and which contain recycled materials are often asphalt-cement mixtures (ACM). They consist of reclaimed asphalt, aggregate increasing gradation, cement and asphalt binder from asphalt emulsion. Exploitation properties of such a conglomerate depend on its durability parameters. Main features which influence on a future road pavement durability are stiffness modulus and fatigue durability of a ACM material [4]. This material is a base for bearing layers in a road pavement construction.

Based on experiences in various countries, it is possible to say that examinations of asphalt-cement mixtures correspond mainly to estimating the strength and the stiffness modulus. Basic parameters for recycled materials in a cold recycling process in Germany and South Africa are: modulus of elasticity and indirect tensile strength [5, 6]. In France following features are estimated: compaction index, tensile strength, tensile modulus, aggregate size, type of the binder [7–9]. In Holland there are tested: type and size of aggregate, proper quality of a binder, impurities in composition and homogeneity of a mixture [10]. The Austrian guidelines suggest to perform following tests: compression strength, indirect tensile strength, modulus of elasticity, water erosion durability, frost resistance, type of a binding agent [11]. In Sweden before the compacting process of ACM mixture there is a necessity to check: Marshall's stability, modulus of elasticity and air void content [12]. The tests of ACM in Canada are concentrated on: indirect tensile strength, compression strength and modulus of elasticity [13]. In USA the samples are tested on Hveem's stability, and on indirect tensile strength [14, 15]. The British instruction for cold recycling suggests to test stiffness modulus and resistance on permanent deformation [16–18].

Recycling materials in road pavements are used in Poland only for several years. Specifications [19, 20] introducing cold recycling technology with emulsion and cement binders. These guidelines set the requirements only for: reclaimed asphalt, aggregate, binding agents. They take into account air void content in a road layer, total amount of asphalt, the Marshall's stability and deformation, indirect tensile strength and IT-CY stiffness modulus.

As yet there have not been any fatigue criterions for ACM materials. This issue is fundamental to the fatigue durability of a road pavement. The fatigue durability problem of asphalt-cement mixtures has not been sufficiently studied yet. There are applications of asphalt concretes (AC) and lean concretes criterions to asphalt-cement mixtures. Such an approach is not correct because ACM mixture contains asphalt and cement binders. For that reason the authors decided to lead research on fatigue durability of asphalt-cement mixtures. In the article ACM fatigue durability analysis is shown depending on composition and physical properties of a tested material.

2. Test principle

In a laboratory a stiffness and a fatigue durability of ACM mixtures can be estimated in 4 point bending tests (4PB-PR). A scheme of this test is shown in Fig. 1.

Under the load (strain) influence a reaction of a material is recorded as a deflection in the middle of a sample's length. It is possible to calculate the stress when the cross-section of the sample is known. In the apparatus a strain is given in a dynamic form and the applied load is cyclical, sinusoidal, with a determined frequency. In each load cycle it is possi-

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ble to estimate the dynamic complex stiffness modulus E^* of the material using values of force and displacement – Eq. (1) or (2) [21–25].

$$E^* = \frac{\sigma(t,T)}{\varepsilon(t,T)}, \tag{1}$$

$$E^* = \sqrt{E_1^2 + E_2^2}. \tag{2}$$

where E^* – dynamic complex stiffness modulus of ACM mixture [MPa], σ – stress in the load cycle [MPa], ε – strain in the middle of the sample's length [–], T – temperature [°C], t – loading time [cycle].

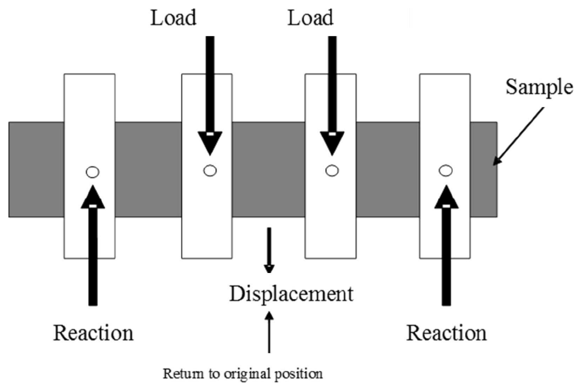

Fig. 1. Loading scheme in four point bending test

Parts E_1 and E_2 are the real and the imaginary components. Load is sinusoidal and dynamic with various, established frequencies. Typical record of loading (stain) and reaction of the material (stress) are shown in Fig. 2.

