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DEPENDENCE OF THE RECYCLED ASPHALT MIXTURE PHYSICAL AND MECHANICAL PROPERTIES ON THE GRADE AND AMOUNT OF REJUVENATING BITUMEN

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Abstract. Due to destructive factors (traffic loads, climatic and weather conditions, improper exploitation materials), bitumen properties irreversibly change in unservicable asphalt concrete. Due to irreversible processes of oxidation the aged bitumen stiffens, its physiochemical properties, ductility, adhesion and cohesion as well as sectional composition (relative amounts of asphaltenes, oils and resins) change. Bitumen in the reclaimed asphalt pavement (RAP) may be restored to properties approximate to those of the virgin bitumen by adding the following rejuvenators: softening or rejuvenating agents as well as soft bitumen. The article presents the experimental data on RAP obtained from laboratory tests conducted with Marshall specimens without additives when RAP was supplemented by different types of virgin road bitumen, the paving grade of which was 50/70, 70/100, 100/150, 160/220, respectively. The content of newly added binder of all types to RAP was 0.5%, 1.0%, 1.5%, 2.0%, and 50/70 in addition and 4.0% and 6.0% of RAP mass. The total bitumen content increased by the same percentage amount in the reclaimed asphalt, which was not always optimal. Marshall specimens were formed with these bitumen contents, the tests of which enabled to identify stability (S), flow (F), Marshall quotient (S/F), air voids content (V_m), bulk density (SDD – $\rho_{b\ SD}$) of asphalt concrete samples and the maximum density of asphalt. Having extracted all RAP and reclaimed asphalt samples according to the differential method, the factual content of soluble binder in them and its penetration, softening point, Fraass breaking point, ductility and penetration index Ip were calculated. The dependences of the reclaimed asphalt physical and mechanical parameters on the virgin rejuvenating bitumen grade and its added percentage amount were obtained. Data analysis and their generalization was conducted.

Keywords: reclaimed asphalt pavement (RAP), recycling, bitumen, aging, hot mix asphalt (HMA), rejuvenating, properties, Marshall testing, film interaction, diffusion.

1. Introduction

Hot mix asphalt (HMA) (called "asphalt" outside the United States) is typically a mixture of approx 5% liquid asphalt binder (i.e., asphalt cement, called, "bitumen" outside the United States) and 95% solid aggregate (e.g., crushed stone, gravel, sand, or reclaimed asphalt pavement). In HMA, both liquid asphalt binder and aggregate are heated prior to mixing (hence, the name "hot mix") (Mundt *et al.* 2009).

Asphalt industry faces continuing pressure to optimize the use of available resources as material and transport costs both escalate with fuel prices. The use of locally available materials reduces the energy required to move large quantities at long distances, and the use of recycled asphalt pavement reduces both the quantity of aggregate and the quantity of asphalt required (Bennert, Dongré 2010).

The pavement recycling method, mixture design guidelines and construction practices are well established for hot mix recycling of asphalt concrete pavements (Cohen *et al.* 1989).

In Lithuania as well as other countries, the material of the used asphalt pavement is hot-recycled in place or in-plant (Karlsson, Isacsson 2006; Mučinis *et al.* 2009; Sivilevičius 2011b). The interest in asphalt recycling increased in 1970s because of the petroleum crisis and the development of a large scale milling machine in 1975 (Carter, Stroup-Gardiner 2007).

In case of in-plant asphalt recycling, the upper layer of the reclaimed asphalt pavement (RAP) is milled and the obtained granules are mixed with virgin materials. For that purpose, additional technological equipment for intaking, transporting and dosing RAP, which increase asphalt

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mixing plant (AMP) technological versatility and complex quality indicator *K,* shall be mounted in an AMP (Sivilevičius 2011a). RAP is supplemented by such amount of virgin aggregates and bitumen binder or binder only, which enables to obtain HMA mixture with similar properties as that produced from virgin materials. Design methods of HMA mixtures with the optimal composition of RAP (McDaniel, Anderson 2001; Vislavičius, Sivilevičius 2010; Sivilevičius, Vislavičius 2008) enable to select such maximum permitted RAP content which guarantees rather high properties of the recycled HMA mixture.

The supplementation of the produced HMA mixture with the granules of RAP saves expensive virgin aggregates and bitumen binder, improves environmental protection, reduces power consumption (Alkins *et al*. 2008). Recycling of the existing asphalt pavement materials produces new pavements with considerable savings in material, cost and energy. Furthermore, mixtures containing RAP as well as virgin mixtures were obtained (Xiao, Amirkhanian 2009). However, frequently the technological processes of the design and production of the recycled HMA mixture are more complicated than the processes of design and production of conventional HMA mixtures (Aravind, Das 2007; Bražiūnas, Sivilevičius 2010; Sivilevičius, Šukevičius 2009; Sivilevičius *et al*. 2011).

The properties of asphalt concrete aggregates slightly change in the RAP due to possible crushing. Asphalt binders get stiffer and more brittle with age. Bitumen binder properties change due to irreversible oxidation processes, influencing on its aging, as well as due to the changes in its chemical composition. To slow down bitumen age–hardening, Apeagyei (2011) recommends to use antioxidants investigated in a laboratory. Since aging per se is not a measurable property, the net changes in the chemical and physical properties due to aging have been used to measure the extent of aging by many investigators. As previously noted, the aging index can be computed based on any asphalt (bitumen) property that changes with aging (Apeagyei 2011).

Aging mainly leads to increased stiffness but also brings about changes in physicochemical properties, such as ductility and adhesion. Generally, aging influences binder performance and consequently the asphalt mixture. The main mechanisms related to bitumen aging are oxidation, evaporation, exudation and physical hardening (Karlsson, Isacsson 2006).

Due to age-hardening (temperature cycles, wetting-drying, ultra-violet and traffic loading) or due to extreme cold weather conditions, the stiffness of the binder increases, the relaxation capacity decreases, the binder becomes more brittle, the self-healing potential and fracture resistance of the bitumen decreases, and cracking of the interface between aggregates and the binder occurs (Liu *et al*. 2010).

