VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Justas BRAŽIŪNAS

INVESTIGATION OF TECHNOLOGICAL PARAMETERS OF BITUMEN BATCHING SYSTEM IN THE ASPHALT MIXING PLANT

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
TRANSPORT ENGINEERING (03T)

VGTU
LEIDYKLA
TECHNIKA
Vilnius 2013

Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2009–2013.

Scientific Supervisor

Prof Dr Habil Henrikas SIVILEVIČIUS (Vilnius Gediminas Technical University, Technological Sciences, Transport Engineering – 03T).

The dissertation is being defended at the Council of Scientific Field of Transport Engineering at Vilnius Gediminas Technical University:

Chairman

Assoc Prof Dr Olegas PRENTKOVSKIS (Vilnius Gediminas Technical University, Technological Sciences, Transport Engineering – 03T).

Members:

Prof Dr Habil Rimantas BARAUSKAS (Kaunas University of Technology, Physical Sciences, Informatics – 09P),

Assoc Prof Dr Algirdas JANULEVIČIUS (Aleksandras Stulginskis University, Technological Sciences, Transport Engineering – 03T),

Prof Dr Romualdas KLIUKAS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T),

Prof Dr Alfredas LAURINAVIČIUS (Vilnius Gediminas Technical University, Technological Sciences, Transport Engineering – 03T).

Opponents:

Prof Dr Žilvinas BAZARAS (Kaunas University of Technology, Technological Sciences, Transport Engineering – 03T),

Prof Dr Donatas ČYGAS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T).

The dissertation will be defended at the public meeting of the Council of Scientific Field of Transport Engineering in the Senate Hall of Vilnius Gediminas Technical University at 2 p. m. on 30 January 2014.

Address: Saulėtekio al. 11, LT-10223 Vilnius, Lithuania.

Tel.: +370 5 274 4952, +370 5 274 4956; fax +370 5 270 0112;

e-mail: doktor@vgtu.lt

The summary of the doctoral dissertation was distributed on 27 December 2013.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

© Justas Bražiūnas, 2013

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Justas BRAŽIŪNAS

ASFALTO MAIŠYTUVO BITUMO DOZAVIMO SISTEMOS TECHNOLOGINIŲ PARAMETRŲ TYRIMAS

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
TRANSPORTO INŽINERIJA (03T)

VGTU
LEIDYKLA
TECHNIKA
Vilnius 2013

Disertacija rengta 2009–2013 metais Vilniaus Gedimino technikos universitete.

Mokslinis vadovas

prof. habil. dr. Henrikas SIVILEVIČIUS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, transporto inžinerija – 03T).

Disertacija ginama Vilniaus Gedimino technikos universiteto Transporto inžinerijos mokslo krypties taryboje:

Pirmininkas

doc. dr. Olegas PRENTKOVSKIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, transporto inžinerija – 03T).

Nariai:

prof. habil. dr. Rimantas BARAUSKAS (Kauno technologijos universitetas, fiziniai mokslai, informatika – 09P),

doc. dr. Algirdas JANULEVIČIUS (Aleksandro Stulginskio universitetas, technologijos mokslai, transporto inžinerija – 03T),

prof. dr. Romualdas KLIUKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T),

prof. dr. Alfredas LAURINAVIČIUS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, transporto inžinerija – 03T).

Oponentai:

prof. dr. Žilvinas BAZARAS (Kaunas technologijos universitetas, technologijos mokslai, transporto inžinerija – 03T),

prof. dr. Donatas ČYGAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Disertacija bus ginama viešame Transporto inžinerijos mokslo krypties tarybos posėdyje 2014 m. sausio 30 d. 14 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.

Adresas: Saulėtekio al. 11, LT-10223 Vilnius, Lietuva.

Tel.: (8 5) 274 4952, (8 5) 274 4956; faksas (8 5) 270 0112;

el. paštas doktor@vgtu.lt

Disertacijos santrauka išsiuntinėta 2013 m. gruodžio 27 d.

Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).

VGTU leidyklos „Technika“ 2223-M mokslo literatūros knyga.

© Justas Bražiūnas, 2013

Introduction

The research problem

The structure of various bitumen batching systems (BBS), which should carry out the same functions in operating asphalt mixing plants (AMP) differs. The differences and handling methods of the structure have different impact on the processes occurring in the technological pipeline and batcher and do not always comply with the requirements set on the quality of the produced asphalt mixture.

The system of improving technological parameters, which should guarantee that the quality of the liquid transported in the system does not impair (its quality parameters change minimally), and the batcher batches (measure) bitumen in required mass (batching process is maximally accurate and stable), should be available or created. The system should be functional, economical, ecological and modern.

The relevance of the work

A lot of money is allocated to construct and maintain asphalt pavement for roads in Lithuania. However, this money is not sufficient, which impacts on significant degradation of their condition. Unfavourable climatic conditions in Lithuania, when ambient air temperature fluctuates from minus 30 °C to plus 30 °C and changes from positive to negative one 60–80 times per year, and water content in open air voids of asphalt pavement layer fluctuates within a wide range impact on the road pavement damage and deformation and increase its rapidity. Proper bitumen content and its properties in hot mix asphalt (HMA) mixture impact on the long-term mechanical strength of the laid asphalt road pavement and the required road exploitation properties. When producing HMA mixture in transport technological equipment, AMP, relations between the structure and interaction of the mixture established in bitumen batching and component mixing technological processes ensure long-term road pavement strength, texture, evenness, degree of damage and rheological properties.

The object of the research

The object of the research is the technological parameters of the batching system of bitumen transported in asphalt mixing plant and mixer and their impact on the quality of HMA mixture production.

The aim of the work

The aim of the work is to present scientifically based improved technological parameters of the periodic asphalt mixing plant bitumen batching system, enabling to produce high quality hot mix asphalt mixture.

The tasks of the work

The following tasks were set to the work:

1. To investigate the impact of bitumen binder viscosity, effective bitumen content and air void content on the change of HMA dynamic modulus.

2. To investigate bitumen batching, discharge into a mixer and oxygen diffusion into bitumen occurring during technological mixing operations, carbonyl compound formation processes and their impact on the change of properties of hot binder in short-term ageing period.

3. To identify and systematize the most important factors influencing on the dispersion scope of bitumen content in HMA mixture lot. To determine factual deviations from job-mix formula (JMF) of component content in the produced HMA mixture and to apply them when calculating the parameters of these components‘ content distribution.

4. To investigate the effectiveness of BBS technical reconstruction when reducing binder dosing errors, saving electricity and improving the production management process.

5. To conduct active experiment under real production conditions, when HMA mixture is produced for different BBS by two periodical asphalt mixing plants when mixing time and temperature of the aggregate is changed, which enables to identify the impact of these technological factors on the bitumen properties and physical and mechanical parameters of asphalt mixture Marshall sample.