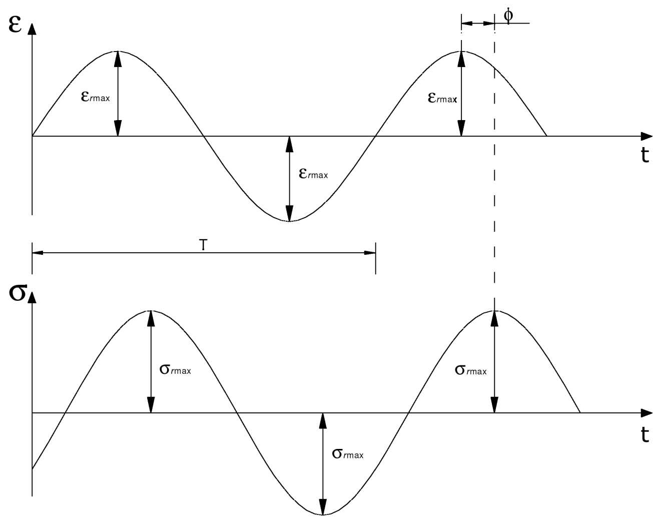

Fig. 2. Sinusoidal load and the phase angle Φ

The frequency has an influence on a stiffness modulus value. In back calculations there is a necessity to take into account the mass of moveable parts (including specimen). Values of E_1 and E_2 are calculated directly from Eqs. (3) and (4).

$$E_1 = \gamma \cdot \left(\frac{F}{z} \cdot \cos(\phi) + \frac{\mu}{10^6} \cdot \omega^2 \right), \tag{3}$$

$$E_2 = \gamma \cdot \left(\frac{F}{z} \cdot \sin(\phi) \right), \tag{4}$$

where F – load leads to sample's deflection [kN], z – deflection in the middle of the sample's span [mm], ϕ phase angle [°], ω – loading frequency [rad/s], μ – mass factor, γ – form factor.

While performing the fatigue examinations a maximum number of loading cycle is recorded, which is needed to obtain a stiffness slope to determined level – Fig. 3. For bituminous mixtures it is 50% of initial stiffness of tested material.

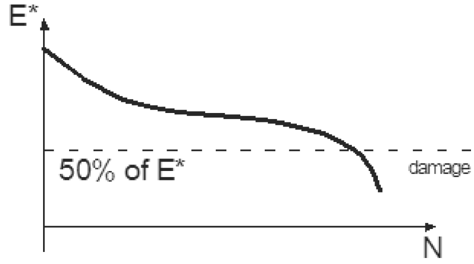

Fig. 3. Fatigue examination

3. Samples preparation

In the 4 PB-PR laboratory examinations prismatic beams as samples are used. Nominal dimensions of these beams are: $b = 60$ mm, $h = 50$ mm, $L = 354$–357 mm (distance between the two outer clamps).

Individual beams are cut to determined dimensions from compacted ACM slab. This slab should be obtained using roller compactor, which allows to compact the material to needed compaction level P_{98}–P_{100}. Compaction index of ACM mixtures shouldn't be lower than 98% [19] comparing to designed bulk density of the material.

During the analysis various recipes of ACM mixtures were used with different cement and asphalt binder contents and also various air void content. As a base a mixture of recycled materials was used containing: reclaimed asphalt 15%, recovered stone material form sub base layer 28.3%, granite stone from base layer 28.3% and aggregate increasing gradation 28.3%. The cement CEM I 42.5 content was 2.4%, 3.4% and 4.4%, respectively. The asphalt binder content form an asphalt emulsion was set on 3.5% and 5.5%, respectively. To get an optimal compaction of the ACM mixture a total water amount was set at level of 6.1%.