Chemical reactions take place inside asphalt when it is exposed to heat, air (oxygen), light or other environmental physical actions. Oxidation causes the oils to convert to resins and the resins to asphaltenes (Noureldin, Wood 1989).

Investigation (Cheng *et al*. 2002) shows the aging effect on the surface energy of the same asphalt. Aging can significantly affect the surface energy characteristics of the asphalt. The adhesive strength depends not only on the surface energy of asphalt but also on the surface energy of aggregate.

Asphalt concrete mixture is susceptible to distresses of rutting (permanent deformation), stripping (separation of asphalts from aggregates), and cracking, etc. (Xu *et al*. 2010).

Research (Widyatmoko 2008) demonstrates that the asphalt mixtures containing RAP performed at least similar to, or better than, those of conventional asphalt materials. The fatigue resistance of the recycled mixtures appears to be at least similar to or better than that of the control mixtures without RAP. The fatigue performance appears to improve with increasing proportions rejuvenating binder in the mixture (consequently, at higher RAP contents). The mixtures containing RAP were not sensitive to moisture induced damage overall (Widyatmoko 2008).

The inclusions of RAP into HMA mixtures in Shu *et al.* (2007) study generally increased the tensile strength and reduced the post–failure tenacity in indirect tensile strength test. The inclusions of RAP also generally decreased the dissipated creep strain energy threshold and energy ratio, which may result in the short fatigue life of HMA mixtures.

The laboratory tests (Tabakovič *et al*. 2010) have shown that the introduction of RAP to the binder course mix resulted in an improvement in all mechanical properties. In particular, it was found out that the mix containing up to 30% RAP displayed improved fatigue resistance relative to the control mix manufactured from virgin materials. Higher RAP contents lead to increased stiffness, as shown by the results (Valdés *et al.* 2011) for stiffness modulus, dynamic modulus and tensile stiffness index IRT.

The effect of moisture content and dry density on the resilient behavior of RAP was identical to a typical granular material. RAP is expected to have higher resilient modulus than a typical granular material if it was properly compacted and good drainage system was provided (Attia, Abdelrahman 2010).

The rejuvenator percentage affected greatly the performance-based properties of the blend of aged binder and the rejuvenator (Shen *et al*. 2007a; 2007b). The rutting resistance parameters decreased, while the fatigue resistance parameters and the shrinkage parameters improved as the rejuvenator percentage increased.

The grade and optimal amount of a suitable rejuvenator depend on the composition and properties of RAP, especially on the properties of the aged bitumen, which may be identified in experimental investigations conducted in a laboratory. The aim of this study is to identify the impact of the grade and the percentage amount of the rejuvenating virgin bitumen on the properties of the recycled bitumen and physical and mechanical parameters of Marshall's specimens formed from RAP with the rejuvenator.

2. Theoretical penetration of the bitumen mixed of two grades

The primary function of bitumen is to act as an adhesive (Read, Whiteoak 2003). Due to vehicles' loads and environmental factors, which speed up oxidation and other irreversible physicochemical processes in films coating particles, stiffen the aged bitumen contained in RAP, which becomes hard (non plastic) and brittle. Processes occurring in bitumen at the molecular level change the properties of asphalt concrete, which increases mechanical strength and later causes cracking.

Adsorption layers of the aged bitumen directly interacting with the particles of aggregates have one advantage: its (bitumen's) molecules are less agile than the molecules of loose bitumen. The content of asphaltenes increases in bitumen (up to 37–45%); the content of resins reduces and that of paraffin-naphthene hydrocarbons increases. The results (Firoozifar *et al.* 2011) showed that increasing the asphaltene content in bitumen decreases its thermal stability, while increase the resistance of samples to thermal decomposition after IDT.

Aging increases the Lifshitz-van der Walls component and decreases the acid-based component. Thus, the healing ability of the binder should drop because of the aging of the binder (Cheng *et al.* 2002).

Bitumen aging in asphalt concrete occurs according to the same mechanism as in loose bitumen, although there are certain peculiarities influenced by aggregates in asphalt concrete. Molecules of adsorption layers of bitumen are less agile than the molecules of loose bitumen, which reduces its reaction capacity.

Aging of the road asphalt concrete may be described as the increase of its brittleness temperature influenced by weather and climatic factors as well as fatigue due to vehicle loads. Provided the change of asphalt concrete brittleness temperature is known, when it is influenced by the factors mentioned above, crack propagation kinetics of the used road pavement may be predicted.

One major thrust of Witczak and Fonseca (1996) research has been to show the influence of short – and long-term aging on original asphalt cement binder viscosity – temperature relationship. By using field data and considering the basic consistency characteristics of asphalt binders, Witczak (2005) developed models for both aging effects. These models are based on the fact that most asphalt cements exhibit a linear relationship when a loglog viscosity (η), in units of centipoises, versus log temperature (T_R in degrees Rankine) plot is drawn (Bonaquist, Christensen 2005):

$$\log\log\eta = A + VTS\log T_R, \tag{1}$$

where A and VTS – regression constants reflecting the specific type of asphalt cement and aging conditions of the material.

