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# EFFECT OF FILM THICKNESS ON RESISTANCE TO PERMANENT DEFORMATION IN ASPHALT MIXTURES

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**Abstract.** The resistance of asphalt mixtures against permanent deformation is one of important requirements that have to be verified in the design process of asphalt mixtures. In the case of asphalt concrete the *European Standard EN 13108-1:2006 Bituminous Mixtures. Material Specifications. Part 1: Asphalt Concrete* allows empirical (compositional recipes and requirements) or fundamental approach for testing of permanent deformation resistance. A fundamental approach specifies asphalt concrete in terms of performance-based requirements linked to limited prescription of composition and constituent materials. In this design approach a triaxial cyclic compression test is used to verify resistance to permanent deformation. The presented study investigates characteristics of resistance to rutting of asphalt concrete mixtures (eight mixtures of AC 11 from different producers) determined by triaxial cyclic compression test. The basic conclusions and statements of main factors influenced resistance to rutting (type of binder, binder content, and aggregate gradation) have been worked out from prevenient experience and experimental measuring. But measured test results presented in the following paper point out differences in resistance however the bitumen contents are relatively the same. During detailed investigation the tested asphalt mixtures had small differences in aggregate gradation. Changes in gradation make change of aggregate specific surface and the mixture needs different bitumen content to coat aggregate particles, to bound them to each other and to make stiff material resistant to rutting. The results from measuring of resistance to permanent deformation show the relation between aggregate specific surface and bitumen film thickness and permanent deformation.

**Keywords:** asphalt mixture, bitumen film thickness, creep rate, permanent deformation, specific surface, triaxial cyclic compression test, wheel tracking test.

## 1. Introduction

The wheel tracking tests according to *EN 12697-22:2003+A1:2007 Bituminous Mixtures. Test Methods for Hot Mix Asphalt. Wheel Tracking* are usually used to verify a permanent deformation resistance of asphalts. The application of the European Standard *EN 13108-1:2006 Bituminous Mixtures. Material Specifications. Part 1: Asphalt Concrete* for asphalt concrete allows using another test method (triaxial cyclic compression test) to verify permanent deformation resistance. A fundamental approach specifies asphalt concrete in terms of performance-based requirements linked to limited prescription of composition and constituent materials. A triaxial cyclic compression test is able to eliminate disadvantages of wheel tracking tests, particularly the different stress distribution in a test sample in comparison with pavement.

Resistance to permanent deformation is one of the properties that are expected from asphalt mixture in asphalt pavement construction. Asphalts in surface courses are designed to withstand high traffic and environment induced stresses without exhibiting unsatisfactory cracking and rutting and possessing a texture to ensure adequate skid resistance. Binder courses are usually designed by preventing permanent deformation by combining qualities of stability and durability. To design mixture that performs all these requirements in maximum values is unreal.

A higher binder content in mixture ensures durability and water resistance of the course. The aggregates are covered with a thicker asphalt film and the mixture is resistant to break due to the loss of adhesion (stripping) or loss of cohesion, i.e., softening of asphalt that weakens the bond between asphalt and aggregate. And the mixture retains the strength and durability. But a higher binder content negatively influences resistance of mixture to permanent deformation. The aggregates covered with a thicker asphalt film resist to stone-on-stone contact and there is skid effect after load. The effect of higher bitumen


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percentage on deformation rates was confirmed by Garde-te *et al.* (2011). Also the asphalt mixes require a minimum amount of bitumen binder to ensure cohesion, durability and a minimum level of fatigue resistance in a mix after it is placed (Oliver 2011).

The asphalt film thickness, according to Sengoz and Agar (2007), has an influence on the moisture susceptibility characteristics of asphalts because it affects durability of the mixture. Thick films which are associated with black flexible mixtures are known to be durable. On the other hand, thin films which are associated with brownish, brittle mixtures tend to crack and ravel excessively thus shortening the service life of the pavement. Mixtures with thick asphalt film are less susceptible to water damage than the mixtures with thin asphalt film since very little quantities of water move through the mixture that contains thick asphalt film thicknesses. Also the film thickness in asphalts in wearing courses is reduced due to ageing which contributes to the decrease in durability.

