VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Darjušas MUČINIS

MODELLING OF THE INTERACTION COMPONENT'S OF RECYCLED HOT MIX ASPHALT AND RESEARCH ITS USE IN THE ROAD PAVEMENT CONSTRUCTION

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
CIVIL ENGINEERING (02T)

VGTU
LEIDYKLA
TECHNIKA
Vilnius 2011

Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2006–2011.

Scientific Supervisor

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

Consultant

Prof Dr Habil Henrikas SIVILEVIČIUS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T).

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

Chairman

Prof Dr Habil Edmundas Kazimieras ZAVADSKAS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T).

Members:

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

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

Prof Dr Habil Vytautas STANKEVIČIUS (Kaunas University of Technology, Technological Sciences, Civil Engineering – 02T),

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

Opponents:

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

Assoc Prof Dr Dainius MIŠKINIS (Lithuanian road administration under the ministry of Transport and Comunication, Civil Engineering – 02T).

The dissertation will be defended at the public meeting of the Council of Scientific Field of Civil Engineering in the Senate Hall of Vilnius Gediminas Technical University at 10 a. m. on 20 January 2012.

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 19 December 2011.

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).

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Darjušas MUČINIS

KARŠTAI REGENERUOTO ASFALTO MIŠINIO KOMPONENTŲ SĄVEIKOS MODELIAVIMAS IR JO NAUDOJIMO KELIŲ DANGOS KONSTRUKCIJOJE TYRIMAS

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
STATYBOS INŽINERIJA (02T)

VGTU
LEIDYKLA
Vilnius TECHNIKA 2011

Disertacija rengta 2006–2011 metais Vilniaus Gedimino technikos universitete.

Mokslinis vadovas

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

Konsultantas

prof. habil. dr. Henrikas SIVILEVIČIUS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

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

Pirmininkas

prof. habil. dr. Edmundas Kazimieras ZAVADSKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Nariai:

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

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

prof. habil. dr. Vytautas STANKEVIČIUS (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija – 02T),

dr. Audrius VAITKUS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Oponentai:

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

doc. dr. Dainius MIŠKINIS (Lietuvos automobilių kelių direkcija prie Susisiekimo ministerijos, statybos inžinerija – 02T).

Disertacija bus ginama viešame Statybos inžinerijos mokslo krypties tarybos posėdyje 2012 m. sausio 20 d. 10 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 2011 m. gruodžio 19 d.

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

VGTU leidyklos „Technika“ 1960-M mokslo literatūros knyga.

Introduction

Topicality of the problem. The freedom of movement is one of the fundamental human values, which is implemented by developing the transport system. Most passengers and cargoes are transported by road nowadays, the efficiency of which depends on the performance properties of asphalt pavement. The properties of asphalt pavement deteriorate under the influence of destructive factors, and the application of recycling methods and technologies does not always provide a strong and durable recycled pavement layer. It can also be due to the insufficient study of the interaction processes between old and virgin materials, and of the factors affecting variation, which depends on the specific and unpredictable conditions.

The usual in Lithuania one life-cycle of asphalt pavement does not meet the needs of the contemporary and future society and road builders because of the increased price and depletion of crude oil and mineral material resources, the extraction of different components from crude oil for the production of fuels and chemicals, and the protection of the environment against pollution caused by waste material. By pursuing the economic benefits, new methods are being developed to reuse (i.e., to recycle) the waste asphalt pavement material.

Research object. The homogeneity of asphalt pavement granules, which are not suitable for operation; their interaction with rejuvenators; physical-mechanical properties of the recycled hot-mix asphalt mixture; rutting resistance of the recycled HMA mixture; the minimum allowed quantity of RAP granules used in the production of HMA mixture.