The performance of an asphaltic pavement structure is significantly influenced by the modulus of asphalt layers. In general, the modulus is effected by the mix characteristics, rate of loading, and local environmental conditions (Witczak, Fonseca 1996). By incorporating recent field studies on the aged viscosity of conventional asphalt cements, a revised model for the dynamic modulus of asphalt mixtures has been developed using the actual bitumen viscosity as the most important predictor variable in place temperature. The final dynamic modulus model developed from statistical study was (Witczak, Fonseca 1996).

$$\begin{gathered}\log E = -0.261 + 0.008225 p_{200} - 0.00000101(p_{200})^2 + \\ 0.00196 p_4 - 0.03157 V_a - 0.415\frac{V_{beff}}{(V_{beff}+V_a)} + \\ \frac{\left[1.87 + 0.002808 p_4 + 0.0000404 p_{38} - 0.0001786(p_{38})^2 + 0.0164 p_{34}\right]}{1+e^{(-0.716\log f - 0.7425\log\eta)}},\end{gathered} \tag{2}$$

where E – asphalt mix dynamic modulus, 10^5 psi; η – bitumen viscosity, 10^6 poise (at any temperature, degree of aging); f – load frequency, Hz; V_a – percent of air voids in the mix, by volume; V_{beff} – percent of effective bitumen content, by volume; p_{34} – percent retained on 3/4 – in sieve, by total aggregate weight (cumulative); p_{38}– percent retained on 3/8 – in sieve, by total aggregate weight (cumulative); p_4 – percent retained on No. 4 sieve, by total aggregate weight (cumulative); p_{200} – percent passing No. 200 sieve, by total aggregate weight.

The effective asphalt binder properties indicate (Bennert, Dongré 2010) a stiffening of the „effective" asphalt binder properties at 15% and 20% RAP content mixes. At 25% RAP content, the stiffening seems to descrease to dynamic modulus values similar to the 15% RAP and phase angle values similar to the 0% RAP.

The tension and compression dynamic modulus and the compression creep compliance master curves for a control mixture and mixtures containing 15%, 25% and 40% processed RAP were presented and discussed by Daniel and Lachance (2005). The addition of 15% RAP increased the stiffness of the mixture and decreased the compliance, as would be expected. This indicates that the mixture containing RAP will be more resistant to permanent deformation and less resistant to fatigue and thermal cracking in the field.

Masad *et al.* (2008) presents the analysis of nonlinear viscoelastic behavior of unaged and aged asphalt binders tested using a dynamic shear rheometer (DSR) at several temperatures and frequencies. The authors came to the conclusion that the long-term response of the binder can be obtained by conducting short-term tests at multiple stress levels.

The properties of the old bitumen shall be restored in the asphalt pavement recycling process. For that purpose it is recommended to use the fresh road bitumen of more liquid types, which are selected according to the penetration of the aged bitumen contained in RAP.

When virgin aggregates are not added in the asphalt recycling process, virgin bitumen or another rejuvenating agent is placed into the hot mixed RAP mixture (Fig. 1). Due to adhesion larger than cohesion the virgin bitumen gradually turns from bulk condition into films coating RAP particles. The homogeneity of its films depends on the duration of its mixing process, and its thickness depends on the percentage amount of the input virgin new bitumen.

The grade of the virgin bitumen binding material is identified according to the following penetration dependence equation:

$$Pen_{25R} = Pen_{25A}^{a} \times Pen_{25V}^{b} \quad (3)$$

or

$$Pen_{25R} = 10^{\frac{a \log Pen_{25A} + b \log Pen_{25V}}{100}}, \quad (4)$$

where Pen_{25R} – penetration of recycled (summed, composite) bitumen at the temperature of 25 °C, needle sticking depth of 0.1 mm; Pen_{25A} – penetration of soluble part of the aged bitumen contained in RAP at the temperature of 25 °C, needle sticking depth of 0.1 mm; Pen_{25V} – virgin bitumen penetration at the temperature of 25 °C, needle sticking depth of 0.1 mm; *a, b* – part of the aged and virgin bitumen in recycled (complex) bitumen ($a + b = 1$).

It is convenient to estimate penetration Pen_{25R} of the recycled bitumen from a nomogram.

Required penetration Pen_{25V} of the virgin (rejuvenating) bitumen is calculated according to the following Eq (5):

$$Pen_{25V} = \left(\frac{Pen_{25R}}{Pen_{25A}^{a}} \right)^{\frac{1}{b}}. \quad (5)$$

If the aged bitumen is recycled by mixing it with the virgin viscous or cut-back road bitumen, the amount of the aged bitumen *a* in the mixture of both bitumen (recycled bitumen) is calculated according to the following Eq (6):

$$a = 1 - b = \frac{\log Pen_{25V} - \log Pen_{25R}}{\log Pen_{25V} - \log Pen_{25A}}, \quad (6)$$

where *a* – amount of the aged bitumen in the recycled bitumen in unit parts; *b* – the amount of the virgin (rejuvenating) bitumen in the recycled bitumen in unit parts ($a + b = 1$).

The properties of the bitumen, which results from the blend of the aged bitumen, present in the reclaimed material, with the new bitumen are estimated by the following Eq (7) (Pereira *et al.* 2004).

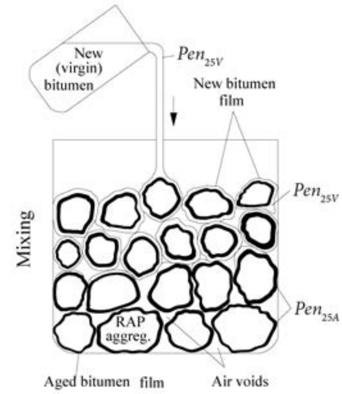

Fig. 1. Conversion of the virgin bitumen from bulk condition into films coating RAP particles in the beginning of the mixing process

$$\log Pen_{25FB} = R_R \frac{P_{RB}}{P_{FB}} \log Pen_{25RB} + \left(1 + R_R \frac{P_{RB}}{P_{FB}} \right) \log Pen_{25NB}, \quad (7)$$

$$P_{NB} = P_{FB} - R_R P_{RB}, \quad (8)$$

where R_R – recycling ratio; P_{RB} – percentage of bitumen in the reclaimed bituminous material (RBM); P_{FB} –percentage of bitumen in the final mixture; P_{NB} –percentage of virgin bitumen added; Pen_{25FB} – penetration value at the temperature of 25 °C for the blended bitumen; Pen_{25RB} – penetration value at the temperature of 25 °C for the recycled bitumen from the RBM (aged bitumen); and Pen_{25NB} – penetration value at the temperature of 25 °C for the virgin bitumen.