Several works presented the relationship between voids, surface area, film thickness, and stability for dense-graded asphalt mixtures. The authors (Campen *et al.* 1959) recognized that thicker asphalt binder films produced mixes that were flexible and durable, whereas thin films produced mixes that were brittle, tended to crack and ravel excessively, retarded pavement performance, and reduced useful service life. On the basis of the data they analysed, the average film thicknesses ranging from 6 μm to 8 μm were found to provide the most desirable pavement mixtures. They also concluded that the film thickness decreases as the surface area of the aggregate increases. However, the asphalt binder requirement of a mix is not directly proportional to its surface area. The asphalt binder requirement was found to increase as the surface area increased, but at a rate much lower than that guided by a relationship of direct proportionality.

Radovskiy (2003) observed that the current method of calculating film thickness does not take into account a degree of mix compaction: conventional film thickness is the same for a loose mix and the compacted mixture. The thickness of separating film is not only a function of asphalt content, but also a function of compaction. As the grains come closer together during compaction, the binder comes out of the contact zone. Thinner the film in the contact zone, thicker the film separating the grains from the air voids.

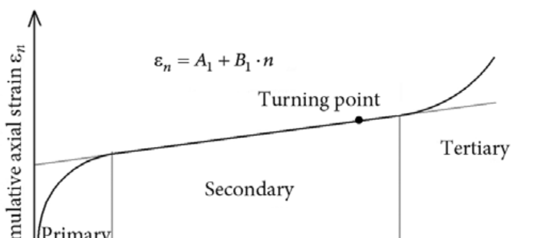


**Fig. 1.** The typical creep curve of asphalt mixtures according to *EN 12697-25:2005 Bituminous Mixtures. Test Methods for Hot Mix Asphalt. Cyclic Compression Test*

Kandhal *et al.* (1998) proposed that rather than specifying minimum voids in the mineral aggregate (*VMA*) requirement based on minimum asphalt content as used in Superpave (Superior Performing Asphalt Pavements) mix design procedure, a more rational approach is to directly specify a minimum average asphalt film thickness of 8 μm. They pointed out that the term "film thickness" is difficult to define. To calculate an average film thickness, the surface area is determined by multiplying the surface area factors (given in the manual the *Mix Design for Asphalt Concrete and Other Hot Mix Types MS-2*, 1993) by the percentage passing the various sieve sizes. However, they did not find the background research data for the surface area factors in the literature. They concluded that further research is needed to verify these surface factors and the concept of film thickness.

The resistance to permanent deformation as one of the properties that are necessary to be tested in type testing was verified on asphalt AC 11 from the batch plant production in Slovakia. The test results presented in following part of paper point out differences in mixtures however the bitumen contents were relatively the same (5.66–5.74%).

## 2. Permanent deformation

The permanent deformation with cracking and potholes is the most often distress in asphalt pavement. It represents accumulation of small amounts of deformation that occurs each time a load is applied. With increasing Annual Average Daily Traffic (*AADT*), heavy vehicles first, a heavy axle load forms stresses in asphalt layers and forms rutting characterized by downward and lateral movement of the mixture. Permanent deformation (rutting) in asphalt layers develops in three stages (Fig. 1):

- *primary (initial) stage* is part of deformation, where asphalt mixture is formed and compacted by traffic (densification, volume reduction);
- *secondary (middle) stage* is considered to be representative of deformation behaviour for the greater part of lifetime of pavement and constant rate rutting; traffic load (horizontal and vertical) causes shear stresses in asphalts and there is a displacement of asphalt mixture and flow rutting due to shear stress;
- *tertiary (last) stage* is characterized by accelerating rutting, excessive rapid plastic deformations considering number of load; it is typical characteristic of asphalts unsuitable from permanent deformation point of view.

