

DEPENDENCES OF SMA MIXTURE AND ITS BITUMINOUS BINDER PROPERTIES ON BITUMEN BATCHING SYSTEM, MIXING TIME AND TEMPERATURE ON ASPHALT MIXING PLANT

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Received 13 May 2013; accepted 21 Jun 2013

Abstract. Bitumen holds the aggregate in hot mix asphalt (HMA). Without asphalt binder, HMA would simply be crushed stone or gravel. A bitumen batching system (BBS) is comprised of bitumen storage, transportation, weighing and discharge equipment in an asphalt mixing plant (AMP). The function of the equipment is to batch the binder heated up to working temperature and to discharge it into a mixer in batches. In the entire system, the binder is exposed to high temperature and oxygen. Bitumen is slowly oxidized when it is in contact with oxygen. The degree of oxidation is highly dependent on temperature, time and thickness of a bitumen film. This article models the key factors influencing on the dynamics of bitumen oxidation in BBS equipment. Stone mastic asphalt (SMA) mixture was produced from the same materials according to the same job-mix formula (JMF) in neighbouring batch type AMP by changing the mixing time of materials from 20 to 60 s. Bitumen binder was separated from the taken SMA samples and its gradation was identified. Thus, Marshall specimens were produced and tested. Penetration Pen_{25} of bitumen binder recovered in rotary evaporator, softening point T_{sp} was determined and penetration index I_p was calculated. The presented findings of experimental investigation show that the properties of bitumen binder in BBS working at two different technologies changed inconsistently. Due to gravitation, the bitumen intensively flowing into a mixer (BBS1) is impacted by oxidation more than the bitumen batched by a high-pressure pump (BBS2).

Keywords: bitumen; hot mix asphalt (HMA); stone mastic asphalt (SMA); bitumen batching system (BBS); job-mix formula (JMF); oxidation, short-term ageing; rheology; penetration; viscosity; asphalt mixing plant (AMP).

Reference to this paper should be made as follows: Bražiūnas, J.; Sivilevičius, H.; Virbickas, R. 2013. Dependences of SMA mixture and its bituminous binder properties on bitumen batching system, mixing time and temperature on asphalt mixing plant, *Journal of Civil Engineering and Management* 19(6): 862–872. <http://dx.doi.org/10.3846/13923730.2013.843587>

Introduction

By volume, a typical HMA mixture is about 85% aggregate, 10% asphalt binder, and 5% air voids. Stone mastic asphalt (SMA) consists of coarse aggregates and a mastic of fine aggregate, mineral filler and asphalt binder. The mastic fills the voids between the coarse aggregates. The coarse aggregates interlock to form a stone skeleton. The bitumen is often reinforced with stabilizing agents such as small fibres or polymers. Because of the stone skeleton SMA mixture can provide a very stable and durable rut-resistant wearing course for highway applications (Lavin 2003).

Bitumens have very unusual engineering properties that must be carefully controlled in order to ensure good performance (Bražiūnas, Sivilevičius 2011). One of the most important characteristics of asphalt binders that must be addressed in test methods and specifications

is that their precise properties almost always depend on their temperature. Asphalt binders tend to be very stiff and brittle at low temperatures, thick fluids at high temperatures, and leathery/rubbery semi-solids at intermediate temperatures.

Such extreme changes in properties can cause performance problems in pavements (Vislavicius, Sivilevičius 2013). At high temperatures, a pavement with a binder that is too soft will be prone to rutting and shoving. On the other hand, a pavement that contains a binder that is too stiff at low temperatures will be prone to low-temperature cracking (Jenks *et al.* 2011).

Essentially, satisfactory performance of bitumen on the road can be ensured if four properties are controlled: rheology, cohesion, adhesion and durability. The rheology characteristics of bitumen at a particular temperature are determined by both constitution (chemical composi-

tion) and structure (physical arrangement) of the molecules in a material. Changes of constitution or structure or both will result in a change to the rheology (Read, Whiteoak 2003). Various mathematical equations, mostly Generalised Modified Sigmoidal Model, are applied to simulate rheological properties of unmodified and modified bitumens (Yusoff *et al.* 2013).

The chemical composition of bitumen is extremely complex; therefore, when conducting experimental investigations it is divided into two main fractions called asphaltenes and maltenes. Maltenes are resolved into saturates, aromatics and resins. The four groups are not well-defined and there is some overlap between the groups. However, this does enable bitumen rheology to be set against broad chemical composition (Redelius 2009). Four generic fractions play an inconsistent role in the temperature susceptibility of bitumens and the correlation degree of each fraction is somewhat different. The existence of aromatics and asphaltenes can lower the sensitivity to temperature changes whereas saturates and resins may have an adverse impact on the temperature susceptibility of bitumens. As for the correlation degrees, resins show the closest correlation with the temperature susceptibility of bitumens, then asphaltenes and aromatics, and the correlation between temperature susceptibility and saturates is relatively weak (Firoozifar *et al.* 2011; Liang *et al.* 2010). The physical properties of asphalt binder vary tremendously with temperature (Anderson 2011). Application of chemical composition mathematical models enables to identify viscoelastic properties of bitumen (Behzadfar, Hatzikiriakos 2013; Greenfield 2011).

Bitumen in common with many organic substances is affected by the presence of oxygen, ultraviolet radiation and by changes in temperature (Zhang *et al.* 2011; Huang, Zeng 2007). In bitumen, these external influences cause it to harden, resulting in a decrease in penetration (Pen_{25}), an increase in softening point (T_{sp}) and, usually, an increase in penetration index (I_p). The most important mechanisms of bitumen hardening are: oxidation, volatilisation, steric or physical factors, and exudative hardening. Hardening due to oxidation has long been considered the main cause of ageing to the extent that other factors have been given scant consideration (Petersen, Glaser 2011). Polar groups containing oxygen are formed and these tend to associate into micelles of higher micellar weight thereby increasing the viscosity of bitumen (Greenfield 2011; Read, Whiteoak 2003). Oxidation intensity mostly depends on temperature (De Moraes *et al.* 2010) as well as the duration and intensity of contact with oxygen, thickness of bitumen film coating mineral fillers (Herrington 2012). Heating time and temperature have significant impact on bitumen rheological properties, such as viscosity, complex modulus, and creep stiffness (Dessouky *et al.* 2011). Tran *et al.* (2010), Huh and Robertson (1996) evaluated the prediction models of bitumen's critical high temperature on the properties of HMA mixture.