After the compaction process the samples were removed from the molds after 3 days period to avoid any damages. Directly after the compaction samples had low cohesion. Thereafter the samples were left for the 28 day period in a room with temperature at a level of +20C, to get a full cement hydration.

4. Examinations of complex stiffness modulus

For selected recipes of asphalt-cement mixtures a set of four point bending tests (4PB-PR) was carried out. Examinations of the dynamic complex stiffness modulus were carried out according to a constant strain ε method. The loading frequency was set at level of 10Hz and the strain was equal to $\varepsilon = 50{*}10^{-6}$ m/m. Values of the stiffness modulus in various temperatures were estimated basing on the preliminary analysis.

Changes in a temperature level directly influence on stiffness of ACM mixtures, but extent of these changes is much lower than in conventional asphalt concretes (AC) [9]. Values of stiffness modulus were recorded in the temperature range from $-10°$C to $+55°$C. In Fig. 4 an example tendency of changes in stiffness, depending on temperature was shown. It is possible to estimate average stiffness of ACM mixtures in $+10°$C temperature (cement content 3.4% and asphalt binder content 3.5%).

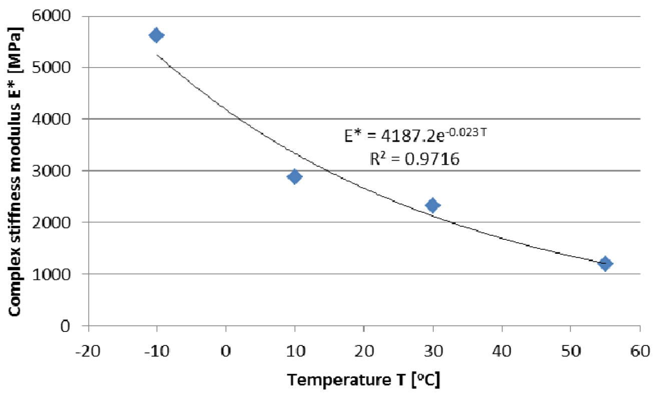

Fig. 4. Stiffness of ACM versus temperature

The value of complex stiffness modulus drops down with an increase of the temperature asymptotic to value about 1000 MPa. For a yearly average temperature $+10°$C complex stiffness modulus has a value about 3500 MPa.

5. Examinations of fatigue durability

An important factor which decides on a road pavement quality is a durability of structure layers. Durability it is a material's resistance on destructive factors activity. The highest influence on a durability of road pavements has a fatigue durability. In the laboratory a set of fatigue examinations was carried out according to the 4PB-PR method. In these tests the same samples are used as in a case of complex stiffness modulus test – Fig. 4.

The fatigue durability of ACM mixtures was estimated in $+10°$C temperature. Such a temperature is equal to yearly average temperature which can occur in ACM road pavements' layers (sub base, base layer).

In Fig. 5a a typical stiffness modulus slope (fatigue) of asphalts concretes is shown. As a damage moment of AC sample a fatigue damage D is assumed. In AC analysis this damage is a number of load cycles which is needed to obtain 50% of initial stiffness of the material. In case of ACM mixtures' tests with typical micro strain level ($\varepsilon = 115{*}10^{-6}$ m/m – $130{*}10^{-6}$ m/m), it was recorded that these materials had quite different working conditions – Fig. 5b. Temporary decreases in stiffness are possible to record after which the sample is still able to take loading cycles. Further the stiffness of ACM mixtures is significantly lower than the stiffness of conventional asphalt concretes. Asphalt-cement mixtures reach 5 to 10 times lower stiffness, than asphalt concretes.