The proportion between the virgin and aged binder can be estimated by using viscosity mixing rule (Aravind, Das 2007) as follows, so that the resultant mix achieves the target viscosity at the reference temperature:

$$\ln(\eta_t) = p_{ob} \ln(\eta_0) + p_{nb} \ln \eta_n, \quad (9)$$

where η_t, η_0, η_n– represent viscosity of target mix, aged and virgin binder at the reference temperature, respectively; p_{ob}, p_{nb} – represent fraction of aged and virgin binder, respectively (i. e. $p_{ob} + p_{nb} = 1$).

The quantity of rejuvenating binder to be added to the trial mixes of the recycled mixture, was calculated as follows (Kandhal, Mallic 1997; Widyatmoko 2008):

$$P_{nb} = \frac{(100^2 - rP_{sb})P_b}{100(100 - P_{sb})} - \frac{(100 - r)P_{sb}}{100 - P_{sb}}, \quad (10)$$

where P_{nb} – the percent of virgin bitumen (rejuvenating binder, plus recycling agent, if used) in the recycled mixture; r – the new aggregate expressed as a percent of the total aggregate in the recycled mixture; P_{sb} – the percent, bitumen content of RAP; P_b – the percent, bitumen content of total recycled asphalt mixture or asphalt demand, determined by empirical formula above.

The approximate bitumen demand of the combined aggregates of the target wearing course and base course mixtures containing RAP were calculated from the Eq (11) (Doh *et at*. 2008; Kandhal, Mallic 1997):

$$P_b = 0.035P_{CA} + 0.045P_{FA} + K \times P_{MF} + F, \qquad (11)$$

where P_b – the approximate total bitumen demand of recycled mixture, percent by weight of mixture; P_{CA} – the percent of mineral aggregate retained on 2.36 mm sieve (coarse aggregate); P_{FA} – the percent of mineral aggregate passing the 2.36 mm sieve and retained the 75 μm (0.075 mm) sieve (fine aggregate); P_{MF} – the percent of mineral aggregate passing 75μm sieve (mineral filler); K – the 0.15 for 11–15% passing 75 μm sieve, 0.18 for 6–10% passing 75 μm sieve, 0.20 for 5% or less passing 75 μm sieve; F – the 0–2.0%, based on absorption of light or heavy aggregate. In the absence of other data, a value of 0.7% is suggested.

Having mixed RAP with the virgin binder mechanically, it is important that aged and virgin bitumen homogeneously distributed in reclaimed films and completely blended.

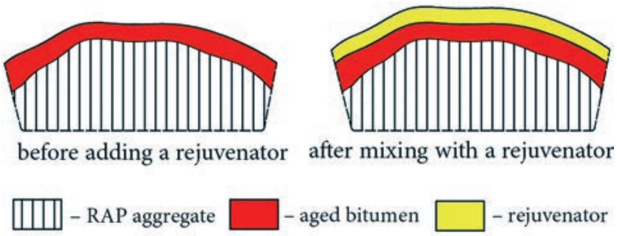

Fig. 2. Structure of a bitumen film coating a mineral particle of the reclaimed asphalt pavement mixture

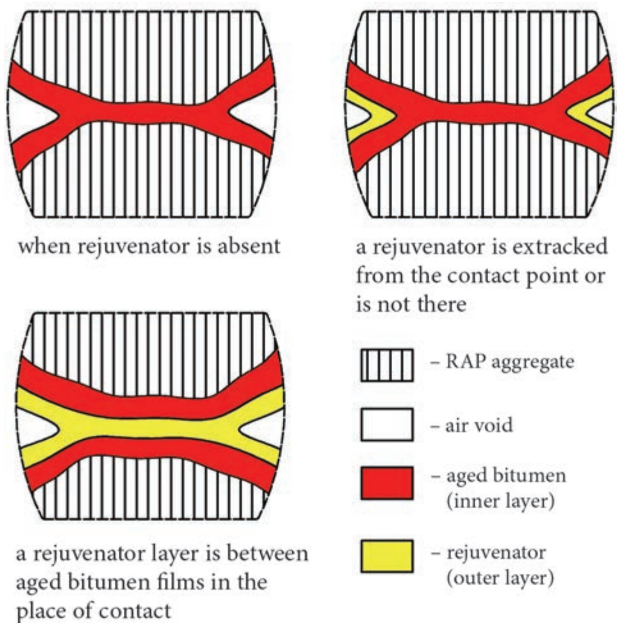

Fig. 3. The structure of the bitumen film in the place of the contact of two adjacent particles in the RAP

3. Blending of aged and virgin bitumen layers in a recycled film

In hot in-plant or in-place asphalt recycling operations virgin binder and aggregate are mixed with RAP. The virgin binder should be a rejuvenator or soft bitumen in order to achieve a final mix of virgin and aged binder showing acceptable consistency (Karlsson, Isacsson 2006).

When RAP is mixed with virgin aggregates and virgin binder, partial blending of RAP binder occurs in the HMA. Agencies limit the amount of RAP because the degree of blending between the RAP and the virgin materials is not known (Shirodkar *et al.* 2011).

The first laboratory investigations of diffusion of a rejuvenator into an aged binder were performed by Carpenter and Wolosick (1980).

Asphalt is considered a combination of asphaltenes, resins, and oils. Many other fractional classifications have been reported about asphalt composition. Asphaltenes are moreviscous than the resins and oils, respectively (Noureldin, Wood 1989).

Milled granules of the RAP contain under ten, over ten or several tens of particles, cemented with the aged bitumen. In hot recycling process water evaporates when granules are heated and mixed. When temperature rises, the aged bitumen which binds particles of RAP granules turns to viscous from stiff and finally becomes liquid, the reduced cohesion of which causes decomposure of granules. The adhesion between the asphalt and aggregate is higher than the cohesion within the binder at around room temperature (Cheng *et al.* 2002).

Loose RAP particles or whole granules are coated with the aged bitumen, which shall be rejuvenated. When a rejuvenator (or liquid virgin bitumen) is added or sprayed, it coats RAP particles with films of a certain thickness. Therefore, each RAP particle contains double coating: the inner layer coating the particle contains aged viscous bitumen and the outer layer detached from the particle contains a rejuvenator (virgin liquid bitumen) (Fig. 2).