The research methods

The following methods were employed in the work: passive and active experimental investigations under real production conditions, sample testing in laboratory, mathematical statistics, mathematical simulation methods. *Statgraphics Centurion XVI*, *SPSS 16* software packages were used. The following data were used: laboratory testing data from three certified laboratories; two AMP handling computer data. The following equipment was used: infrared thermography camera *IR-Flexcam Pro*; non-contact thermometer, bitumen and asphalt mixture samples, extractor, rotating evaporator, penetrometer *Humboldt H-125*; softening point determination device (ring and ball), Marshall sample production and compression equipment.

The scientific novelty

When preparing the dissertation, the following novel findings for transport engineering were obtained:

1. It was theoretically estimated that such BBS technological parameters as bitumen batch mass percent deviations, which impact on the effective bitu-

men content and air voids, and temperature, which determines viscosity, are significant factors influencing on the dynamic modulus of the produced HMA mixture.

2. The presented mathematical model enables to determine the distribution of oxygen pressure in the course of time in a different size bitumen drop falling into a mixer, when oxygen diffusion which depends on temperature, and heat conductivity, which depends on temperature, density and specific heat are taken into account.

3. The model of bitumen content in the produced HMA mixture batch (one-day or one-mix-formula), distribution parameter (dispersion) was presented, which reveals the impact and interaction of separate factors‘ dispersion.

4. It was proved that currently valid Lithuanian normative documents regulating permitted deviations from JMF in HMA mixture component content are too liberal and do not always comply with the real constantly upgraded AMP technical capabilities.

5. During the active experimental investigation carried out under real production conditions it was identified that the method of bitumen discharge from a batcher, temperature and time of mixing materials with hot mineral aggregates impact on the properties of bitumen binder in the produced HMA mixture.

The practical value

1. The evaluation and improvement method of hot mix asphalt mixture production internal control was presented. Due to a large number of taken samples, this method enables to estimate dependable parameters of position and dispersion of factual deviations from JMF of components of separate kinds and types of asphalt mixtures produced in each asphalt mixing plant in one working season, the sample taking of which is small.

2. Passive and active experimental investigations were conducted in three Lithuanian asphalt mixing plants. Therefore, the findings of the dissertation investigations which prove a necessity to reduce the temperature of materials are topical for hot mix asphalt mixture production plants and their use enables the staff of these plants to improve the quality of HMA production process.

3. It was proved that the permitted deviations from JMF of HMA mixture bitumen and mineral fillers content regulated in the Lithuanian regulations ĮT ASFALTAS 08 may be tightened. The specified digital values of component content in hot mix asphalt mixtures tolerances in the new edition of regulations may be presented only upon conducting additional tests of the mixtures produced in other models of AMP.

Defended propositions

1. The parameters of mixing bitumen with mineral aggregates‘ technological processes occurring in BBS are stochastic and have impact on bitumen binder composition and the following physical and mechanical properties of the produced HMA mixture: air void content, stability, flow, Marshall quotient and dynamic modulus.
2. Variation of bitumen properties occurring due to oxidation depends on the technology of bitumen binder batching and discharging into a mixer. When bitumen is sprayed by high pressure jet (HPJ) and discharged by high debit gravitation flow (HDGF) into a mixer, its penetration decreases and softening point increases unevenly.
3. When mineral aggregates are overheated, the most important factor for bitumen binder short-term ageing is not bitumen batching and discharging technology, but the temperature of mineral aggregates mixed with it.
4. Some modern AMP are capable of producing HMA mixture of higher quality than required in the norms. Provided more comprehensive investigations with more asphalt mixing plants are conducted and conclusions made in this paper are approved, statistical tolerances set in Regulations *ĮT ASFALTAS 08* may be justly tightened (reduced). Reduced tolerances would enable to improve the quality of HMA mixture production and to use the structural capabilities of AMP better.

The scope of the work

The dissertation consists of the Introduction, four chapters, general conclusions, the list of references as well as the author’s publications on the topic of the thesis and annexes. The length of the dissertation is 138 pages and includes 53 figures, 16 tables and 5 annexes. 142 references were used in the dissertation.

1. Analysis of research works investigating the variation of bitumen characteristics in technological equipment and factors of asphalt pavement

No comprehensive investigation has been carried out on why and how bitumen characteristics change when asphalt mixing plant (AMP) bitumen batching systems (BBS) of different structure and parameters are used in hot mix asphalt (HMA) mixture production technological process. Publications on the experiments conducted not in a laboratory but under real production conditions, especially with the data from active experiments conducted in AMP, are scarce. The analysis of research works shows that currently scientists frequently investigate the variation of characteristics of bitumen as a binding material when it is

not mixed with mineral aggregates and its performance in the road pavement asphalt layer. The possibilities of applying new additives, which improve bitumen characteristics and inhibit its oxidation reactions, are investigated. A large body of scientific publications are devoted to long-term ageing of bitumen binders in road pavement asphalt; however, its short-term ageing during the process of asphalt mixture production is much more important and significant, which due to its complexity has not been analysed enough.

2. Modelling of bitumen characteristics variation processes in technological equipment

Theoretical investigation conducted by Witczak *et al.* on bitumen binder short-term and long-term ageing prognosing initial and specified mathematical models (regression equations) showed that bitumen temperature, viscosity and its effective content in the mixture, which depends on bitumen dosing errors, have impact on HMA dynamic modulus *E*. The increasing viscosity increases dynamic modulus *E* during a short period; however, during a long period road pavement asphalt starts to scale due to larger viscosity. Increase of effective bitumen content consistently reduces *E* value. Air void content up to 3.5 % has no impact; whereas when it is higher than 3.5 %, it reduces its dynamic modulus *E*.

Effected by high temperature and oxidation processes in the equipment of AMP, bitumen changes its chemical and group composition irreversibly, which, in turn, worsens the structure, adhesion, cohesion and rheology of the binder in the road pavement asphalt layer. When studying the formation of carbonyl content in bitumen at high temperatures, it could be seen that (Fig. 1) the amount of carbonyl r_{CA} in organic binder varies. The formation of r_{CA} compounds is rapidly increasing when the temperature of bitumen binder ranges from 180–190 °C and higher.

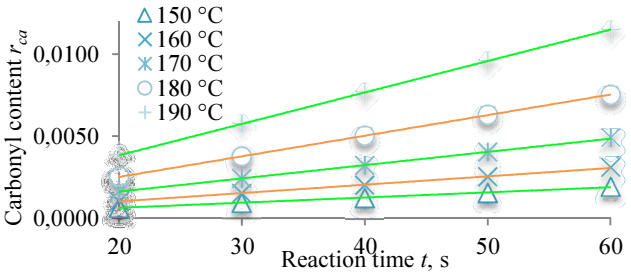

Fig. 1. Effect of temperature on carbonyl formation in bitumen during oxidation period of 20–60 s at 150–190 °C temperatures

Two BBS which differ by the method of mixing the batched bitumen in the mixer are under investigation (Fig. 2). Due to the differences of BBS technical parameters and flow (debit, pressure, jet characteristics), the batched bitumen binder is sprayed into the mixer in drops (high pressure jet)) or is discharged by high gravitation flow.