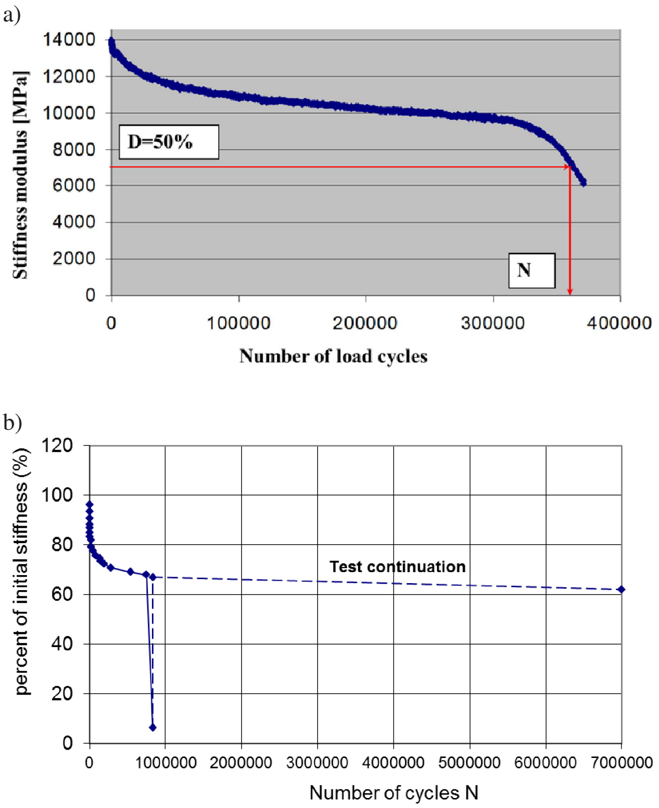

Fig. 5. Fatigue of AC and ACM

Taking into account these factors – different fatigue criterions should be applied to asphalt-cement mixtures fatigue estimation.

In view of the above obligations, fatigue examinations of ACM mixtures were carried out with the modified fatigue damage $D_{ACM} = 30\%$. Fatigue tests were carried out using various strain levels within the range ($150{*}10^{-6}$ m/m – $215{*}10^{-6}$ m/m). The main purpose was to obtain fatigue lines (curves) characteristic for each recipe of asphalt-cement mixtures. In that way an influence of asphalt and cement content on a fatigue life time was estimated.

Three levels of loading were applied for each recipe. Based on fatigue characteristic of ACM mixtures, a damage micro strain ε_6, in one million load cycle was calculated – Table 1. Typical fatigue curve of ACM mixtures is shown in Fig. 6.

For tested ACM mixtures a minimal level of damage stain which guarantees one million load cycles was $\varepsilon_6 = 170{*}10^{-6}$ m/m – for fatigue damage $D_{ACM} = 30\%$. As a result of fatigue analysis for optimal recipes of ACM mixtures, a new fatigue equation was introduced for mixtures containing recycled materials.

Table 1
Fatigue examinations of ACM mixtures

ACM recipe	Applied strain ε [*10^{-6} m/m]	Average number of cycles to damage $N_{f/30}$ (damage $D = 30\%$)	Average damage strain ε_6 [m/m *10^{-6}]
C – cement content 3.4% A – asphalt binder content 3.5%	170	848.213	168.7
	180	12.812	
	200	3.121	
C – cement content 4.4% A – asphalt binder content 3.5%	170	1.200.000	171.1
	180	137.478	
	190	36.344	
C – cement content 3.4% A – asphalt binder content 5.5%	180	6.500.000	187.1
	185	1.830.000	
	190	390.000	
C – cement content 2.4% A – asphalt binder content 3.5%	190	8.500.000	198.6
	200	352.000	
	215	46923	