Ageing influenced bitumen chemistry and rheology significantly (Siddiqui 2010). However, chemical and rheological changes were generally not consistent, and consequently, ageing susceptibility of bitumens may be ranked differently when different evaluation methods are used (Lu, Isacson 2002).

To reduce the deterioration of bitumen properties as much as possible and thereby to improve the properties of HMA mixture, the following additives of bitumen are used: antioxidants (Apeageyi 2011), modifiers (Haddadi *et al.* 2008), and adhesion enhancers. One of the prime roles of a bitumen modifier is to increase the resistance of the asphalt to permanent deformation at high road temperatures without adversely affecting the properties of bitumen or asphalt at other temperatures. Studies (Nien *et al.* 2008; Doğan, Bayramli 2009; Topal *et al.* 2011) have proved that the use of various polymer additives to improve the properties of the mixture is well-grounded. Polymer modification of asphalt binders has increasingly become the norm in designing optimally performing pavements, particularly in the United States, Canada, Europe and Australia. Specific polymers that have been used include rubber, SBR, SBS and Elvaloy (Yildirim 2007). Styrene-Butadiene-Styrene (SBS) triblock copolymer is commonly used for modifying physical, mechanical and rheological properties of bitumen (Słowik 2012).

The mechanism of adhesion between aggregates and bitumen should be understood to improve the lifetime of roads. The essential function of bitumen is to bind aggregates and to ensure the adhesion with the surface (Boulangé, Sterczynski 2012). Several parameters influence this adhesion: porosity and roughness of the aggregates, wettability between bitumen and aggregates and chemical composition at the interface (Bhasin, Little 2009; Horgnies *et al.* 2011). When producing mixtures with reclaimed asphalt pavement (RAP), aged and virgin bitumens are mixed. To maintain mechanical and physical properties of the recycled mixture, RAP quantity, homogeneity, mark of the aged and virgin bitumens, their penetration, quantity of virgin bitumen should be taken into account (Čygas *et al.* 2011; Baptista *et al.* 2013).

HMA mixture is produced by AMP of various structure and capacity, which use various technological schemes (Mogawer *et al.* 2012). A batch-type AMP has become most popular (Sivilevičius, Šukevičius 2009; Brown *et al.* 1989).

A complex value indicating the quality of HMA mixture produced by an AMP largely depends on the deviations of the content of HMA mixture components due to the errors in materials batching (White, Brown 1977; Brown *et al.* 1989; Stroup-Gardiner, Brown 2000; Sivilevičius, Vislavičius 2008). The improvement of material batchers at the enterprises producing HMA mixture allows not only decreasing the deviations of the amounts of HMA components from the values specified by job-mix formula (JMF) (Bražiūnas, Sivilevičius 2010), but also decreasing bitumen oxidation and increasing the

reliability and durability of the equipment, as well as simplifying its control, maintenance and repair (Brock 1986).

The hardening of bitumen during spraying or stiffening of asphalt material that occurs during mixing and placement is called short-term ageing (Said 2005; Lund, Wilson 1984). All the aggregate and filler is coated with a thin film of bitumen usually between 5 and 15 µm thick. Thus, when bitumen is mixed with hot aggregate and spread into thin films in an asphalt pugmill, conditions are ideal for the occurrence of oxidation and the loss of volatile fractions within the bitumen (Jemison *et al.* 1991). Hardening of bitumen during these processes is well known and is taken into account when selecting the grade of bitumen to be used. As a very rough approximation, during mixing with hot aggregates in a convention pugmill, the penetration of paving grade bitumen falls by about 30%. However, the amount of hardening depends on a number of factors such temperature, mixing time, bitumen film thickness, etc. The minimisation of hardening during mixing depends on careful control of all these factors. Control of the temperature and the bitumen content are particularly critical. It could be stated that the BBS, in which bitumen ageing processes occur more slowly, is better.

Bitumen short-term ageing processes are investigated in scientific literature; however, experimental investigations proving the dynamics of these processes are scarce. The aim of the paper is to identify how bitumen properties change after its storage, transportation, batching and mixing processes in AMP. It also aims to compare the impact of BBS operating according to different technological schemes on the properties of bitumen binder and the produced SMA mixture.

1. Impact of oxidation on bitumen properties

The following technological production factors impact on the structure of the produced HMA mixture: temperature of materials and their weight in per cent in the mixture, the completion of bitumen conversion from volumetric state into a film; thickness and homogeneity of bitumen films coating the finest particles; mixing time and exposure of bitumen to ambient air oxygen, its surface area.

The key factor impacting on the lowest temperature of asphalt mixture is a necessity to obtain a required viscosity of bitumen. Liquid bitumen coats mineral particles properly and ensures the required resilience of HMA mixture when laying and compacting it. The temperature higher than that at which optimal viscosity of bitumen is obtained is not justified as it frequently deteriorates asphalt concrete exploitation properties. First of all, it is related with irreversible changes of bitumen structure and properties occurring due to thermal oxidation processes at high temperature. These processes rapidly speed up in the bitumen spread into thin films on mineral particles.

High temperature, at which bitumen integrates with aggregates, causes the change of its chemical composi-

tion and structure, i.e. ageing of bitumen. The key factors influencing on the bitumen spread into a thin film are ambient air oxygen, high temperature, water and surface of an aggregate.