Permanent deformation is a condition of pavement failure caused by accumulation of permanent deformations by repeated axle load. Rutting of asphalt mixture typically occurs during the summer under higher air and pavement temperatures when deformation increases according to the amount of load cycles. Loading forms the deformation in asphalt layers. After unloading the elastic deformation immediately goes back due to materials elastic and viscoelastic properties. But a certain part of deformation (plastic and viscoplastic) remains irreversible cause of viscous material properties.

The rheology as "the study of the flow" is the science of study and evaluation of the flow and permanent deformation of time- and temperature- dependent materials, such as bitumens and asphalts. This viscoelastic, viscoplastic behaviour of bitumens, as materials response to applied loads, is illustrated by the well-known Burgers model. At low temperatures and high loading frequencies, the asphalts behave purely elastic. At high temperatures and long loading times the asphalts will behave viscous. This shear property of a bitumen binder is a key property in providing rut resistance of asphalts that was verified by Choi (2011).

During the loading cycle, aggregates are pushed against each other, reorient, change position, and deform the binder in between. This change in the microstructure brings the material to a specific viscoplastic and hardening state at the end of the loading cycle. However, during the rest period, the confined binder between the aggregates apply residual stresses to the surrounding aggregates causing them to redistribute and change position and orientation, such that the viscoplastic state of the material (which is related to the material's microstructure) at the end of the rest period is different from its state at the end of the preceding loading cycle. Darabi *et al.* (2012) related this distinct behavior to the cyclic viscoplastic-softening (or hardening-relaxation) behavior of asphalt concrete at high temperature.

In developing an experimental testing method for evaluating rutting resistance of asphalts, most researchers have used the wheel tracking test, the uniaxial compressive creep test, the triaxial repeated load test, the indirect tension test, and the bending creep test (Xu *et al.* 2014).

### 3. Laboratory test method

Resistance of permanent deformation in this study was investigated by triaxial cyclic compression test and wheel tracking test.

#### 3.1. Triaxial cyclic compression test

Test method B of *EN 12697-25:2005 Bituminous Mixtures. Test Methods for Hot Mix Asphalt. Cyclic Compression Test* determines resistance to permanent deformation of a cylindrical specimens of asphalts. The specimen is placed between two plan parallel loading platens in triaxial chamber and is subjected to a confining pressure $\sigma_c$ on which a cyclic axial pressure $\sigma_a(t)$ – haver-sinusoidal or block-pulse loading (Fig. 2) is superposed. The requirements for values of pressures, frequencies and test temperatures are defined by the standard *EN 13108-20:2008 Bituminous Mixtures. Material Specifications. Part 20: Type Testing* (Table 1).

During the test the changes in height of specimen are measured at specified numbers of load applications (Fig. 3). And the cumulative axial strain $\varepsilon_n$ (permanent deformation) of test specimen is determined as a function of the number of load applications:

$$\varepsilon_n = 100.\frac{h_0 - h_n}{h_0}, \tag{1}$$

where $\varepsilon_n$ – the total axial deformation of the test sample after $n$-loading cycles, %; $h_0$ – the average height after preloading of the sample, mm; $h_n$ – the average height after n loading cycles, mm.

The results are represented in a creep curve as given in Fig. 1. The resistance of permanent deformation of tested mixture is characterized with parameter $f_c$ by interpreting the creep curve. The creep rate $f_c$ is determined in the (quasi) linear part of creep curve (Stage 2 in Fig. 1) as the slope expressed in microstrain/loading cycle:

$$f_c = B_1 \cdot 10^4, \tag{2}$$

where $B_1$ – the slope of least square linear fit of the creep curve between 3000 and 10 000 load applications and it is determined by the following Formula (3):

$$\varepsilon_n = A_1 + B_1 \cdot n, \tag{3}$$

where $\varepsilon_n$ – the total axial deformation of the test sample after $n$-loading cycles, %; $A_1$ and $B_1$ – the parameters of the linear regression; $n$ – is the number of load cycles.