Particles of non-compacted reclaimed HMA mixture touch each other and are not cemented into a strong conglomerate. Therefore, the aged bitumen is in the inner layer of the particle, and the rejuvenator is in the outer layer. When the reclaimed HMA mixture is laid and compacted, RAP particles interact with each other. It is only the film of the aged bitumen, the aged bitumen film with a rejuvenator extracted in the area of air voids or the rejuvenator layer separating two aged bitumen films (Fig. 3) that may be in the place of the contact between the two pressed particles of the compacted asphalt pavement layer.

When air voids occur among particles of the same size ball shape particles of the recycled HMA pavement, Carpenter and Wolosick (1980) presented the diffusion process of the rejuvenator into the aged bitumen films. Researchers proved that an air void is between two loose RAP particles, which are coated with the rejuvenator (outer layer) and the aged bitumen (inner layer) films, which in the course of time partially blend due to diffusion.

The data from the extraction (Carpenter, Wolosick 1980) clearly indicate that the outer and inner layers are not the same consistency for an appreciable time following mixing. The penetration at the temperature if 25 °C for each layer is plotted as a function of time after mixing (Fig. 4). The data clearly show the outer and inner layers to be approaching the same consistency, indicated by the penetration value of the rejuvenated sample. The long–term consistency is stiffer than that of the rejuvenated asphalt cement and indicates the hardening produced in the laboratory mixing procedure.

They hypothesized (Carpenter, Wolosick 1980) that the diffusion of rejuvenators into aged bitumen at asphalt recycling could be described in steps as follows. First, the rejuvenator forms a very low–viscosity layer that surrounds the aggregate, which is coated with very high–viscosity aged asphalt cement. Then, the rejuvenator begins to penetrate the aged asphalt cement layer, thereby decreasing the amount of new rejuvenator covering the bitumen–coated aggregate particles and softening the old bitumen. After a given time period, no raw rejuvenator remains, and the diffusion of the rejuvenator continues. Simultaneously, the viscosity of the inner layer (closest to the aggregate) is lowered, and the viscosity of the outer layer is increased (Karlsson, Isacsson 2006).

Laboratory investigation of diffusion of bitumen rejuvenators into old binders were performed by Carpenter and Wolosick (1980). They hypothesised that the modifier initially forms a very low viscosity layer that surrounds the aggregate, which is coated with very high viscosity aged asphalt cement. During and after recycling, the consistency of each layer should vary with time due to the diffusion process, finally reaching the same consistency, close to that of a mixture of rejuvenator and old binder of corresponding content (Karlsson, Isaccson 2003).

The objective of the present study (Huang *et al.* 2005) is to find out how much aged RAP asphalt binder will be blended into virgin asphalt binder under normal mixing conditions. And, if the composite layered system does exist, to find out how it will influence the performance of the HMA mixture. It can be envisioned that if the aged asphalt binder could not be fully blended with virgin asphalt or rejuvenating agent, it forms a layer coating the RAP aggregate. Owing to long–term aging, this layer is much stiffer than the virgin binder. Thus, a composite layered system exists in the RAP–virgin materials mixture. Such a composite structure would be favorable in reducing the stress concentration and potentially would enhance the performance of asphalt mixtures (Huang *et al.* 2005).

According to the theory of Королев (1986), the formation of the bitumen film starts when bitumen is mixed with mineral aggregates in the mixing process and completes when the asphalt mixture is laid or compacted, when it cools in the asphalt concrete pavement. The bitumen film on the surface of the particle is saturated with the high content of molecular weight made up of asphaltenes and resins. The average film thickness is not a measured physical property, but a parameter calculated from a materials volumetric characteristics and gradation (Li *et al.* 2009).

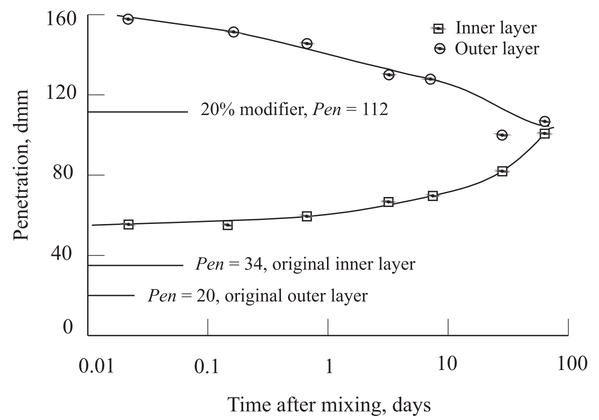

Fig. 4. Penetration of the outer and inner layers as a function of time (by Carpenter, Wolosick 1980)

Due to adsorption in a bitumen line layer, the bitumen structure changes due to the field of mineral aggregate surface forces. Due to the exposure to the zone of these forces the structure of bitumen changes. Following the principle of „relay effect“, its bulky molecular compounds make up chains perpendicular to the surface of a mineral particle. The strength of chain links reduces when receding from a particle. At the distance of a few micrometers it is practically equal to zero. Then bitumen acquires bulk properties. The carried out research (Королев 1984; 1986) enabled to distinguish three zones in an oriented bitumen layer, which are characterized by a typical structure and physical-mechanical properties. A stiff zone is next to the particle which contains a structured zone of asphaltenes. Furthest from the particle surface is a diffusion zone, where the concentration of asphaltenes decreases, and the concentration of aromatic hydrocarbons and paraffino-naphtene carbohydrates increases.