As explained above, a significant amount of bitumen hardening occurs during mixing and, to a lesser extent, during hot storage and transportation. However, hardening of the binder will continue on the road until some limiting value is reached. This behaviour is described as “long-term ageing” and is illustrated in Figure 1, which shows the ageing index of the bitumen after mixing, storage, transport, paving and subsequent service (Read, Whiteoak 2003; Apeageyi 2011).

Thermal oxidation ageing processes of various materials are described by the laws of kinetics of chemical reactions. The equation of the speed of these processes may be written as follows (Pecionyj 1990):

$$\frac{dc}{d\tau} = k \cdot c^e, \quad (1)$$

where: c – concentration of the material exposed to ageing in period τ ; k – speed constant; e – reaction order.

Due to the oxidation processes occurring in bitumen hydrocarbons and resins resulting in coarse components, a relative indicator of change in chemical composition of bitumen may be an increased content of asphaltenes.

Technological operations of mixing bitumen with aggregates are related with the impact of high temperature on bitumen resulting in oxidation processes in bitumen, which changes its chemical composition and structure (Kolbanovskaja, Michajlov 1973). An assumption could be made that bitumen oxidation speed varies at temperature according to Arrhenius (1887) equation, which relates reaction speed, activation energy and temperature:

$$v = k \cdot e^{-\frac{E}{RT}}, \quad (2)$$

where: v – speed of chemical reaction; k – reaction speed constant; E – activation relative reaction; R – universal gas constant; T – absolute temperature.

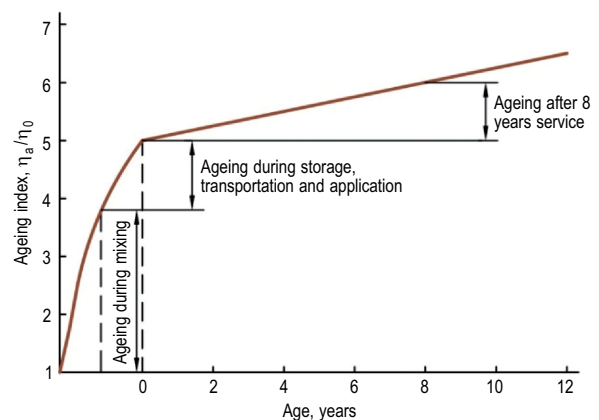


Fig. 1. Ageing of bitumen during mixing, subsequently during storage, transportation and application in service (Read, Whiteoak 2003)

The results of bitumen ageing process may be evaluated by ageing index I_a (Apeageyi 2011). Ageing index I_a computations based on the single-point measurements are one of most common procedures used to estimate ageing and provide ranking among different asphalt binders. Ageing index is defined as the ratio of a given binder property after a given level of ageing to that before ageing, as shown in Eqn (3):

$$I_a = \frac{\text{Physical property of aged bitumen}}{\text{Physical property of original bitumen}} \quad (3)$$

When mixed, particles of the aggregate are usually coated with a thin film of bitumen usually between 5–15 μm thick. When bitumen is in the condition of a thin film or a drop, the most active oxidation and volatilisation processes occur. It was determined that reducing the thickness of a bitumen film significantly increases the viscosity of the bitumen. The latter is measured by the ageing index, which is defined as the ratio of the viscosity of the aged bitumen η_a , to the viscosity of the virgin bitumen η_0 . If the thickness of a film coating the particles of aggregate increases from 4 μm to 10 μm , ageing index I_a decreases from 7.0 to 5.5 (Read, Whiteoak 2003).

Viscosity is a fundamental property that describes the resistance of a liquid to deformation or flow based on the internal friction of its molecules. During manufacture and compaction of asphalt mixture, there are optimum bitumen viscosities. If the viscosity of the bitumen is too high during mixing, the aggregates will not be properly coated and if the viscosity is too low, the bitumen will coat the aggregate easily but may drain off the aggregate during storage or transportation. For satisfactory coating, the viscosity should be approximately 0.2 Pa·s (Pascal-seconds).

Fluidity or viscosity is the primary consideration in pumping, transporting, and storing of bitumen. Viscosity is affected by temperature and by the type and grade involved. Figure 2 relates viscosity to temperature for four paving grades and two oxidized grades. Three lines indicating the approximate design pumpability, mixability, and sprayability are shown as well. At higher temperatures and lower viscosities, pumping is optimized;

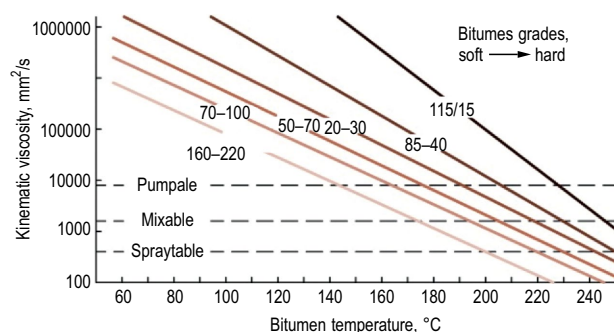


Fig. 2. Viscosity as a function of temperature for paving grade bitumen and for air-blown bitumen (85 °C softening point and 110 °C softening point). Design pumpability, mixability and sprayability (Sørensen, Wichert 2009)

whereas at lower temperatures and higher viscosities pumping efficiency decreases rapidly. Thus, viscosity and its control by temperature is an important consideration in respect to all handling operations.

Theoretically, the thickness of a bitumen film may be calculated in several ways. In 1992, Hweem (Read, Whiteoak 2003) calculated surface area factors, assuming a spherical particle shape and a specific gravity of 2.65:

$$T = \frac{b}{100-b} \cdot \frac{1}{\rho_b} \cdot \frac{1}{SAF} \quad (4)$$

where: T is bitumen film thickness, mm; ρ_b – density of bitumen, kg/m^3 ; SAF – surface area factor, m^2/kg and b – bitumen content, % by weight.