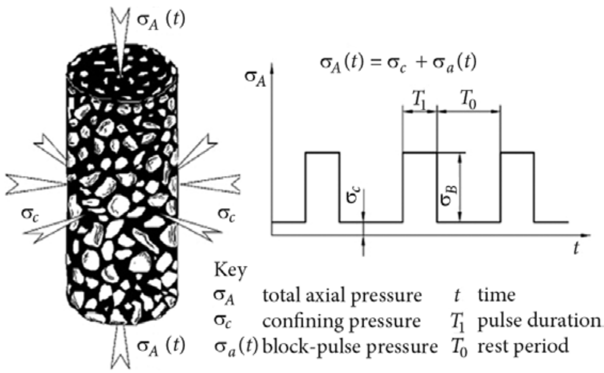


**Fig. 2.** The principle of sample loading by block-pulse cyclic impulses according to *EN 12697-25:2005*

**Table 1.** The test conditions for wearing course according to *EN 13108-20:2008*

| Layer | Test temperature | Stress | | Frequency | Cyclic axial pressure form |
|---|---|---|---|---|---|
| | | Confining | Axial | | |
| Wearing course | 50 °C | 150 kPa | 300 kPa | 3 Hz | haver-sinusoidal |
| | | | | 1 s /1 s | block-pulse |

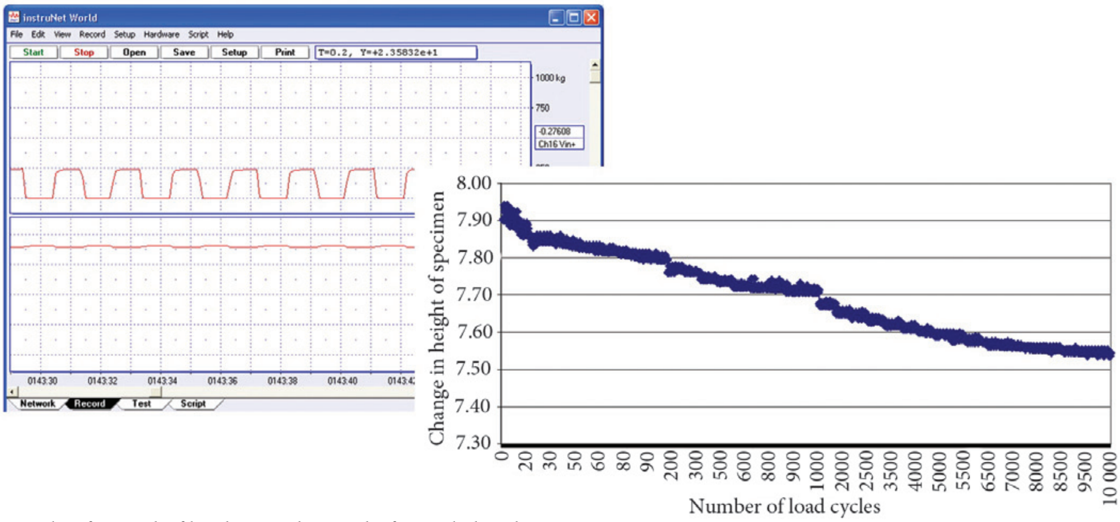


**Fig. 3.** Example of record of loading and record of sample height

The apparatus used for experimental measuring of resistance to permanent deformation by triaxial cyclic compression test is shown in Fig. 4.

### 3.2. Wheel tracking test

Permanent deformation tests were carried out according to *EN 12697-22:2003+A1:2007* in small-size device according to method B (conditioning in air). Slabs placed in the equipment were tempered during 4 h at test temperature of 50 °C. After that the loaded wheel fitted with treadless tyre (a tyre of outside diameter 200 mm, width 50 mm and thickness 20 mm) moved 10 000 times forwards and backwards on the fixed specimen. Vertical position of the loaded wheel was measured automatically and recorded in data acquisition system. The wheel tracking slope was calculated:

$$WTS_{AIR} = \frac{\left(d_{10000} - d_{5000}\right)}{5}, \quad (4)$$

where $WTS_{AIR}$ – wheel tracking slope in mm per $10^3$ load cycles; $d_{5000}$, $d_{10000}$ – rut depth after 5000 load cycles and 10 000 load cycles, mm.