Aim and task of the work. Aim of the work – to provide a scientifically-based model of dynamics of the interaction between the components and the results of this interaction, this should help to design and produce high quality HMA mixtures with granules of recycled asphalt pavement of Lithuanian roads. In order to achieve the aim of the research, the following tasks were set:

1. To analyze the world scientific literature on the asphalt pavement recycling-related problems and the possible solutions to these problems; factors affecting asphalt pavement distresses and their influence on the performance of recycled asphalt; the interaction between old and virgin materials; the properties of recycled asphalt mixture; and the recycling process technologies.
2. To model factors determining the homogeneity of recycled asphalt.
3. To model the theoretical viscosity for two types of blended bitumen or for another rejuvenating agents, and the dynamics of old and virgin bitumen blending due to the diffusion process occurring in the two-layer film.
4. To provide systemized scientific principles of asphalt pavement recycling.

5. To study the dynamics in the use of recycled asphalt pavement in foreign countries and in Lithuania.

6. To study the component composition and properties of granules of milled, broken and crushed recycled asphalt taken from Lithuanian roads and city streets.

7. To determine the influence of rejuvenating bitumen type and its percentage amount on the physical and mechanical Marshall parameters of recycled hot mix asphalt (HMA) mixture and on the properties of recycled total bitumen.

8. To determine the rutting resistance of recycled HMA mixture by taking different amounts of granules of recycled asphalt.

9. To provide new deterministic and stochastic modeling methods to determine the influence of the amount and properties of granules of recycled asphalt on the component composition and homogeneity of recycled HMA mixture.

Research methodology. The following research methods were used in this paper: mathematical analytical, graphical and mathematical modeling, mathematical statistics; experimental laboratory, stochastic modeling; experimental in situ (properties of recycled asphalt pavement).

Scientific novelty

1. There is a hypothesis that the old and not suitable for service asphalt pavement material taken from roads or other elements of transport infrastructure (e.g. airport pavement, parking lots) can be successfully reused provided that the properties of old asphalt are restored close to the properties of HMA mixture (in compliance with the normative documents of the country), for the production of which only virgin material is used.

2. Factors determining the inhomogeneity of granules of recycled asphalt were systemized and modeled, their stochastic nature and unpredictability of influence on the homogeneity were determined.

3. The process of mechanical and diffusion blending of old bitumen (present in RAP) and rejuvenating virgin binder and the viscosity of total bitumen, and the process taking place in two-layer films coating mineral particles were modeled.

4. A scientifically-based asphalt pavement recycling principles were systemized and can be used in practice in combination with theoretical regulations in order to produce recycled HMA mixtures of proper structure and good properties.

5. The data on the extraction and use of RAP granules in Lithuanian road construction companies was collected for the first time. It shows that the amounts of this material available in Lithuania and in other foreign countries are rather large and have a tendency to increase each year.

6. The component homogeneity of granules of recycled asphalt was determined and statistically evaluated by the performance of experiments on

representative samples. The original comparison methodology of dispersion of granulometric composition was provided.

7. The influence of different types and amounts of rejuvenating virgin bitumen on the physical and mechanical characteristics (determined in accordance with the Marshall Method) of recycled HMA mixture was studied.

8. The dependence of old bitumen, present in recycled asphalt, standard properties restored by virgin (rejuvenating) bitumen, on the percentage amount and type of rejuvenator was determined. It helped to evaluate the efficiency of the recycling process.

9. The influence of recycled asphalt on the rutting resistance of recycled HMA mixture was determined by taking flat specimens of different reclayment asphalt pavement (RAP) amounts, the same granulometric composition and optimal amount of total bitumen and by performing wheel tracking tests.

10. The method for the determination of the maximum allowable amount of granules of recycled asphalt in recycled HMA mixture was provided. This method was based on the deterministic and stochastic modeling. It helped to obtain recommended numerical values of RAP amount of the individual components differentiated in accordance with the type and the intended use of the mixture.

Practical value of the work results. The scientifically-based methods proposed to improve the quality of produced in Lithuania HMA mixtures with RAP granules:

1. It is proved that RAP granules should be milled off, loaded, transported and stored in such a way that ensures the maximum homogeneity of the recyclable material and ensures that rain water would not get into it, and that the material would not transform into hard lumps under the influence of the sun's rays heat. The RAP granules milled from different roads must be stored into separate stockpiles. When it is not possible, the material is homogenized by a special machine or by mixing with a loader.