The aged bitumen film of the recycled asphalt contains layers (Fig. 5). Bitumen can be classified into four groups: asphaltens, resins, aromatics and saturates (Read, Whiteoak 2003). Asphalt is considered a combination of asphaltenes, resins and oils. Asphaltenes are more viscous than resins and oils, respectively (Noureldin, Wood 1989). The stiff zone at the particle surface contains asphaltenes, which is coated with viscous resin and oil. When RAP is mixed with a rejuvenator (virgin liquid bitumen), due to diffusion a rejuventor penetrates into the outer layer of the aged bitumen film. In the course of time, due to the interaction between both bitumen, part of their film is recycled, which thins and almost destroys the rejuventor layer. The aged bitumen layer is recycled into the stiff asphaltene zone.

The completion time of virgin and existing bitumen in RAP mixing depends on the bitumen properties (viscosity, chemical composition, thickness of films) and

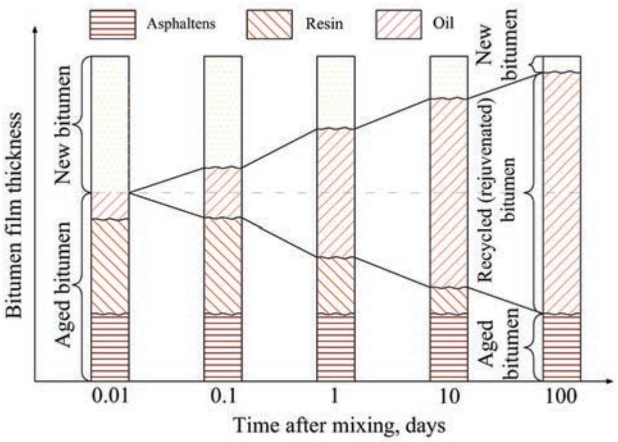

Fig. 5. The dynamic model of mixing the aged and virgin bitumen layers which coat the aged particle of the recycled asphalt

surrounding conditions (temperature, pressure). The dynamics of diffusion processes occurring in the aged bitumen and the rejuventor has not been investigated yet. Having speeded up the diffusion processes, recycling results could be obtained sooner.

4. Research methodology

RAP granules milled from the wearing course of several roads and city streets were stored in a warehouse for several months. To evaluate RAP component composition (bitumen and water amount, grading of mineral fillers), 43 samples, 40–50 kg each, were taken from random places of its pile. From all samples, poured into sacks, almost equal parts of RAP were taken, which represented all RAP stockpile. Having mixed and quartered them, 18 portions of equal composition, 6 kg each, were prepared. Each mixed sample of RAP was poured on the tray and heated until the temperature of 150 °C.

The first 6 trays with dried RAP were filled with hot (150 °C) road bitumen 50/70 0.5%, 1.0%, 1.5%, 2.0%, 4.0% and 6.0% of RAP mass. 7–10 trays were filled with road bitumen 70/100 0.5%, 1.0%, 1.5% and 2.0%. 11–14 trays with hot RAP were filled with road bitumen 100/150 (as well as 0.5%, 1.0%, 1.5 % and 2.0%). Trays with RAP No. 15–18 were used for recycling RAP with road bitumen 160/220, by adding 0.5%, 1.0%, 1.5% and 2.0% of it, respectively.

RAP mixtures with virgin bitumen binder of various grades and percentage amounts were thoroughly mixed in a laboratory mixing plant. 4 Marshall specimens were formed by an impact compactor from the recycled mixture prepared in each tray, by impacting it 50 times on both sides. Approx 1 200 g of the mixture were used to identify the max density and approxy 800 g of the mixture were used to identify the factual amount and grading of the recycled (rejuvenated) soluble binder content in bitumen.

Marshall stability (S), Marshall flow (F), bulk density (SSD – S_{bssd}), and Marshall quotient ($Q = S/F$) were estimated from 3 Marshall's specimens formed in each series (tray). Air voids content (V_m) was calculated as well.

Having carried out tests on the physical and mechanical properties of the recycled (of various grade and quantity of rejuvenating bitumen) asphalt mixture from all 18 series after extraction, soluble binder (bitumen with solvent) was extracted by a rotary evaporator, which was recycled (recovered asphalt cement), i. e. separated from a solvent (trichlorethylene). The following properties of the soluble recovered bitumen were identified: penetration (Pen_{25} 0.1 mm), softening point (T_{SP} °C), Fraass breaking point (T_{FBP} °C), ductility (D_{25} cm). Penetration index I_p was calculated according to the following formula (Read, Whiteoak 2003; Sengoz, Isikyakar 2008; Sengoz *et al.* 2009):

$$I_p = \frac{1952 - 500\log(Pen_{25}) - 20T_{SP}}{50\log(Pen_{25}) - T_{SP} - 120}, \tag{12}$$

where Pen_{25} – bitumen penetration according to the needle sticking depth of 0.1 mm at the temperature of 25 °C; T_{SP} – bitumen softening point, identified according to the ring and ball method, °C.

5. Properties of RAP mixture recycled with various grade and quantity of rejuvenating bitumen

The primary function of bitumen is to act as an adhesive. The adhesion characteristics of a bitumen are assessed by a retained Marshall test.

Having tested Marshall specimens produced from RAP and various grade and quanities of the rejuvenating virgin road bitumen in a laboratory according to the standard methodology, trends of the dynamics of physical and mechanical parameters were obtained (Fig. 6).

When the amount of virgin bitumen in RAP is increased, the stability, Marshall quotient and air void content of the mixture decrease, and the flow of the mixture increases. If the amount of the virgin bitumen in RAP mixture is the same, but grade designation of bitumen is different, the stability and Marshall quotient are higher in the RAP mixture with more viscous (higher penetration) rejuvenating bitumen. The flow increases when more liquid rejuvenating bitumen is added to RAP.

If bitumen penetration Pen_{25} increases from 30 dmm to 55 dmm, asphalt stability according Marshall reduces from 7–8 kN to 3.5 kN. If bitumen softening point T_{SP} is increased from 50 °C to 65 °C, asphalt stability according to Marshall increases from 3.5 kN to 7.5 kN, and the deformation caused by a wheel–tracking rate reduces from 5.0 mm/h to 0.8 mm/h (Read, Whiteoak 2003).