The result of the test was determined as the average $WTS_{AIR}$ of two specimens. Proportional rut depth for material $PRD_{AIR}$ (in %) was calculated from the rut depth $RD_{AIR}$ (in mm) at 10 000 load cycles and specimen thickness.

**Fig. 4.** Apparatus used for triaxial cyclic compression test

## 4. Experimental measuring

Tested mixtures were asphalt concrete AC 11 with styrene-butadiene-styrene (SBS) polymer modified bitumen PmB 45/80-75 from batch plants. All mixtures fulfilled requirements defined in *EN 13108-1:2006* and complementary Slovak criteria (*KLAZ 1/2010 Katalógové listy asfaltových zmesí* [*Catalogue Sheets of Asphalts*] (*in Slovak*)). The aggregate gradation and the bitumen content of eight tested mixtures are given in Table 2.

**Table 2.** Aggregate gradation and asphalt content of tested mixtures

| Sieve size, mm | Unit | Gradation of AC 11 mixtures passing, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Limits |
| 16 | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 11.2 | | 96.8 | 98.2 | 97.0 | 97.4 | 97.3 | 97.0 | 95.5 | 95.6 | 90–100 |
| 4 | | 46.7 | 52.7 | 46.8 | 48.2 | 55.0 | 50.6 | 49.8 | 49.7 | 45–67 |
| 2 | | 32.2 | 34.6 | 33.5 | 33.0 | 35.9 | 33.0 | 33.0 | 33.5 | 25–50 |
| 0.50 | | 13.0 | 15.3 | 16.0 | 16.1 | 17.4 | 15.8 | 15.9 | 17.1 | 10–33 |
| 0.063 | | 6.5 | 6.8 | 7.9 | 7.5 | 7.1 | 7.2 | 7.0 | 8.2 | 4–11 |
| Bitumen content, | % | 5.74 | 5.66 | 5.70 | 5.70 | 5.70 | 5.70 | 5.70 | 5.70 | min 5.40 |
| Bulk density, | $g \cdot cm^{-3}$ | 2.306 | 2.373 | 2.354 | 2.397 | 2.379 | 2.370 | 2.391 | 2.382 | – |
| Air void content, | % | – | – | 2.70 | 2.90 | 3.10 | 3.00 | 3.20 | 3.00 | 2.50–4.00 |

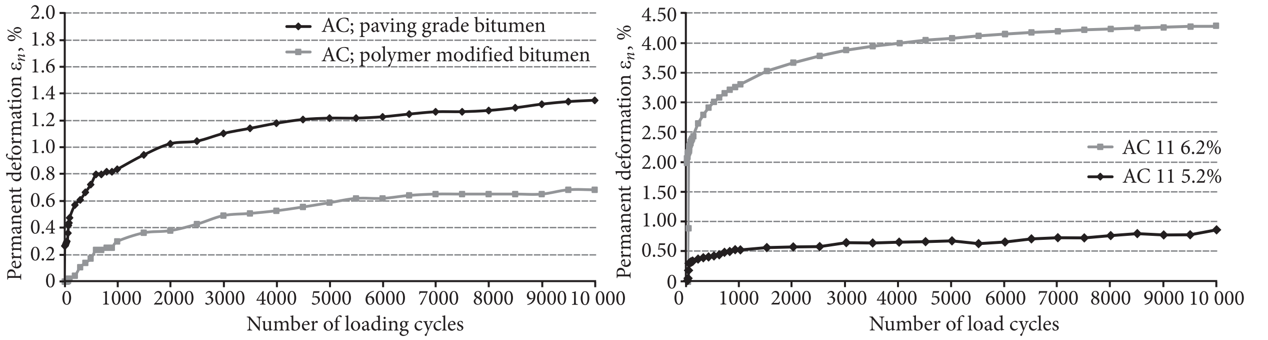


**Fig. 5.** The creep curve of AC 11 with different binder type – left and different binder content – right (Bežilla *et al.* 2009; Komačka *et al.* 2011)