Another method gives an approximation of the binder film thickness using Francaise formula used in 1991 (Read, Whiteoak 2003):

$$T = \frac{b}{\frac{2650}{SG_a} \cdot \sqrt[3]{(0.25G + 2.3S + 12s + 135f)}} \quad (5)$$

where: SG_a – density of the aggregate, kg/m^3 ; G – proportion by mass of aggregate over 6.3 mm; S – proportion by mass of aggregate between 6.3 mm and 3.15 mm; s – proportion by mass of aggregate between 3.15 mm and 0.80 mm; and f – proportion by mass of aggregate smaller than 0.80 mm.

Surface activating materials (surfactants, SAM), which impact on bitumen and aggregate surface molecular interaction processes, alleviate bitumen moistening and spreading on mineral surface. These two processes are two compulsory preconditions for the adhesion of the two materials. One of the methods enabling to improve bitumen moistening and spreading on the surface of aggregate is the reduction of its viscosity by increasing the temperature or diluting it with plastifiers. When temperature is reduced to 100 °C, coating of mineral disperse material surface with bitumen is reduced.

2. Experimental investigation

2.1. Bitumen batching systems analysis

The Lithuanian asphalt concrete production company *PLLC Fegda*, where two batch type asphalt mixing plants (AMP) operate, was selected for the investigation. HMA mixture was produced in two different plants. AMP1 is newer and more modern technological equipment with the maximum capacity of 160 t/h ($Q_{\text{max}} = 160 \text{ t/h}$), made in Germany; whereas AMP2 is older equipment made by the same manufacturer with the maximum capacity $Q_{\text{max}} = 240 \text{ t/h}$. The equipment of these two AMP, which pump, transport, weigh and discharge bitumen into a mixer, differs as well.

BBS1 (Fig. 3) bitumen is pumped from storage tanks into a weigh bucket by *Steimel TFE 10-240* rotary gear pump at the debit of 230–340 l/min.

The binder is transported to the weigh bucket 2 via 80 mm diameter pipe at the distance of approximately

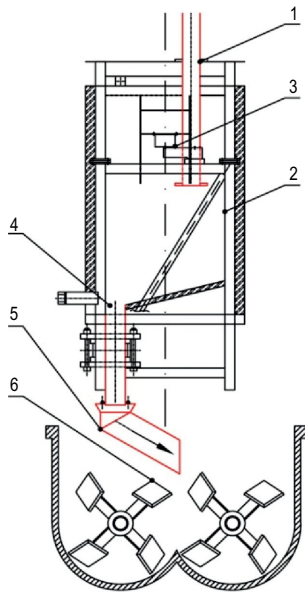


Fig. 3. A schematic view of major structural elements of bitumen batching system 1 (BBS1): incoming pipe (1); weigh bucket (2); weighing mechanism (3); outgoing pipe (4); batching pipe (5); mixer (6)

50 m. When a set amount of bitumen is pumped into the bucket, the weighing mechanism 3 sends information into the main computer, which switches the valve. The weighed out bitumen batch (138 kg according to JMF) flows through an outgoing pipe 4 and incoming pipe 5 at its own pressure from the weigh bucket into a mixer at one intensive turbulent flow (gravitational method).

BBS2 (Fig. 4) bitumen is pumped from storage tanks into the weigh bucket by the same rotary gear pumps. In the beginning of AMP exploitation of this system, only two bitumen storage tanks with separate transportation systems were used. Therefore, bitumen could be pumped into the weigh bucket via two pipes 1. Later, when there was a need to store 3–4 types of bitumen, this system was modernized. More storage tanks were built, and pumping pipelines were handled with automatic valves. BBS2 binder was transported about 8 m to bucket 2.

When a required batch is weighed out, like in BBS1, bitumen flow is directed with a 3-position valve and bitumen flows in a closed system (remixing occurs). Sliding vane pump 5 *Blackmer NP3 C* sprays bitumen batched in weigh bucket 2 (201 kg according to JMF) into mixer 7 at the debit of approximately 500l/min. via outgoing pipe 4 and spray bars 6. The new AMP2 equipment contained original mixer spray bars with much smaller diameter holes allow to spray bitumen into a mixer in drops. The dusty environment used to glue those holes in a mixer, which protracted bitumen discharge into a mixer. Therefore, it was decided to shorten mixer spray bars and to enlarge spray holes at their ends so that they did not obstruct.

These two systems differ in the technology of discharging the weighed out bitumen. When weighed out bitumen is discharged at the high BBS1 debit flow into

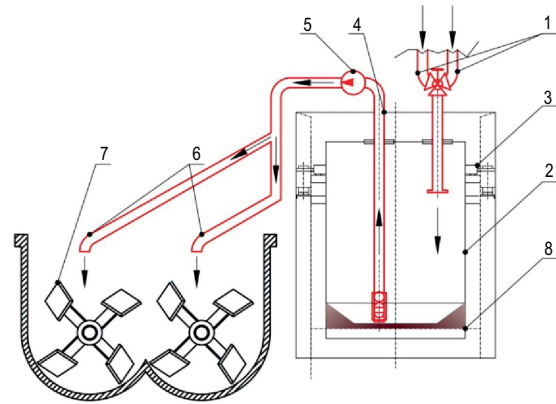


Fig. 4. A schematic view of major structural elements of bitumen batching system 2 (BBS2): incoming pipes (1); weigh bucket (2); weighing mechanism (3); outgoing pipe (4); pump for pumping the weighed out bitumen into mixer (5); mixer spray bars (6); mixer (7)