Similar trends could be pointed out from the data of investigation carried out in this study. As the aim of this laboratory investigation was not to identify the optimal amount of the recycled bitumen, virgin mineral aggregate was not added. When the percentage amount of the rejuvenator was increased in RAP mixture, the total amount of bitumen was frequently higher than optimal.

Having tested the produced Marshall specimens and extracted soluble bitumen from them, which is made up from aged and virgin bitumen, and having separated it from a solvent in a rotary evaporator, its properties were identified (Fig. 7). Penetration grade bitumens are specified by the penetration and softening point tests.

When the percentage amount of virgin bitumen of all grades is increased in RAP mixture, recycled bitumen penetration Pen_{25} increases (viscosity reduces), softening point T_{SP} and Fraass breaking point T_{FBP} decrease. The values of the calculated penetration index I_p also decrease and are positive, except those of bitumen, which was recycled with the rejuventor (virgin bitumen of grade 50/70), when 2.0% or more of it were added. Penetration index I_p of the rejuvenator of all grades was negative.

When bitumen penetration index I_p is increased from −1.5 to +1.5, the rut depth of pavement decreases according to concave curve from 10 mm to 5 mm, and when penetration index I_p is increased from −1.0 to +4.5, its relative deformation decreases from 1.2 to 0.2 (Read, Whiteoak 2003).

The data of previously conducted investigations (Mučinis *et al.* 2009) showed that RAP is heterogeneous: not only its grading varies within a wide range, but the quantity of the aged bitumen as well. RAP from the stockpile of the same warehouse was used in this experiment. To produce Marshall specimens, RAP sample units were mixed by homogenizing the mixture in the laboratory. However, absolute homogeneity of a sample of 18 RAP mixture samples was not obtained as amount A of the reclaimed soluble bitumen identified by extracting the mixture was not always the same as that of the aged and virgin rejuvenating bitumen sum B in RAP (Fig. 8).

In most cases, bitumen amount A extracted from Marshall specimens was less than the calculated pilot bitumen amount B (Fig. 8). The difference between A and B bitumen amounts increased when the amount of the rejuvenating bitumen added to RAP mixture was increased. In an ideal case, lines shall be horizontal.

6. Conclusions

1. An asphalt pavement layer deformed and deteriorated due to destructive factors of transport loads and weather conditions, may be recycled if HMA mixture, the properties of which are similar to those of HMA mixture produced only from virgin materials, is produced by adding rejuvenating agents or virgin aggregates. The most complicated task is to select a suitable rejuvenator or virgin bitumen grade and required percentage amount. The best results of recycling works can be achieved when RAP bitumen properties changed due to aging, rejuvenator's properties and its distribution around RAP mixture particles' films structure as well as factors influencing on the aged and virgin bitumen diffusion dynamics have been identified dependably and precisely.

2. Physical and mechanical parameters of Marshall specimens produced from RAP and various grade 50/70, 70/100, 100/150, 160/220 rejuvenating virgin bitumen in a laboratory show that when the viscosity of the added

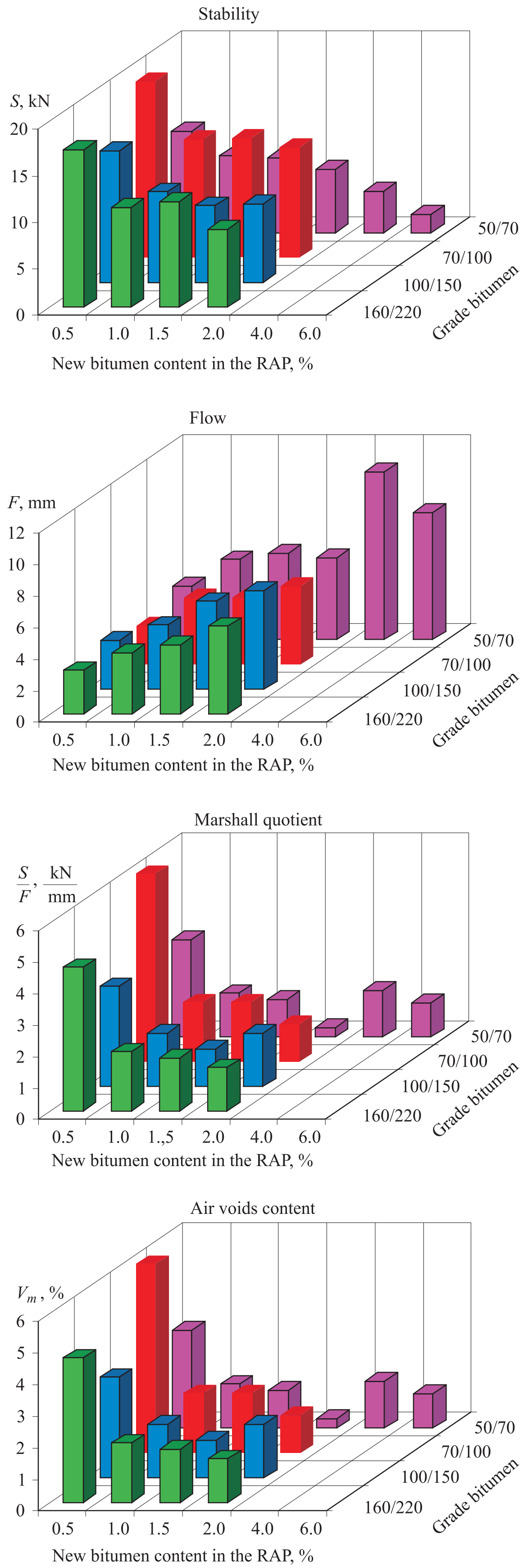

Fig. 6. Impact of various grade rejuvenating bitumen amount in RAP mixture on the physical and mechanical properties of Marshall specimens