To determine oxygen concentration C_{O_2} distribution at different depths of bitumen drop or flow (according to one coordinate x), the mathematical model was constructed according to the main equation (1). The obtained result enables to determine the scope of oxidation due to oxygen concentration C_{O_2}.

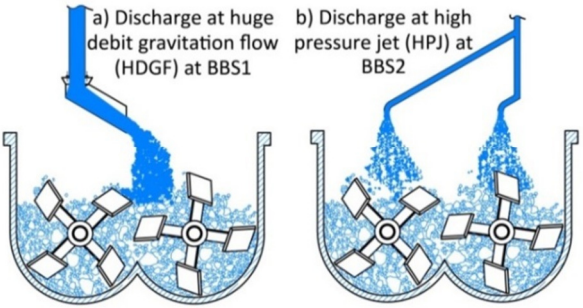

Fig. 2. Technologies of discharging weighed hot bitumen into a mixer in various bitumen batching systems

$$\left(\frac{\partial C_{O_2}}{\partial t}\right)=\left(\frac{\partial D}{\partial x}\right)\left(\frac{\partial C_{O_2}}{\partial x}\right)+D\left(\frac{\partial^2 C_{O_2}}{\partial x^2}\right)-r_{O_2}, \quad (1)$$

here C_{O_2} – oxygen concentration; r_{O_2} – oxygen consumption (absorption); x – depth coordinate; P – pressure; D – diffusitivity which depends on the level where oxygen diffusion occurs.

$$\left(\frac{\partial P}{\partial t}\right)=\left(\frac{\partial D}{\partial x}\right)\left(\frac{\partial P}{\partial x}\right)+D\left(\frac{\partial^2 P}{\partial x^2}\right)-\left(\frac{cRT}{h}\right)\frac{r_{O_2}}{c}, \quad (2)$$

here c – coefficient, which depends on the material. The initial equation is expressed as follows:

$$\frac{\partial P}{\partial t}-\frac{\partial D}{\partial x}\frac{\partial P}{\partial x}-D\frac{\partial^2 P}{\partial x^2}+b(P)=0. \quad (3)$$

Depth L under investigation (according to coordinate x) is divided into finite elements (FE) through the use of the first Hermite polynomials. Pressure in finite element e is calculated as follows:

$$P_e(t,x) = \left[N(\psi = \frac{x}{L_e}) \right] \{q_e\}, \tag{4}$$

here $[N(\psi)]$ – shape function matrix; $\{q_e\}$ – the unknown quantities of the finite element; L_e – length of the finite element. The finite element of two nods is used when the unknown vector equals to:

$$\{q_e\}^T = \left[P_1, \frac{\partial P_1}{L_e \partial \psi}, p_2, \frac{\partial P_2}{L_e \partial \psi} \right]. \tag{5}$$

Having integrated diffusion and thermal conductivity equations, the following equation is obtained:

$$[H_k]\{\Delta Y_k\} = \{R_k\}, \tag{6}$$

here $\{\Delta Y_k\}^T = \left[\{\Delta q_k\}^T, \{\Delta T_k\}^T\right]$; $\{R_k\}$ – vector of the right sides; $[H_k]$ – matrix of coefficients.

The specified solution of equation system (6) equals to:

$$\{Y_{t+\Delta t,k+1}\} = \{Y_{t+\Delta t,k}\} + \{\Delta Y_k\}. \tag{7}$$

Having taken into consideration thermal properties and temperature of bitumen, the presented task enables to determine the distribution of pressure in bitumen drop falling into a mixer or flow by their depth and time. When pressure distribution in a drop is determined, CO_2 distribution in the bitumen binder drop or flow under investigation may be determined from other dependences.

The per cent amount of the batched bitumen in the produced asphalt mixture should comply with the job-mix formula, and its content in separate batches should vary within a narrow range, i.e. it should be stable (consistent). The size of bitumen content dispersion in the produced HMA mixture depends on stochastic factors influenced by the parameters of mixture production technological process, sample taking and random and systematic errors of laboratory tests. When the mass of bitumen batches is not changed in HMA mixture production (there are no systematic errors), its content mixture sample dispersion σ_B^2 consists of dispersions, the correlation of which is presented in the model (Fig. 3).

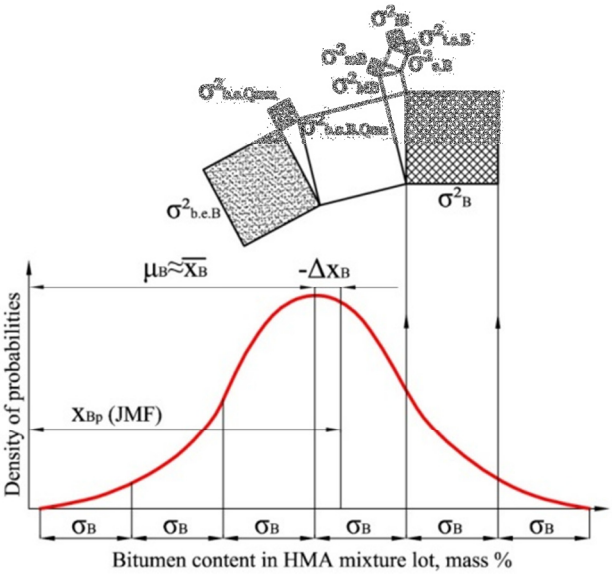

Fig. 3. The model of interrelation between variances constituting bitumen content variance σ_B^2 in HMA mixture lot

$$\sigma_B^2 = \sigma_{iB}^2 + \sigma_{b.e.B}^2 + \sigma_{b.e.Qma}^2 + \sigma_{mB}^2 + \sigma_{t.e.B}^2, \quad (8)$$

where σ_{iB}^2 – is inherent bitumen content variance in HMA lot, depending on the highest possible uniformity of the particles and thickness of the enveloping films; $\sigma_{b.e.B}^2$ is variance caused by batching error of the bitumen mass; $\sigma_{b.e.Qma}^2$ is variance caused by the total batching error of mineral aggregates mass in HMA mix batches; σ_{mB}^2 is variance caused by the error in mixing the materials of HMA mix batch due to mixing drawbacks and mixer's defects; $\sigma_{t.e.B}^2$ is variance caused by HMA sample testing errors. Decreasing the variances described by the model (8), the variance of bitumen content in HMA lot σ_B^2, can be decreased, and more homogenous mixture of higher quality can be obtained.