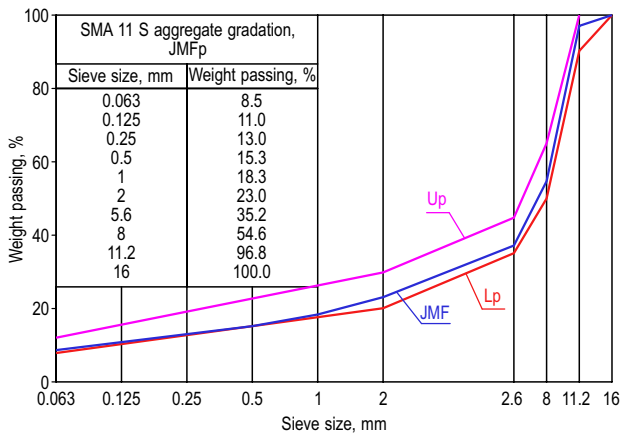
a mixer, the area of the binder's loose surface exposed to ambient air oxygen is smaller; therefore, there is a probability that it oxidizes less. When a bitumen batch is discharged into a mixer at high pressure in BBS2 of two small diameter pipes, it falls in sprays and has a larger surface area and, therefore, oxidizes more rapidly. So far, no investigation has been conducted to verify whether it is true.

2.2. Used materials

Bitumen storage tanks, from which the binder is transported via pipelines, are the same in AMP1 and AMP2, therefore, the assumption is made that PMB 45/80-55 bitumen used in the production of pilot SMA mixtures was transported of the same properties in both BBS1 and BBS2. When producing HMA mixture of the same composition in AMP1 and AMP2 from the same materials, its mixing time was changed. SMA 11 S mixtures were mixed with bitumen for 20, 30, 40, 50 and 60 seconds in a mixer.

SMA 11 S mark HMA mixture for both AMP was produced according to the same job-mix-formula. The normative document *The Lithuanian Specification of Technical Requirements for Automobile Road Asphalt Mixtures TRA ASFALTAS 08* regulates the requirements for each HMA mark gradation of the mixture. Lower (L_p) and upper (U_p) permitted tolerances of per cent passing are stipulated in *TRA ASFALTAS 08*, and those of the designed SMA 11 S mixture in a job-mix formula (JMF) (Fig. 5).

Optimal asphalt mixture gradation is determined through application of stochastic and deterministic optimization models (Sterling 2011; Sivilevičius et al. 2011). To produce SMA 11 S gradation mixture, granite screenings (0/2 mm), three fraction granite crushed stone (2/5 mm; 5/8 mm; 8/11 mm), activated mineral powder were used. Adhesion enhancing additive *Iterlene* and cellulose fibre additive *CPA* were used in the mixture.

Fig. 5. SMA 11 S aggregate gradation (JMF_p)

By volume, SMA mixture was about 81.96% aggregate, 15.37% asphalt binder, and 2.7% air voids (test report No. 091049).

2.3. Sample taking and testing

Experimental investigation consists of two stages: mixture sample taking and sample testing in a laboratory. During the first stage of the experiment SMA mixture samples were taken and temperature was measured according to the procedures stipulated in standards. The produced SMA mixture was discharged from a mixer directly into a truck's body and not to storage silos. Therefore, its cooling, segregation and additional bitumen oxidation were avoided. All 10 samples, 5 from each AMP, taken according to standard LST EN 12697-27: 2002 (2002), when a mixture was mixed for 20, 30, 40, 50, 60 s, were tested during the second stage in a certified laboratory.

The bitumen quantity and gradation were identified in asphalt samples. The rest of each sample was used to test Marshall specimen. Marshall stability, flow, Marshall quotient, maximum density, air void content, voids filled with bitumen (VFB), voids in mineral aggregate (VMA) were investigated. 10 samples of the bitumen extracted and recovered in rotary evaporator and the bitumen taken from a storage tank before production were tested as well. Bitumen sample penetration (Pen_{25}) and softening point (T_{sp}) were identified and penetration index (I_p) was calculated.

Pfeiffer and Van Doormaal (Read, Whiteoak 2003) 1936 wrote an equation for the temperature susceptibility that assumes a value of about zero for road bitumen. For this reason, they defined the penetration index (I_p) as (Galooyak *et al.* 2010):

$$I_p = \frac{1952 - 500 \cdot \log(Pen_{25}) - 20T_{sp}}{5 \cdot \log(Pen_{25}) - T_{sp} - 120}, \quad (6)$$

where: Pen_{25} – the penetration at 25 °C in dmm and T_{sp} is the softening point of samples in °C.

3. Properties of the produced HMA mixture and bitumen

Laboratory investigations showed that composition of HMA mixture produced in AMP1 and AMP2 varied inconsiderably and did not exceed tolerances from JMF value (except for the content of particles > 8 mm) (Table 1).

Table 1. HMA mixture fraction composition and bitumen content

Mineral component and bitumen content, %							
Fraction	JMF	Mixing time t_m , s					Max dev. form JMF, ±%
		20	30	40	50	60	
AMP1							
> 8	45.4	48.8	57.4	52.0	50.6	50.6	+12
> 5.6	62.7	64.8	68.1	63.0	62.2	63.9	+5.4
> 2	77.0	76.7	77.6	75.7	75.8	75.9	-1.3
0.063–2	14.5	14.0	13.4	14.3	14.9	14.6	-1.1
< 0.063	8.5	9.4	9.0	10.1	9.3	9.5	+1.6
Bit.	6.6	6.6	6.3	6.8	6.6	6.6	-0.3
AMP2							
>8	45.4	53.1	47.5	43.8	52.3	53.4	+8.0
>5.6	62.7	67.7	65.4	64.3	67.5	68.1	+5.4
>2	77.0	77.2	76.5	76.1	77.3	76.9	-0.9
0.063–2	14.5	14.8	15.1	15.3	14.8	14.1	+0.8
< 0.063	8.5	8.0	8.4	8.6	7.8	9.0	+0.5
Bit.	6.6	6.6	6.7	6.9	6.4	6.8	+0.3

The content of mineral powder (size < 0.063 mm) in all HMA mixture samples produced in AMP2 was less than in those produced in AMP1. The weight passing in per cent of these particles differed from JMF within tolerance limits, i.e. it was less than ±3%. The weight in per cent of > 8 mm size and > 5.6 mm size aggregates in 9 out of 10 samples exceeded the amount set in JMF. The content of > 2 mm (coarse aggregate) and 0.063–2 mm (fine aggregate) in the produced SMA mixture deviated inconsiderably (the largest -1.3% and +0.8%) from JMF requirements (±8.0%). The largest deviations of bitumen content in the produced SMA mixture (-0.3% and +0.3%) complied with tolerance requirements (±0.5%). It shows that SMA of the same component composition was produced in both AMP. It was only the SMA mixture mixed for 30 s in AMP1 that the quantity of particles larger than 8 mm varied by +12.0% from JMF, i.e. it did not comply with the requirements of tolerances (±8.0%).