The tested mixtures have been produced in batch plants in Slovakia and the materials (course and fine aggregates and binders) for production of AC 11 mixture to wearing course of pavement with higher traffic load had to satisfy requirements according to Slovakia regulations: geometrical requirements (grading – Gc90/15, shape index – $SI_{20}$, flakiness index – $FI_{20}$, fines content – $f_1$ for coarse and $f_{10}$ for fine aggregate), physical requirements (resistance to wear – $LA_{25}$, water absorption – $WA_{24}1$ for coarse and $WA_{24}2$ for fine aggregates) and durability (magnesium sulphate soundness – $MS_{18}$).

From previous experimental measuring (Bežilla *et al.* 2009) the assumption of better results of resistance to permanent deformation of modified bitumen versus paving grade bitumen was verified and confirmed. And in the same way the increase in the content of binder decreases the resistance to permanent deformation of the mixture (Fig. 5).

The achieved results of the creep rate $f_c$ and parameter $WTS_{AIR}$ of eight tested mixtures of asphalt concrete AC 11 are displayed in Fig. 6. The values of parameter $WTS_{AIR}$ are within the range 0.03 mm/1000 load cycles and 0.06 mm/1000 load cycles (limit value for this type of mixture is 0.07 mm/1000 load cycles), parameter $PRD_{AIR}$ in the range 2.9% and 4.6% (limit is 5.0%) and the values of a parameter $f_c$ are within the range 0.05 and 0.16 and belong to the category $f_{cmax0.2}$ defined in *EN 13108-1:2006*. The practical experiences with carrying out the triaxial cyclic compression test (with the test conditions according to *EN 13108-20:2008*) point to worse distinguishing of asphalt mixtures with different resistance to the permanent deformation (Manthos 2009; Zdřálek, Hýzl 2009). The main reason is the higher confining pressure which creates a stiff pressure cover round the test specimen restraining the shear stress.

Tested mixtures of the asphalt concrete AC 11 were with the same type of PmB bitumen and with more or less the same bitumen content (5.66% to 5.74%) even though different results of $f_c$ were obtained.

During detailed investigation there were small differences in aggregate gradation (Fig. 7). Aggregate forms 95% of mixture and the aggregate gradation is a dominant factor that influences mixture stability. The changes in

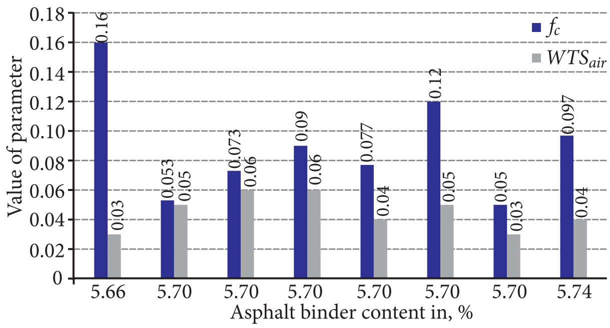


**Fig. 6.** Comparison of results of cyclic compression test $f_c$ and wheel tracking test $WTS_{air}$ of tested mixtures AC 11