When applying properties of standard deviations and dispersions, component content dispersion parameters may be calculated having only job-mix formula x_p and component content in HMA mixture sample deviations Δx_i, not

absolute values x_i, which depend on a concrete job-mix formula. It is well-known that during seasonal works AMP produces HMA mixture of various types and marks with various job-mix formula x_p of each component. When investigating AMP capabilities to meet the requirements of statistical tolerances, instead of absolute values x_i deviations Δx_i may be used to calculate standard deviation s_x or dispersion s_x^2. It enables to investigate HMA mixtures of all job-mix formulas as a whole by determining the stability (dispersion and variation) of any component in HMA mixture.

3. Investigation of influence of technological parameters of bitumen batching system on the quality of hot mix asphalt mixture

Having investigated and evaluated standard deviation values of 765 composite samples taken from HMA mixture produced in AMP operating in one asphalt plant during the period of four years, the factual quality of mixture production was identified. To use the technological capabilities of the AMP better, the deviations from JMF of HMA mixture separate components content, obtained from composite sample may be reduced to ±0.4 % (Fig. 4) (instead of currently set ±0.5 or ±0.6 %), mineral fillers to ±2.3 % (instead of ±3.0 %). To obtain specified tolerance values, additional tests of HMA mixtures produced in various AMP should be conducted.

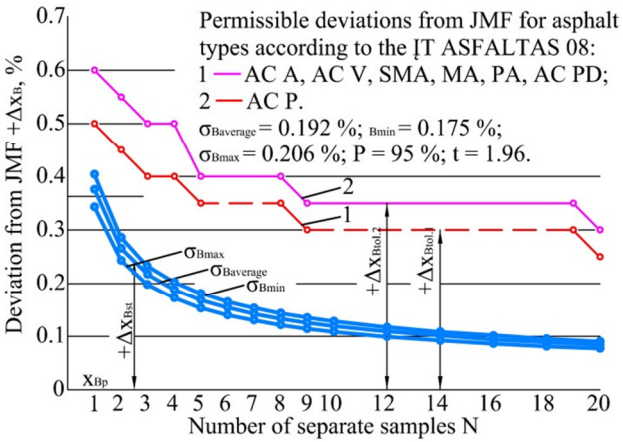

Fig. 4. Recommended values of hot mix asphalt mixture bitumen content statistical tolerances

Having measured the factual outside temperature of separate elements of bitumen transported by AMP thermovision camera, it was determined that energy is lost in BBS and, therefore, it is used ineffectively. Due to unsealed BBS equipment, energy losses increase, it becomes more difficult to control and handle the temperature of bitumen in BBS, viscous bitumen fouling occurs, which inhibit or stop altogether the flow of liquid bitumen in a pipeline. Unevenely sealed and at some places not sealed at all technological equipment frequently become the cause of overheating bitumen.

To avoid cooling in the least sealed places, an operator sets too high temperature of bitumen, which speeds up the degradation of the binder.

4. Experimental investigation of purposive change of bitumen batching system technical and technological parameters of asphalt mixing plant

HMA mixture produced in 2 working seasons in AMP was investigated to determine its production quality. The old BBS was ineffective, difficult to handle and it weighed bitumen not accurately and stably enough. When investigating and evaluating the effectiveness of BBS reconstruction according to the test results of HMA mixture samples, it was found out that standard deviation and arithmetic mean of soluble bitumen content deviations from JMF before and after reconstruction almost did not change. However, having distributed all deviations from JMF by the intervals of 0.10 %, it was identified that before BBS reconstruction 46.9 % of a batch was produced with bitumen debit, out of which 5.7 % with larger than 0.30 % binder debit; whereas after its reconstruction HMA mixture batches produced with bitumen debit made up 40.1 %, out of which 5.2 % with deviation higher than 0.30 %.

The reconstruction of BBS equipment increased the accuracy and stability of batching only insignificantly; however, the production process became easier to handle due to the installed automatic container valves and more dependable pipeline heating system. After reconstruction, the plant may produce asphalt mixtures of various types on the same working day due to additionally installed container.

An active experiment conducted under real asphalt mixture production conditions showed that the method of bitumen discharge from the batcher, its temperature and time of mixing with hot mineral aggregate have impact on the characteristics of bitumen binder in the produced stone mastic asphalt (SMA) mixture. Bitumen short-term ageing process varies due to oxidation when bitumen batch is discharged from the weighing bin into a mixer by mass (Fig. 2) at concentrated high pressure flow (BBS1) and spraying it by high pressure in jets

and drops (BDS2), due to different area of surface interacting with ambient air oxygen. This process is speeded up by high temperature and increasing time of pitch of bitumen.

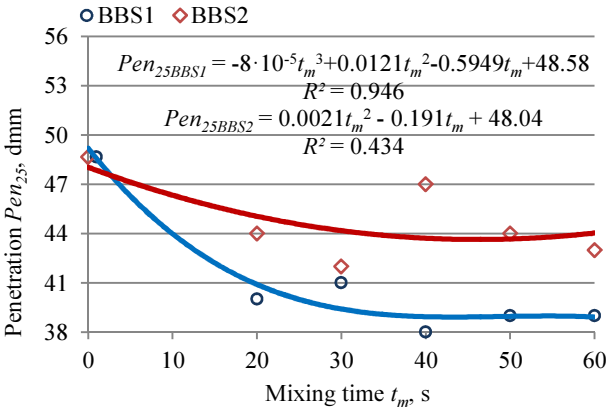

Fig. 5. Dependence of separated soluble bitumen penetration (Pen_{25}) of SMA mixture produced in AMP1 and AMP2 asphalt mixing plants on mixing time

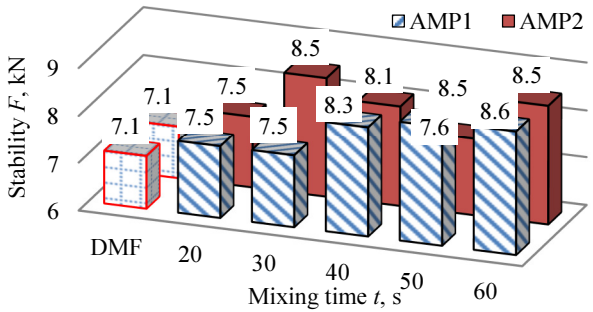

Fig. 6. Stability of stone mastic asphalt mixture

When weighed by different BBS and discharged bitumen is mixed in continuous two-valve AMP mixers of similar parameters from 20 s to 60 s (mixing time is changed by 10 s step), the penetration of soluble bitumen extracted from SMA mixture samples and separated by rotating evaporator (Fig. 5) reduced from 49 dmm to 39 dmm (AMP1) and from 49 dmm to 43 dmm (AMP2), and its softening point increased from 55 °C to 59 °C (AMP1) and from 55 °C to

58 °C (AMP2). It was determined that mixing time has impact on the physical and mechanical properties of SMA mixture. When the mixing time is increased from 20 to 60 s, the maximum density of SMA mixture produced in AMP1 and AMP2 increased, air void content decreased to 1.8–1.9 %. Marshall stability of the samples of the mixture produced in AMP1 increased from 7.5 kN to 8.6 kN when mixing time increased to 60 s, AMP2 – from 7.5 kN to 8.5 kN. When mixing time of SMA mixture is increased, its flow tends to decrease.