In AMP mixer the mixture is mixed at high working temperature (Grabowski *et al.* 2013), which is impacted by the aggregate heated in a drying and heating drum and bitumen heated in storage tanks. Taking into account that bitumen oxidation is mostly influenced by its temperature and the change of bitumen properties due to oxidation, it was important to identify the mixing temperature of the

Table 2. HMA mixture production and samples temperature

Mixing time t_m , s	The arithmetic average of HMA mixture production temperature in the AMP (computer data), °C	
	AMP 1	AMP 2
20	173.1	174.0
30	172.6	175.3
40	184.5	177.5
50	177.9	186.5
60	179.3	193.4
HMA mixture samples temperature, °C		
	AMP 1	AMP 2
20	169	181
30	171	171
40	187	182
50	192	196
60	not measured	186

mixer. During the investigation, temperature displayed on the AMP handling computer and measured *in situ* (SMA samples taken from the truck's body) was analysed (Table 2).

Bitumen was stored in storage tanks at the temperature of 160 °C. As the binder was pumped into AMP1 and AMP2 from the same capacity storage tank, it could be stated that its temperature after transportation via pipelines was approximately 160 °C. It is more difficult to maintain stable temperature of aggregates. Due to their high volumetric content in the mixture, overheated aggregates may increase the total temperature of HMA mixture considerably. According to *The Installation Rules of the Roads Pavement Asphalt Layers IT ASFALTAS 08*, the temperature of SMA mixture produced with PMB 45/80-55 mark binder will not be lower than 150 °C and not higher than 180 °C. Some asphalt mixture batches were of critical temperature or even exceeded it, which could speed up the oxidation processes. Dependence of change in bitumen quality parameters (Pen_{25} , T_{sp}) on mixture production temperature is described in regression equations (Fig. 6). The temperature of the mixture produced in AMP1 mixer influenced the change of bitumen penetration by approx. 90% ($R^2 = 0.902$) and softening point by approx. 79% ($R^2 = 0.789$). When the mixture was produced in an older AMP2 mixer, its bitumen penetration also decreased, and softening point increased; however, the impact of temperature was less than that in AMP1. The change of bitumen properties when the temperature of mixing the mixture in a mixer was increased from 172 °C to 187 °C was the same in AMP1 and AMP2. Therefore, it could be stated that the temperature of mixing SMA mixture in a mixer influenced on the change of bitumen properties due to its oxidation.

The findings of laboratory investigations of bitumen extracted from SMA 11 S mixture samples showed that the change of quality parameters Pen_{25} , T_{sp} , I_p of bitumen binder depends on BBS and mixing time t_m (Fig. 7).

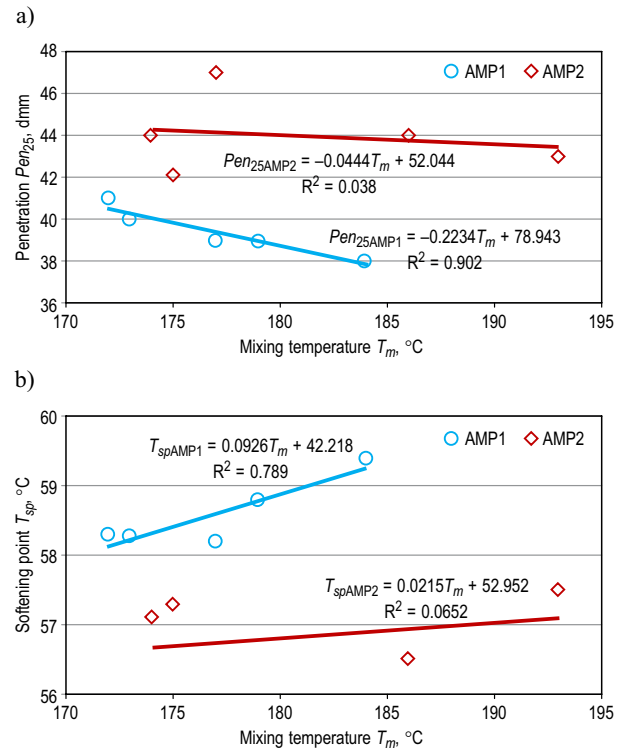


Fig. 6. Dependence of bitumen properties of the mixture produced in AMP1 and AMP2 on mixing temperature T_m of HMA mixture: penetration (Pen_{25}) (a); softening point (T_{sp}) (b)

Various equation forms were used in regressive analysis and the description of the data obtained during experiments. The change of each indicator (Pen_{25} , T_{sp} , I_p) of the bitumen produced in both BBS when changing the mixing time of HMA mixture was described by curved-line regression equation with the highest determination coefficient R^2 . Pen_{25} of the bitumen used in BBS decreased from its initial value of 48.7 dmm to 39 dmm, when it was extracted from SMA mixture and recovered in rotary evaporator. The change of bitumen penetration Pen_{25} by approx. 95% ($R^2 = 0.946$) was influenced by mixing time t_m of SMA mixture.