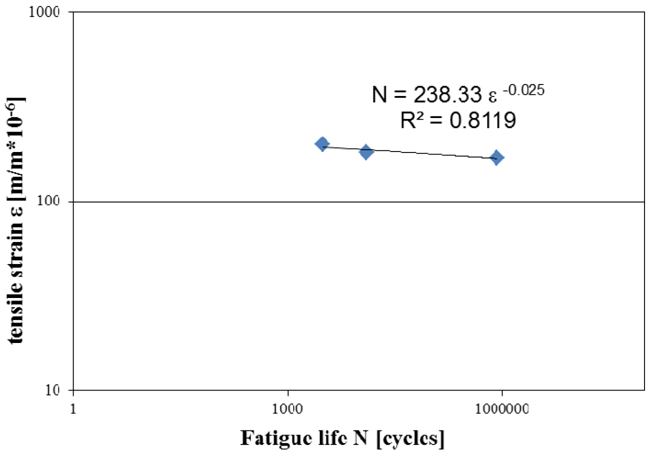

Fig. 6. ACM fatigue curve

6. Fatigue equation of ACM mixtures

Using fatigue examinations with a modified level of fatigue damage $D_{ACM} = 30\%$ and fatigue strain equal to $\varepsilon_6 = 170{*}10^{-6}$ m/m, a new criterion of laboratory fatigue durability (N) estimation for ACM mixtures was suggested. The criterion is defined by Eq. (5)

$$\varepsilon = \varepsilon_6 \cdot \left(\frac{N_{f/30}}{10^6}\right)^{(-0.00173\cdot A - 0.00553\cdot C)}, \quad R^2 = 0.9284, \tag{5}$$

where ε – permissible tensile strain in bending test, ε_6 – level of tensile strain, when the sample is damaged after 10^6 load cycles in following test conditions: four point bending test (4PB-PR), $+10^\circ$C temperature, 10 Hz frequency, (estimated strain for ACM mixtures is equal $\varepsilon_6 = 170{*}10^{-6}$ m/m), $N_{f/30}$ – number of load cycles with permissible level of fatigue damage equal 30% [–], A – asphalt binder content [%], C – cement content [%].

This fatigue equation was obtained in laboratory conditions. The dependency (5) was set using 36 fatigue tests of ACM mixtures. This fatigue equation is significantly different from fatigue equations for asphalt concretes [26] or lean concretes [27]. It is a new criterion for ACM mixtures. The estimated equation can be used in the design process of road pavements which contains ACM layers. But there is a necessity to implement "shift factors", which take into account working conditions of road pavements "in situ". It is proposed that fatigue equation should be in form (6):

$$\varepsilon = \left(\varepsilon_6 \cdot \left(\frac{N_{\frac{f}{30}}}{10^6}\right)^{(-0.00173\cdot A - 0.00553\cdot C)}\right) \cdot f_1 \cdot f_2 \cdot f_3, \tag{6}$$

where f_1 – a shift factor dependent on stiffness of ACM mixture, range between 0.9–1.0, f_2 – a shift factor dependent on bearing capacity of subgrade, range between 0.8–1.0, f_3 –a shift factor dependent on heterogeneity of ACM mixture, range between 0.8–0.95.

In Eq. (6) "ε" it is a strain estimated in asphalt-cement mixture, built in layers of a road pavement structure. Other indications as in dependency (5).

7. Summary and conclusions

In the article the stiffness modulus tests of asphalt-cement mixtures were shown. The influence of composition and temperature on a stiffness of ACM mixtures was found. The fatigue durability of asphalt-cement mixtures was also analyzed. As the result of the examinations, a new level of fatigue damage was suggested. For fatigue damage equal to $D_{ACM} = 30\%$, a damage strain level in one million load cycle was estimated at level of $\varepsilon_6 = 170{*}10^{-6}$ m/m. The tests were carried out in a temperature of $+10^\circ$C. The tests frequency were set at 10 Hz.

So far there was not any fatigue criterion for ACM mixtures. A new fatigue design criterion for asphalt-cement mixtures was set. New criterion can be used to recipe verification. After the application of the shift factors, it is possible to implement this criterion in a design process of road pavement structures which contain asphalt-cement mixtures.

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