General conclusions

1. Deviations of bitumen binder and mineral component content in the produced HMA from job-mix formula (JMF) and dispersion are inevitable due to the stochastic type of technological process, which is effected by the variation of materials‘ properties and separate operations‘ parameters, imperfect structure and varied condition of the equipment construction as well as AMP operator‘s inappropriate actions (human factor). These deviations may be and shall be reduced to statistically and economically sound values.

2. Currently valid deviations from JMF permitted tolerances of bitumen content in asphalt mixture in Lithuania may be tightened. The results of perennial investigation enable to state that liberal values set in the regulating documentation may be reduced: bitumen content identified from single (separate) samples to ±0.4 % (in norms ±0.5 % or ±0.6 %), mineral fillers – to ±2.3 % (in norms ±3.0 %). It is not recommended to change the permitted deviations of sand and crushed stone components.

3. The change of bitumen properties occurring due to short-term oxidation ageing depends on the technology of bitumen batching and discharge into a mixer as well as the time of mixing all asphalt components. During the active experiment conducted in AMP when technological parameters were changed it was found out that when bitumen is batched and mixed, its penetration index increases from –0.1 to 0.12–0.15 when discharging it into a mixer by high pressure in drops, and up to 0.21–0.26 when pouring it at intensive free (gravitational) turbulent flow. When overheated materials are used, the most important factor for bitumen oxidation is not the batching technology but too high temperature of other batched mineral aggregates.

4. When mixing time of SMA 11 S type asphalt mixture is increased from 20 s to 60 s, due to bitumen binder accelerating oxidation impacting on its increasing viscosity and when more and more amount of batched bitumen becomes continuous oriented films of required thickness coating even the finest particles, the most important normative physical and mechanical parameters of asphalt mixture were improved. Air void content of SMA 11 S type asphalt

mixture produced in both AMP according to the same job-mix formula decreased by 30–33 % from 2.7 % (according to JMF) (AMP1 – to 1.6 %, AMP2 – to 1.8 %). When mixed for 20 s, stability by Marshall increased by 13–15 % from 7.5 kN. When mixed for 60 s, flow when mixing materials from 20–30 s to 60 s decreased from 5.4 mm to 3.3 mm; AMP2 – from 4.1 mm to 2.8 mm. When the time of mixing SMA mixture component was increased from 20 s to 60 s, its quality only improved.

5. When investigating the efficiency of BBS reconstruction, it was found out that before reconstruction, 15.13 % of asphalt mixture was dosed with bitumen content deviation from JMF higher than ±0.30 %. When more modern technological equipment was implemented, the deviation of 11.4 % asphalt mixture bitumen binder content was higher than ±0.30 %. In two years after reconstruction, the amount of such mixtures decreased to 8.9 %. The most significant result of BBS reconstruction is its simpler handling enabling to change bitumen batch mass and the mark of batched bitumen immediately and accurately.

6. To maintain sustainable temperature of dried and heated mineral aggregates in AMP during a working day and to reduce the amount of natural gas used to heat them, the stockpiles of these materials should be sheltered. An AMP operator shall constantly monitor the temperature of hot fractions and when it goes up, change the drying-heating mode (intensity of burner's flame) of cold mineral aggregates' immediately. To save energy resources, to reduce air pollution and to protect bitumen from overheating, warm asphalt mixtures may be produced with it instead of hot mix asphalt mixtures. Recently, the use of warm asphalt mixtures has been expanding in the world.

List of published works on the topic of the dissertation

In the reviewed scientific periodical publications

Bražiūnas, J.; Sivilevičius, H. 2013. Dependences of SMA mixture and its bituminous binder properties on bitumen batching system, mixing time and temperature on asphalt on asphalt mixing plant, *Journal of Civil Engineering and Management* 19(6): 862–872. http://dx.doi.org/10.3846/13923730.2013.843587. (*Thomson Reuters ISI Web of Science,* $IF_{2012} = 2.016$).

Bražiūnas, J.; Sivilevičius, H. 2010. The bitumen batching system's modernization and its effective analysis at the asphalt mixing plant, *Transport* 25(3): 325–335. ISSN 1648–4142. http://dx.doi.org/10.3846/transport.2010.40. (*Thomson Reuters ISI Web of Science*).

Bražiūnas, J.; Sivilevičius, H. 2010. Modernizuotos bitumo dozavimo sistemos įtakos karštojo maišymo asfalto mišinio sudėčiai tyrimas / *Mokslas – Lietuvos ateitis: Statyba,*

transportas, aviacinės technologijos = Science – Future of Lithuania: Civil and Transport Engineering, Aviation Technologies. Vilnius: Technika. ISSN 2029-2341. T. 2, Nr. 6 (2010), p. 72–76. (*Index Copernicus*).

In the other editions

Bražiūnas, J.; Sivilevičius, H. 2013. Comparison of not modernized and modernized bitumen batch systems of an asphalt mixing plant / Bražiūnas Justas, Henrikas Sivilevičius // *The Proceedings of the Conference Asphalt Pavements 2013 (AV'2013) = Sbornik pišpěvků pro konference Asfaltové vozovky 2013*. 26-27 November 2013, Czech Republic. Praha : PragoProject, 2013. ISBN 9788090392533. p. 1–9.

Bražiūnas, J.; Sivilevičius, H. 2011. Statistical analysis of component content deviation from job-mix formula in hot mix asphalt, *8th International Conference „Environmental Engineering"*, May 19–20, 2011, Vilnius, Lithuania: selected papers. Vol. 3. *Sustainable Urban development. Roads and Railways. Technologies of Geodesy and Cadastre*. Vilnius: Technika, 2011. ISSN 2029-7106. ISBN 9789955288299. p. 1044–1050. (*ISI Proceedings*)

About the Author

Justas Bražiūnas was born in Kupiškis on 21 of September, 1984. In 2007, he graduated from the Faculty of Transport Engineering of the Vilnius Gediminas Technical University with a degree in Transport Engineering. Later he acquired a Master's degree in Transport Engineering at the same Faculty in 2009. In 2009–2013, he was a doctoral student at the Vilnius Gediminas Technical University. Since 2007 till present Justas Bražiūnas has been working in JSC "Gitana". Since 2012 till present – junior researcher at the Department of Transport Technological Equipment, Vilnius Gediminas Technical University.