Softening point T_{sp} increased from its initial value of 55.0 °C to 58.6 °C, and this change depends on mixing time by approximately 93% ($R^2 = 0.932$).

The change of penetration Pen_{25} and softening point T_{sp} of the bitumen used in BBS2 when increasing mixing time to 60 s was the same as that in BBS1. However, the change of these bitumen quality parameters was influenced only by 42–43% by mixing time t_m of SMA mixture. More than 57% of their change depended on other factors outside regression equation, probably on temperature.

The calculated values of penetration index I_p of the bitumen extracted from mixtures produced in AMP1 increased from its initial value of -0.1 to $+0.26$ AMP1 and up to $+0.15$ of the bitumen extracted from mixtures produced in AMP2.

When applying various BBS, the change of physical and mechanical properties of the produced SMA mix-

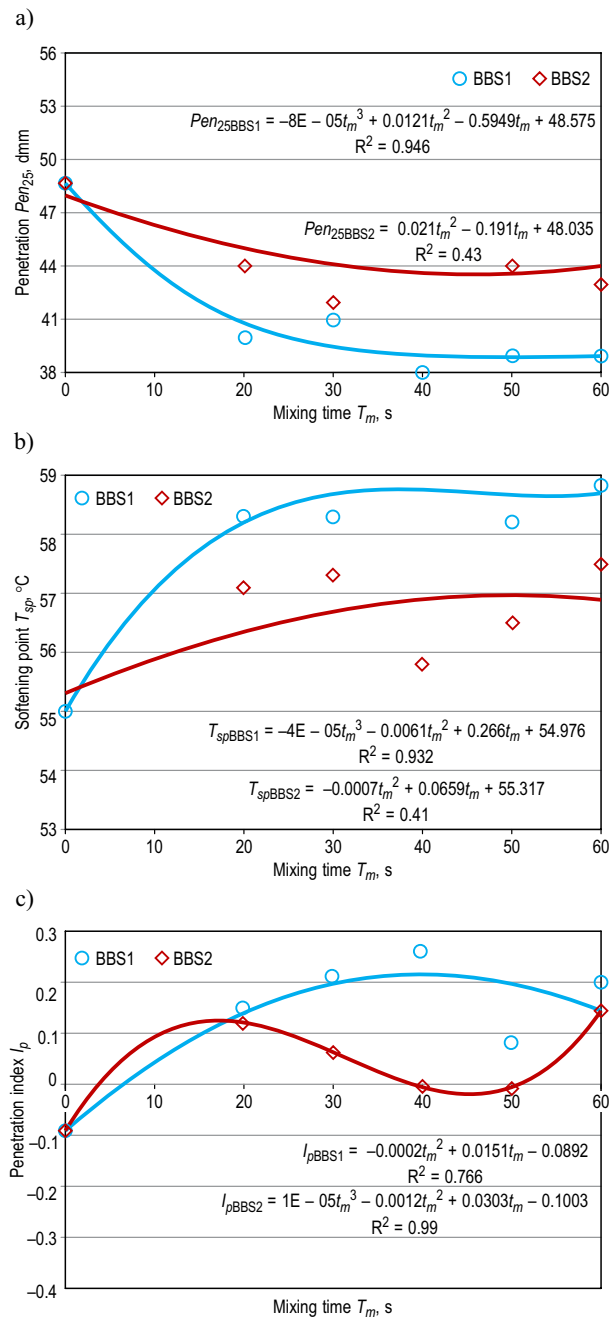


Fig. 7. Dependence of BBS1 and BBS2 batched bitumen properties on mixing time t_m of HMA mixture: penetration (Pen_{25}) (a); softening point (T_{sp}) (b); penetration index (I_p) (c)

ture was influenced not only by the method of bitumen discharge into a mixer, but by mixing time in it as well (Figs 8, 9). Physical HMA mixture parameters (maximum density and air void content) (Fig. 8) varied depending on mixing time. It was found that when mixing time was increased from 20 to 60 s, maximum density increased and air void content decreased inconsistently. The impact of BBS construction on the physical parameters of SMA mixture was insignificant. The study showed that there is no clear correlation between voids filled with bitumen (VFB), voids in mineral aggregate (VMA) and AMP type and mixing time t_m .