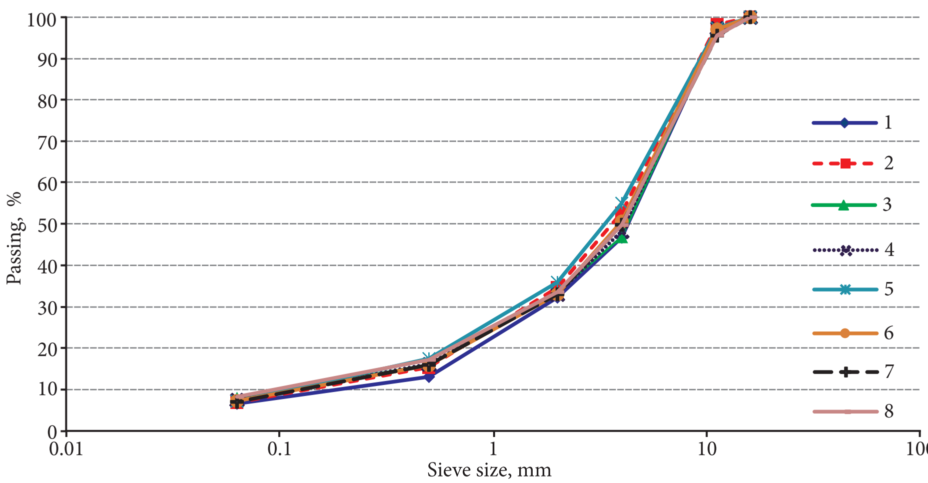


**Fig. 7.** Aggregate gradation of tested mixtures AC 11

**Table 3.** Aggregate surface area and calculated bitumen film thickness of tested mixtures

| Property | Mixtures AC 11 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Surface area, $m^2$/kg | 10.779 | 11.423 | 12.787 | 12.354 | 12.076 | 11.986 | 11.722 | 13.346 |
| Theoretical bitumen film thickness, μm | 5.649 | 5.252 | 4.727 | 4.893 | 5.005 | 5.043 | 5.157 | 4.529 |

gradation make a change of aggregate specific surface (surface area) and the mixture needs different bitumen content to coat and join the aggregate particles.

The thicker asphalt binder films produced mixes which were flexible and durable, while thin films produced mixes which were brittle, tended to crack and ravel excessively, retarded pavement performance and reduced its useful service life (Hmoud 2011).

Various studies have shown that the asphalt mix durability is directly related to film thickness (Kandhal *et al.* 1998). It is recommended that minimum average asphalt film thickness be used to ensure mix durability not only minimum VMA requirement adopted in the Superpave mix design procedure.

Radovskiy (2003) has noted that the thickness of asphalt film is not only a function of asphalt content, but also a function of compaction. As the grains of aggregate come closer together during compaction, the binder comes out of the contact zone.

Generally the specific surface (surface area of aggregates) is determined empirically using surface area factors and gradation of aggregate. *The Shell Bitumen Handbook* of 2003 notes that Hveem calculated surface factors by assuming a spherical particle shape and a specific gravity of 2.650 g.cm$^{-3}$. In Slovakia the aggregate surface area e is calculated by multiplying the total mass of specified fraction expressed as a percentage passing each sieve size by appropriate factor and adding the results together (according to *STN 73 6160:2009 Skúšanie asfaltových zmesí a vrstiev* [Testing of Asphalt Mixtures and Courses] (in Slovak)):

$$\varepsilon = 0.01(0.174G + 0.40g + 2.30S + 15.33s + 140f), \quad (5)$$

where $G$ – the aggregate percentage retained 8 mm sieve by mass, %; $g$ – the aggregate percentage retained 4 mm sieve by mass, %; $S$ – the aggregate percentage retained 0.25 mm sieve by mass, %; $s$ – the aggregate percentage retained 0.063 mm sieve by mass, %; $f$ – the percentage passing the sieve 0.063 mm, %.