Acknowledgment

A lot of specialists and researchers in the field of transport and road pavement construction and bitumen mixture production contributed to this dissertation. I would like to express my sincere gratitude to:

- Road and street construction and building company *Fegda* and its Production Manager Mr Alfredui Meslinas and all production staff for provided opportunities to study bitumen batching systems and HMA mixture production processes. The head of the laboratory Mr Romualdas Virbickas and all laboratory staff of the company *Fegda* for assistance when conducting experimental investigations under real production conditions.

– Mr Irmantas Truska, Head of JSC *Lemminkainen Lietuva L*aboratory, Mr Vladimir Ščerbak, Production Manager, and all company staff for their assistance, valuable practical advice and consultations.

I would also like to express my special gratitude for scientific work supervisor Prof Dr Habil Henrikas Sivilevičius for his support during my studies and provided invaluable knowledge, the authorities of the Transport Technological Equipment Department and all Transport Engineering Faculty, colleagues, dissertation experts for their valuable and improvement enhancing critics, meaningful advice. I am also grateful to my family, close people, colleagues and friends for their support and understanding.

ASFALTO MAIŠYTUVO BITUMO DOZAVIMO SISTEMOS TECHNOLOGINIŲ PARAMETRŲ TYRIMAS

Problemos formulavimas

Skirtingų bitumo dozavimo sistemų, turinčių atlikti tas pačias funkcijas, konstrukcija veikiančiuose asfalto maišytuvuose skiriasi. Konstrukcijos skirtumai ir valdymo būdai turi nevienodą įtaką talpyklose, technologiniame vamzdyne ir dozatoriuje vykstantiems procesams ir ne visuomet atitinka keliamus reikalavimus gaminamo asfalto mišinio kokybei. Reikia turėti arba sukurti tokią technologinių parametrų gerinimo (laidavimo) sistemą, kuri leistų užtikrinti, kad technologiniame įrenginyje transportuojamas skystis nesugestų (kokybės parametrai pablogėtų minimaliai), o dozatorius svertų (matuotų) reikiamos masės bitumo dozes (dozavimo procesas vyktų maksimaliai tiksliai ir stabiliai). Taip pat reikia, kad sistema būtų funkcionali, ekonomiška energiniu požiūriu, ekologiška ir moderni.

Darbo aktualumas

Automobilių kelių asfalto dangai tiesti ir prižiūrėti Lietuvoje skiriamos didžiulės, tačiau vis dar nepakankamos lėšos, dėl to jų būklė labai negerėja. Nepalankios Lietuvos klimato sąlygos, kai aplinkos oro temperatūra kinta nuo minus 30 °C iki plius 30 °C ir iš teigiamos į neigiamą pasikeičia apie 60–80 kartų per metus, o vandens kiekis asfalto dangos sluoksnio atvirose oro tuštymėse svyruoja plačiame rėžyje, nulemia kelio dangos pažaidų ir deformacijos mastą ir didėjimo spartą. Karštojo maišymo asfalto mišinyje esančio bitumo reikiamo kiekio ir savybių užtikrinimas nulemia nutiestos asfalto kelio dangos ilgalaikį mechaninį stiprumą ir reikiamas kelio eksploatacines savybes. Gaminant karšto maišymo asfalto mišinį transporto technologiniame įrenginyje – asfalto maišytuve, bitumo dozavimo ir komponentų sumaišymo technologi-

niuose procesuose sudaryti mišinio struktūros ir sąveikos ryšiai užtikrina ilgalaikį iš jo įrengtos kelio dangos stiprį, tekstūrą, lygumą, mažą pažaidų skaičių ir reologines savybes.

Tyrimų objektas

Tyrimų objektas – asfalto maišytuve transportuojamo bitumo dozavimo sistemos ir maišyklės technologiniai parametrai ir jų įtaka karšto maišymo asfalto mišinio gamybos kokybei.

Darbo tikslas

Darbo tikslas – pateikti moksliškai pagrįstus periodinio veikimo asfalto maišytuve transportuojamo bitumo dozavimo sistemos technologinius parametrus, leisiančius pagerinti karšto maišymo asfalto mišinio gamybos kokybę.

Darbo uždaviniai

Darbo tikslui pasiekti buvo iškelti šie uždaviniai:

1. Ištirti bituminio rišiklio klampos, efektyviojo bitumo kiekio ir oro tuštymių kiekio kaitos įtaką karšto maišymo asfalto dinaminio modulio pokyčiui.
2. Ištirti bitumo dozavimo, išpylimo į maišyklę ir maišymo technologinėse operacijose vykstančios deguonies difuzijos į bitumą, karbonilų junginių susidarymo procesus ir jų įtaką karštojo rišiklio savybių kitimui trumpalaikio senėjimo laikotarpiu.
3. Nustatyti ir susisteminti svarbiausius veiksnius, lemiančius bitumo kiekio karšto maišymo asfalto mišinio partijoje dispersijos dydį. Ištirti faktiškąsias komponentų kiekio pagamintame karšto maišymo asfalto mišinyje nuokrypių nuo darbinės mišinio formulės vertes ir jas pritaikyti šių komponentų kiekio sklaidos leidžiamiesiems parametrams skaičiuoti.
4. Tiriant bitumo dozavimo sistemos techninį modernizavimą ir gamybos valdymo pasikeitimus nustatyti, kiek pakito bitumo kiekio karšto maišymo asfalto mišinyje nuokrypiai nuo darbinės mišinio formulės.
5. Atlikti aktyvųjį eksperimentą gamybos sąlygomis, kai skirtingų bitumo dozavimo sistemų dviem periodinio veikimo asfalto maišytuvais gaminamas karšto maišymo asfalto mišinys keičiant medžiagų maišymo trukmę ir temperatūrą, leidžiantį nustatyti šių technologinių veiksnių įtaką bitumo savybių ir asfalto mišinio Maršalo bandinių fiziniams ir mechaniniams rodikliams.

Tyrimų metodai ir įranga

Darbe taikyti šie metodai: pasyvieji ir aktyvieji eksperimentiniai tyrimai realiomis gamybos sąlygomis, ėminių tyrimo laboratorijoje, matematinės statis-

tikos, matematinio modeliavimo metodai. Tyrimams naudoti *Statgraphics Centurion XVI, SPSS 16* programiniai paketai. Panaudoti šie duomenys: laboratorinių tyrimų duomenys iš trijų akredituotų laboratorijų; dviejų asfalto maišytuvų valdymo kompiuterių duomenys. Panaudota įranga: termografinių tyrimų infraraudonųjų spindulių kamera *IR-Flexcam Pro*; nekontaktinis termometras, bitumo ir asfalto mišinio ėmikliai, ekstraktorius, sukusis garintuvas, sijotuvas ir sietų komplektas, penetrometras *Humboldt H-2510*; minkštėjimo temperatūros nustatymo (žiedo ir rutulio) prietaisas, Maršalo bandinių gamybos, svėrimo, šildymo vandenyje ir gniuždymo įrenginiai.