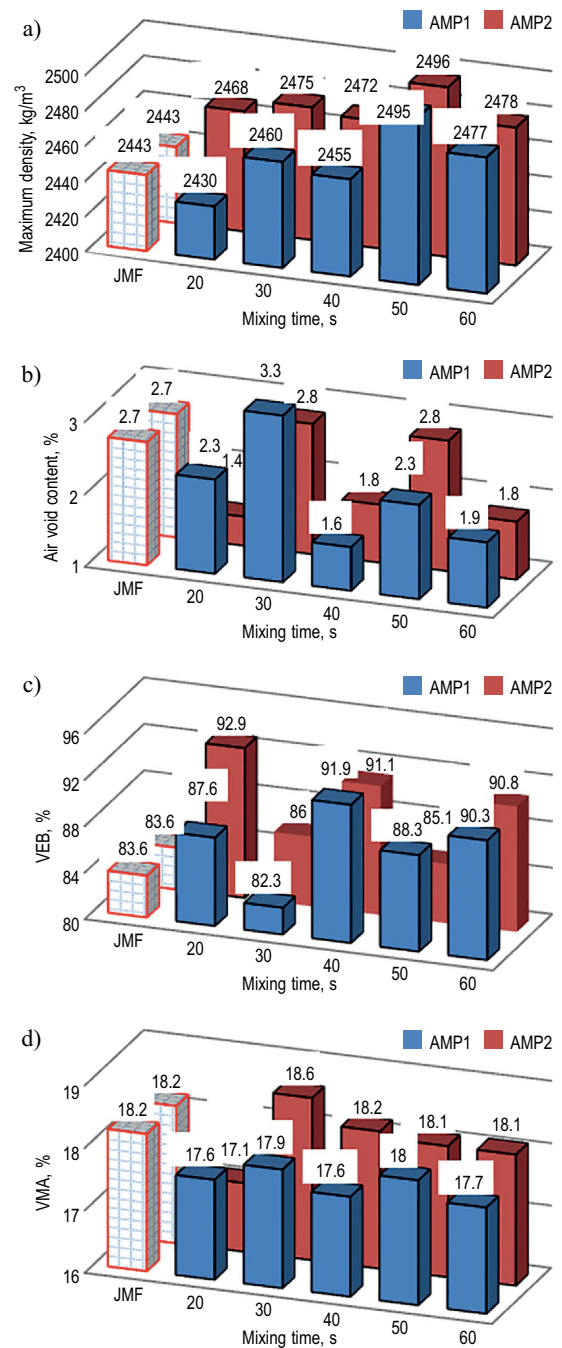


Fig. 8. Physical properties of HMA mixture: maximum density (a); air void content (b); VFB (c); VMA (d)

The aim to obtain higher HMA mechanical strength could be explained by two reasons. First, due to bitumen ageing processes: longer HMA mixing time increases its viscosity. Second, due to longer HMA mixing time, bitumen coats mineral particles better with a continuous film of the required thickness, which increases adhesion forces.

The oxidation process consisted of two stages: oxidation of bitumen discharged from a batcher into a mixer and oxidation during mixing. The longer the mixture is mixed, the longer is the oxidation process. The mixing process of AMP was the same; therefore, the differ-

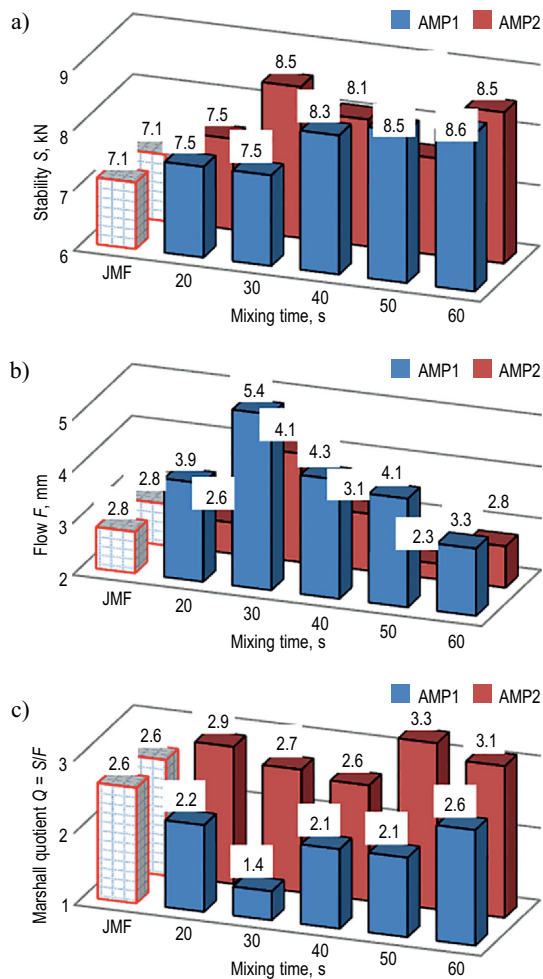


Fig. 9. Mechanical properties of HMA mixture: stability S (a); flow F (b); Marshall quotient Q (c)

ences in mixture strength properties may be explained by different bitumen ageing intensity when bitumen is discharged from a batcher into a mixer and different temperatures of SMA mixture.

It was found that longer mixing time increases HMA mixture stability and decreases flow (Fig. 9). When mixing time t_m of SMA was increased, the content of loose bitumen decreased and the content of oriented bitumen increased, which coated a larger area of the surface of extremely fine particles. The Marshall quotient of SMA mixture produced in AMP2 increased by 7% and that produced in AMP1 by 18%.

Although it is difficult estimating the impact of the type of BBS, mechanical parameters of Marshall specimen show that the Marshall quotient of HMA mixture produced in AMP2 mixer was higher in all cases under investigation.

Conclusions

I_p of the bitumen extracted from SMA mixture and recovered in rotary evaporator after batching in BBS1 and mixing in a mixer increases from -0.1 to 0.21 – 0.26 . I_p of the bitumen batched in BBS2 increases to 0.12 – 0.15 . The bitumen extracted from the SMA mixture produced

in AMP2 had better properties, i.e. smaller penetration variations were observed in all cases under investigation.

There was no evident change of bitumen binder properties extracted from HMA mixture when mixing time was increased to 60 s. Within the range under investigation between 20 s and 60 s, the highest reduction of bitumen penetration was identified when mixing time was 40 s in BBS1 and 30 s in BBS2.

It was identified that mixing time has an impact on the physical and mechanical properties of SMA mixture. Stability at longer mixing time increases from 7.5 kN to 8.6 kN of the mixture produced in AMP1 and from 7.5 kN to 8.5 kN of the mixture produced in AMP2. Flow tends to decrease when SMA mixture is mixed longer.

It was identified that during the processes of storage, weighing, dosing and mixing up to 60 s, bitumen penetration decreases to 22%. This results in a progressive increase in the stiffness modulus of the asphalt, together with a reduction in its stress relaxation capability. This will further increase the likelihood of pavement cracking and fretting.

Due to the increase of HMA mixture production temperature from 172 °C to 187 °C in overheated aggregates, bitumen penetration fell from 41 dmm to 38 dmm in AMP1, and from 44 dmm to 43 dmm in AMP2. Softening point increased from 58 °C to 59 °C in AMP1, and from 56.5 °C to 57 °C in AMP2.

Although the investigation has shown that different batching technologies impact on uneven bitumen short-term ageing, the impact of other parameters such as heat transfer between bitumen, aggregates and AMP equipment, bitumen and aggregate temperature will be investigated in further studies.

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