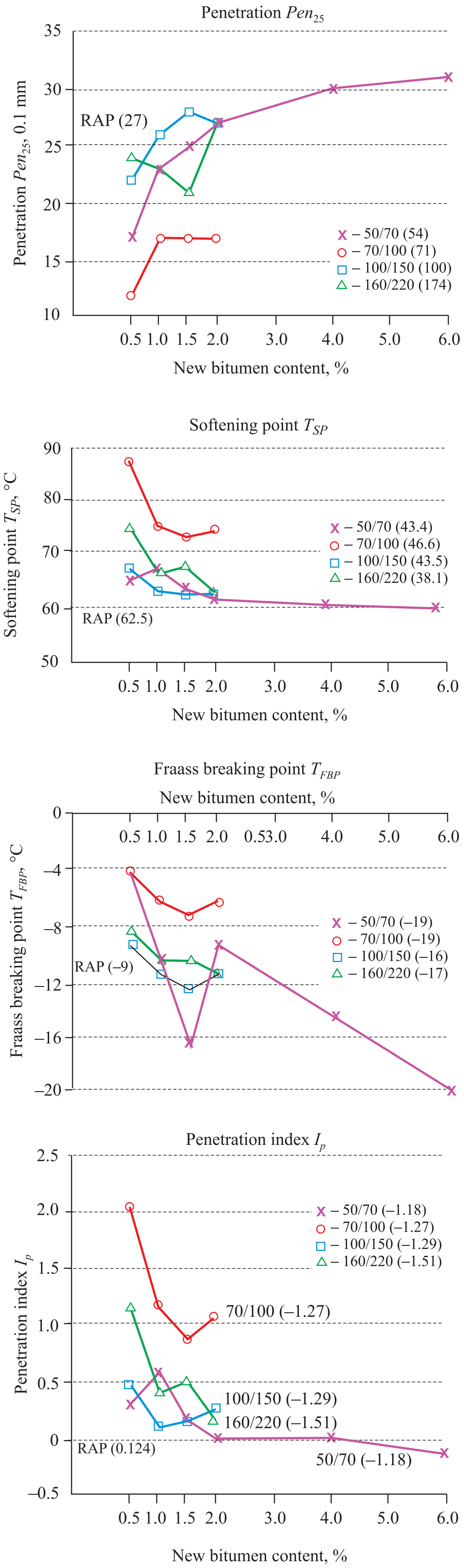

Fig. 7. Dependence of reclaimed (total) bitumen properties on the grade and percentage amount of the rejuvenator (virgin bitumen) in RAP mixture. RAP bitumen and rejuvenating bitumen properties are presented in brackets

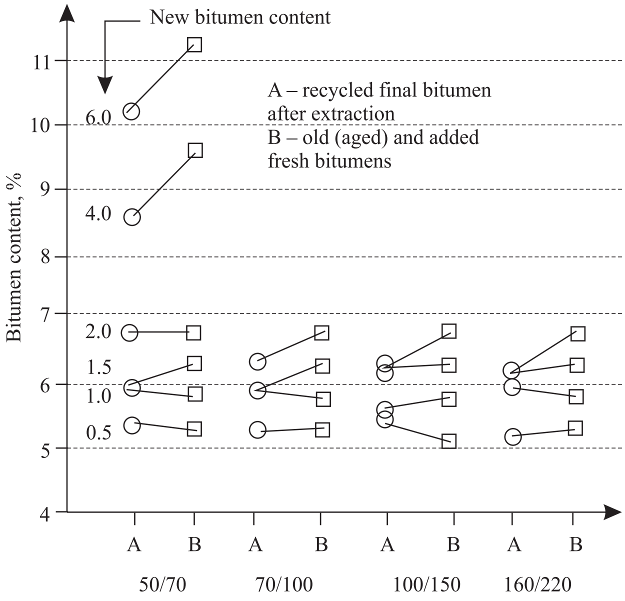

Fig. 8. Recycled bitumen amount in RAP, obtained by extraction (A) and arithmetically adding the values of aged and virgin bitumen (B)

virgin bitumen reduces (penetration increases), its stability and Marshall quotient decrease, but its flow increases and air voids content remains almost the same. When the percentage amount of the rejuvenating bitumen is increased in RAP mixture, its stability, Marshall quotient and air voids content decrease, but the flow of the mixture increases. Samples produced with big amount of the rejuvenating bitumen did not always meet the requirements set to them.

3. When the aged bitumen of RAP was rejuvenated with the virgin bitumen, the total amount of bitumen in the recycled HMA mixture increased, which is frequently higher than the optimal amount and depends on the same grading. Therefore, to meet the condition of the optimal amount of the recycled bitumen and if there is no possibility to reduce its surplus, virgin aggregates should be added to RAP. In this experiment, virgin aggregates were not added.

4. Having extracted the samples of the recycled asphalt and separated the total bitumen of all 18 series from the solvent in a rotary evaporator, the identified properties showed that when the percentage amount of virgin bitumen is increased in RAP mixture, the penetration of the total bitumen increased, the softening point, Fraass breaking point and penetration index decreased. It was supposed that greater changes of total bitumen properties compared with RAP aged bitumen properties, i.e. higher virgin bitumen efficacy when changing aged bitumen properties, would be obtained. RAP aged bitumen penetration Pen_{25} = 27 × 0.1 mm; softening point T_{SP} = 62.5 °C mm; T_{FBP} = –9 °C; penetration index I_P = +0.124. Recycled bitumen with 0.5%, …, 6.0% rejuvenator Pen_{25} changed from 12 × 0.1 mm to 31 × 0.1 mm, T_{SP} = 59.6–86.2 °C, T_{FBP} = –4–(–19) °C, I_P = +2.05–(–0.14), respectively.

5. After recycling RAP, the amount of the extracted soluble bitumen was frequently less than its pilot amount obtained by adding the rejuvenating virgin bitumen amount to the aged bitumen amount average in RAP samples. This discrepancy is explained by the high heterogeneity of RAP not only in a stockpile in a warehouse, but in samples taken from it for laboratory tests.

The analysis conducted in this paper was limited to only one RAP and virgin bitumen source. It is necessary to evaluate the applicability of the analysis method to various RAP and asphalt binders that exhibit different properties from different sources.

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