Darbo mokslinis naujumas

1. Teoriniu tyrimu apskaičiuota, kad bitumo dozavimo sistemos technologiniai parametrai – bitumo dozių masės procentiniai nuokrypiai, turintys įtakos efektyviojo bitumo kiekiui ir oro tuštymėms, temperatūra, nulemianti klampą, yra reikšmingi veiksniai, turintys įtakos pagaminto karšto maišymo asfalto mišinio dinaminiam moduliui.
2. Pateiktas matematinis modelis leidžia nustatyti deguonies slėgio pasiskirstymą bėgant laikui į maišyklę krintančiame skirtingo dydžio bitumo laše, kai įvertinama deguonies difuzija, priklausanti nuo temperatūros ir šilumos laidumas, priklausantis nuo temperatūros, tankio ir specifinės šilumos.
3. Pateiktas bitumo kiekio, pagaminto karšto maišymo asfalto mišinio partijoje (vienos dienos arba vieno sudėties projekto), sklaidos parametro (dispersijos) modelis, kuriame atskleista atskirų veiksnių dispersijų įtaka ir sietis.
4. Įrodyta, kad šiuo metu Lietuvoje galiojantys norminiai dokumentai, reglamentuojantys karšto maišymo asfalto mišinio bitumo ir mineralinių miltelių kiekio leidžiamuosius nuokrypius nuo darbinės mišinio formulės, yra pakankamai liberalūs ir ne visada atitinka realias nuolat tobulinamų asfalto maišytuvų technines galimybes.
5. Aktyviuoju eksperimentiniu tyrimu, atliktu realiomis gamybos sąlygomis, nustatyta, kad bituminio rišiklio, esančio pagamintame karšto maišymo asfalto mišinyje, savybėms įtakos turi bitumo išpylimo iš dozatoriaus į maišyklę būdas, medžiagų temperatūra ir maišymo su karštosiomis mineralinėmis medžiagomis trukmė.

Darbo rezultatų praktinė reikšmė

1. Pateiktas karšto maišymo asfalto mišinio vidinės gamybos kontrolės įvertinimo ir pagerinimo būdas, leidžiantis iš atskirų rūšių ir tipų asfalto mišinių, pagamintų kiekviename asfalto maišytuve per darbų sezoną, komponentų kiekių faktiškųjų nuokrypių nuo darbinės mišinio formulės, kurių imtys

būna mažos, apskaičiuoti dėl didelės imties patikimus šių komponentų padėties ir sklaidos parametrus.

2. Pasyvieji ir aktyvieji eksperimentiniai tyrimai atlikti trijuose Lietuvoje veikiančiuose asfalto maišytuvuose realiomis gamybos sąlygomis, todėl disertacinio darbo tyrimų rezultatai, įrodantys būtinybę mažinti medžiagų temperatūrą, yra aktualūs karšto maišymo asfalto mišinio gamybos įmonėms ir juos panaudojus leidžia gamyklų personalui gerinti KMA gamybos proceso kokybę.

3. Įrodyta, kad Lietuvoje galiojančiose įrengimo taisyklėse ĮT ASFALTAS 08 reglamentuojami karšto maišymo asfalto mišinio bitumo ir mineralinių miltelių kiekio leidžiamieji nuokrypiai nuo darbinės mišinio formulės gali būti mažinami. Komponentų kiekio karšto maišymo asfalto mišiniuose tolerancijų patikslintas skaitines vertes naujos redakcijos įrengimo taisyklėse bus galima pateikti tik atlikus papildomus kitų modelių asfalto maišytuvų pagamintų mišinių tyrimus.

Ginamieji teiginiai

1. Bitumo dozavimo sistemoje vykstančių technologinių bitumo maišymo su mineralinėmis medžiagomis procesų parametrai turi stochastinį pobūdį ir įtakos bituminio rišiklio sudėčiai bei gaminamo karšto maišymo asfalto mišinio fizinėms ir mechaninėms savybėms: oro tuštymių kiekiui, pastovumui, takumui, Maršalo koeficientui ir dinaminiam moduliui.

2. Dėl oksidacijos vykstanti bitumo savybių kaita priklauso nuo bituminio rišiklio dozavimo ir išpylimo į maišyklę technologijos. Išpurškiant bitumą aukšto slėgio čiurkšle ir išpilant jį didelio debito gravitaciniu srautu į maišyklę, jo penetracija sumažėja, o minkštėjimo temperatūra padidėja nevienodai.

3. Perkaitinus mineralines medžiagas bituminio rišiklio trumpalaikiam oksidaciniam senėjimui svarbiausiu veiksniu tampa ne bitumo dozavimo ir išpylimo technologija, o su juo maišomų mineralinių medžiagų temperatūra.

4. Kai kurie šiuolaikiniai asfalto maišytuvai geba kokybiškiau gaminti karšto maišymo asfalto mišinį nei to reikalauja normos. Įrengimo taisyklėse ĮT ASFALTAS 08 pateiktos statistinės tolerancijos, atlikus išsamesnius tyrimus su daugiau asfalto maišytuvų ir patvirtinus šiame darbe gautas išvadas, gali būti pagrįstai mažinamos. Mažesnės tolerancijos leistų pagerinti gamybos kokybę ir geriau išnaudoti asfalto maišytyvų konstrukcines galimybes.

Darbo struktūra

Disertaciją sudaro įvadas, 4 skyriai, bendrosios išvados, literatūros sąrašas, publikacijų sąrašas ir 5 priedai.

Darbo apimtis – 138 puslapių be priedų. Tekste panaudota: 86 numeruotos formulės, 53 paveikslėliai ir 16 lentelių. Rašant disertaciją vadovautasi 142 mokslinės literatūros ir kitais šaltiniais.

Pirmame skyriuje atlikta mokslo darbų, skirtų bitumo savybių kitimo technologiniuose įrenginiuose ir asfalto dangos sluoksnyje veiksniams tirti, analizė.

Antrasis skyrius skirtas bitumo savybių kaitos procesų jį naudojant technologiniuose įrenginiuose modeliavimui.

Trečiajame skyriuje pateikti bitumo dozavimo sistemos technologinių parametrų įtakos karštojo maišymo asfalto mišinio kokybei tyrimo rezultatai.

Ketvirtajame skyriuje aprašomi du eksperimentiniai tyrimai atlikti realios gamybos sąlygomis: bitumo dozavimo sistemos modernizavimo ir jo veiksmingumo tyrimas ir medžiagų maišymo trukmės ir temperatūros įtakos bitumo ir su juo pagaminto skaldos ir mastikos asfalto mišinio savybėms tyrimas.