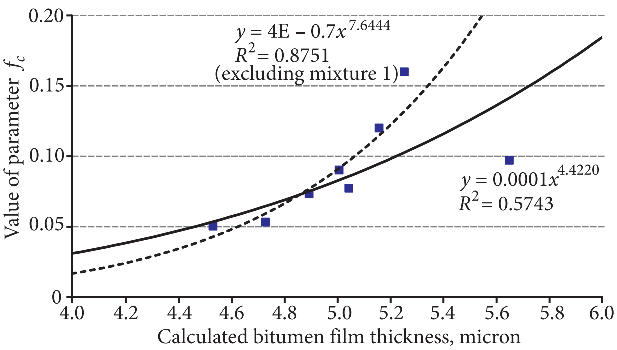


**Fig. 8.** Relation between theoretical bitumen film thickness and results of permanent deformation resistance of AC 11

The aggregate surface is important since it affects the amount of bitumen needed to coat the aggregate. Asphalts that have high surface area and low bitumen content are undesirable because these mixes will have a thin bitumen film on aggregate and will probably have not enough durability. Theoretical bitumen film thickness is calculated from specific surface area and effective bitumen content in mixture according to *The Shell Bitumen Handbook* of 2003 (Eq (6)):

$$T = \frac{b}{100-b} \cdot \frac{1}{\rho_b} \cdot \frac{1}{SA}, \quad (6)$$

where $T$ – the bitumen film thickness, mm; $b$ – the effective bitumen content in mixture, %; $\rho_b$ – the density of bitumen, kg/m$^3$; $SA$ – the aggregate specific surface (surface area $SA = \varepsilon$ according to *STN 73 6160:2009*), m$^2$/kg.

The calculated surface area and theoretical bitumen film thickness of tested mixtures are showed in Table 3. Comparison of reached results of permanent deformation resistance with calculated film thickness is shown in Fig. 8.

The effective binder thickness depends on the asphalt density and the porosity of aggregate. The aggregate porosity is usually expressed by water absorption as a weight percentage of fully saturated voids to dry rock. The pore size and pore size distribution to which the binder penetrates decreases the asphalt film thickness. The tested mixes were from different batch plants without specific knowledge about the properties of aggregate used. To express the effective binder content it is necessary to know the effective bulk density of aggregate which was not determined. The requirements in Slovak Republic allow using only aggregate with maximum 1% absorption that minimises an amount of absorbed binder in the aggregate.

When measuring the resistance to permanent deformation it was observed that a relation between aggregate surface area and bitumen film thickness and permanent deformation exists. With higher bitumen content the film thickness increases and the aggregate particles are not enough close to make stone-on-stone contact and strength structure and the resistance to permanent deformation of mixture decreases. Exceptional results were represented by Mixture 1 that had greater calculated bitumen film thickness. From all tested mixtures the Mixture 1 had more coarse particle size distribution and the least content of fine particles (6.5%), thus, with lower aggregate surface area (calculated by appropriate factors) and bitumen content (5.74%) the calculated theoretical bitumen film thickness is larger. But the less surface area of aggregate and mainly the coarse aggregate skeleton resulted in better resistances to rutting.

To confirm conclusions the measurements of asphalt film thickness and the comparison of the calculated theoretical film thickness with the results of film thickness measurements of specific mixture are necessary.

## 5. Conclusions

The evaluation of the asphalt mixtures resistance to permanent deformation by triaxial cyclic compression test is a part of functional performance design of asphalt concrete. The triaxial cyclic compression test method simulates the real stress and tenseness in pavement layers. Eight mixtures of asphalt concrete AC 11 were tested to a resistance to permanent deformation and the reached results were evaluated by next conclusions.

1. The measurements of permanent deformation resistance of asphalts showed the effect of aggregate gradation and bitumen content on the results. The tested mixtures of AC 11 with relatively small differences in aggregate gradation and the same bitumen content had different results.

2. Bitumen film thickness in relation to surface area and bitumen content effects resistance results the parameter $f_c$. With increasing bitumen film thickness there is insufficient interlocking of aggregate and the mixture is unresistant to permanent deformation.

3. The permanent deformation results of all tested mixtures AC 11 belong to the category the maximum creep rate $f_{c\max0.2}$.

4. The interpretation of variance values $f_c$ within 0.05 and 0.16 is possible by aggregate gradation. The differences in gradation make a change in aggregate specific surface. With regard to the used binder content in tested mixtures the theoretical bitumen film thickness were calculated. The mixtures with thicker film thickness had higher creep rate and thus less resistance to permanent deformation.

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