Bendrosios išvados

1. Bituminio rišiklio ir mineralinių komponentų kiekio gaminamame KMA mišinyje nuokrypiai nuo darbinės mišinio formulės (DMF) ir sklaida yra neišvengiami dėl technologinio proceso stochastinio pobūdžio, nulemto medžiagų savybių variacijos, atskirų operacijų parametrų kaitos, netobulos įrenginių konstrukcijos ir pakitusios būklės, taip pat netinkamų ASMA operatoriaus veiksmų (žmogiškojo veiksnio). Šiuos nuokrypius galima ir būtina sumažinti iki statistiškai ir ekonomiškai pagrįstų verčių.

2. Šiuo metu Lietuvoje galiojančios bitumo kiekio asfalto mišinyje nuokrypių nuo DMF leidžiamosios vertės (tolerancijos) yra pakankamai liberalios. Daugiamečio tyrimo rezultatai leidžia teigti, kad reglamentuojančiuose dokumentuose pateiktos tolerancijų vertės gali būti mažinamos: bitumo kiekio, nustatyto iš sudėtinių ėminių iki ±0,4 % (normose ±0,5 % arba ±0,6 %), mineralinių miltelių – iki ±2,3 % (normose ±3,0 %). Keisti smėlio ir skaldos komponentų leidžiamuosius nuokrypius nerekomenduojama. Patikslintas vertes bus galima nustatyti atlikus daugiau tyrimų ir kituose ASMA.

3. Dėl trumpalaikio oksidacinio senėjimo vykstanti bitumo savybių kaita priklauso nuo jo dozavimo ir išpylimo į maišyklę technologijos, temperatūros, taip pat visų asfalto komponentų maišymo trukmės. Aktyviuoju eksperimentu, atliktu ASMA keičiant technologinius parametrus, ištirta, kad dozuojant ir maišant bitumą, jo penetracijos indeksas išpilant jį į maišyklę aukštu slėgiu lašais padidėja nuo –0,1 iki +0,12–0,15, o pilant intensyviu laisvu (gravitaciniu) turbulentiniu srautu nuo –0,1 iki +0,21–0,26. Naudojant perkaitintas mineralines medžiagas, svarbiausias bitumo oksidacijai veiksnys yra ne dozavimo technologija, o kitų sudozuotų mineralinių medžiagų per aukšta temperatūra.

4. Didinant SMA 11 S tipo asfalto mišinio maišymo trukmę nuo 20 s iki 60 s, dėl bituminio rišiklio spartėjančios oksidacijos, nulėmusios jo klampos padidėjimą, ir vis daugiau sudozuoto bitumo iš tūrinio būvio virtus ištisinėmis reikiamo storio orientuotomis plėvelėmis, dengiančiomis ir smulkiausius grūdelius, gerėjo asfalto mišinio svarbiausi normuotieji fiziniai ir mechaniniai rodikliai. Abiejuose ASMA pagal tą patį sudėties projektą pagaminto SMA 11 S tipo asfalto mišinio oro tuštymių kiekis nuo 2,7 % (pagal DMF) sumažėjo 30–33 % (ASMA1 – iki 1,6 %, ASMA2 – iki 1,8 %). ASMA1 pagaminto mišinio bandinių pastovumas pagal Maršalą didėja nuo 7,5 kN iki 8,6 kN ilgėjant maišymo trukmei iki 60 s, ASMA2 – nuo 7,5 kN iki 8,5 kN. Takumas turi tendenciją mažėti, kai SMA mišinio maišymo trukmė ilgėja.Didinant SMA mišinio komponentų maišymo trukmę nuo 20 s iki 60 s, jo kokybė tik gerėjo.

5. Tiriant techninį BDS modernizavimo efektyvumą nustatyta, kad prieš modernizavimą 15,3 % asfalto mišinio buvo dozuojama su didesniu nei ±0,30 % bitumo kiekio nuokrypiu nuo DMF. Įdiegus pažangesnius technologinius įrenginius, 11,4 % asfalto mišinio bituminio rišiklio kiekio nuokrypis buvo didesnis nei ±0,30 %. Praėjus dvejiems metams po modernizavimo, tokių mišinių sumažėjo iki 8,9 %. Svarbiausias BDS modernizavimo rezultatas yra jos paprastesnis valdymas, leidžiantis nedelsiant ir tiksliai pakeisti bitumo dozės masę ir dozuojamo bitumo markę.

6. Siekiant, kad išdžiovintų ir įkaitintų mineralinių medžiagų temperatūra ASMA būtų kuo tolygesnė per darbo dieną, joms pakaitinti būtų sunaudojama mažiau gamtinių dujų, būtina šių medžiagų rietuves uždengti stoginėmis. ASMA operatorius turi nuolat stebėti karštųjų frakcijų temperatūrą ir jai pakilus iki neleistinos ribos nedelsiant keisti šaltųjų mineralinių medžiagų džiovinimo-kaitinimo režimą (degiklio liepsnos intensyvumą). Taupant energinius išteklius, mažinant aplinkos oro taršą ir siekiant apsaugoti bitumą nuo perkaitinimo su juo vietoje karštojo maišymo asfalto mišinio galima gaminti šiltuosius asfalto mišinius, kurių panaudojimas pastaruoju metu pasaulyje nuolat plečiasi.

Trumpos žinios apie autorių

Justas Bražiūnas 1984 m. rugsėjo 21 d. Kupiškyje.
Vilniaus Gedimino technikos universiteto Transporto inžinerijos fakultete 2007 m. įgijo transporto inžinerijos bakalauro laipsnį, 2009 m. – transporto inžinerijos magistro laipsnį. 2009–2013 m. – Vilniaus Gedimino technikos universiteto doktorantas. Nuo 2007 m. iki šiol Justas Bražiūnas dirba įmonėje UAB „Gitana“. Nuo 2012 m. iki šiol jaunesnysis mokslo darbuotojas Vilniaus Gedimino technikos universiteto Transporto inžinerijos fakulteto Transporto technologinių įrenginių katedroje.

Justas BRAŽIŪNAS

INVESTIGATION OF TECHNOLOGICAL PARAMETERS OF BITUMEN BATCHING SYSTEM IN THE ASPHALT MIXING PLANT

Summary of Doctoral Dissertation
Technological Sciences, Transport Engineering (03T)

Justas BRAŽIŪNAS

ASFALTO MAIŠYTUVO BITUMO DOZAVIMO SISTEMOS TECHNOLOGINIŲ PARAMETRŲ TYRIMAS

Daktaro disertacijos santrauka
Technologijos mokslai, transporto inžinerija (03T)

2013 12 27. 1,5 sp. l. Tiražas 70 egz.
Vilniaus Gedimino technikos universiteto
leidykla „Technika“,
Saulėtekio al. 11, 10223 Vilnius,
http://leidykla.vgtu.lt
Spausdino UAB „Ciklonas“
J. Jasinskio g. 15, 01111 Vilnius