2. The study was conducted to determine the dynamics of the long-term blending (due to the diffusion process) of old and virgin recyclable bitumen films. It is not recommended to immediately open the road, which was repaired by the asphalt Remixer, to the traffic until the structure of total bitumen two-layer films would reach the stable preventing the occurrence of ruts.

3. The allowable amount values of recycled HMA mixture components determined by deterministic and stochastic optimization methods can be used to improve the normative documents for the technical requirements, the maximum allowable amount of RAP granules.

Defended propositions

1. Not suitable for service asphalt pavement material can be successfully reused in producing HMA mixtures, provided that the properties of such materials are restored to the required initial level.

2. Traffic and environmental factors affect the condition of asphalt pavement; however it is not the granulometric composition that deteriorates but rather the organic binder (bitumen), which can be restored by using the additional softening and rejuvenating agents, including virgin and more liquid bitumen.

3. A large componential inhomogeneity of granules of milled or broken and crushed asphalt pavement layer limits their maximum amount which can be used.

4. The films of old and virgin bitumen interact during the recycling technological process; a long period of final blending of these films, occurring due to the diffusion, determines the time-varying properties and structure of recycled HMA mixture.

5. The strength properties (determined by the wheel-tracking tests) of Marshall specimens of a properly designed recycled HMA mixture can be no worse than those of HMA mixture produced of virgin materials only.

6. By increasing the percentage of inhomogeneous RAP granules in the recycled HMA mixture, the dispersion parameters of its composition, determined by stochastic modeling of the granulometric composition, are increasing proportionally.

The scope of the scientific work. The dissertation work consists of introduction, four research chapters, conclusions, list of literature, and list of publications. The total volume of the dissertation is 105 pages, 37 numbered formulas, 31 figures and 9 tables.

1. Review on the research study of asphalt pavement recycling

The asphalt pavement being exposed to the destructive factors (transport means, climate and weather conditions) at some point of its service life begins to deteriorate (to wear out and to deform) – damaged pavement reduces traffic speed and comfort, and increases the number of accidents, fuel consumption and vehicle maintenance costs. When the extent of asphalt pavement deterioration reaches a critical level, the course of asphalt pavement is broken or milled off, and the material is recycled. The study of asphalt pavement deterioration causes, dynamics and the influence of factors on the type of distress can be found in the scientific works of Lithuanian and foreign researchers. Studies have shown that one of the most important causes of asphalt pavement deterioration is the ageing of bituminous binder due to oxidation and other factors.

Laboratory tests were conducted in order to make sure that the quality of HMA mixture produced by using RAP granules can be no worse than those of HMA mixture produced of virgin materials only. It has been shown that HMA mixture produced by using a certain amount of RAP granules generally meets

the requirements of standards, provided that the properties and granulometric composition of RAP old binder are properly determined, a proper rejuvenator and its optimal amount are selected, and provided that virgin mineral materials (improving the granulometry) are added.

Research-based methods were used to design a recycled HMA mixture of optimal composition, industrially produced in accordance with a specific technology, which depends on Remixer construction. The production of recycled HMA mixture in large quantities began only after the development of asphalt mixing plants (AMP) equipped with additional mechanisms for receiving, transporting (and heating) and dosing RAP granules. RAP granules can be delivered to AMP sites (mechanisms). The variety of locations of AMP, where RAP granules are delivered to, has both advantages and disadvantages. Bitumen oxidizes and ages in AMP mechanisms or in Remixer. The structure of old and virgin bitumen films varies due to the different recycling technologies applied to HMA mixture. Therefore, the quality of recycled asphalt pavement course is not always the same.

2. Theoretical modeling of the quality of recycled asphalt and of recycling processes

The homegeneity of recycled asphalt pavement to be reclaimed depends on different factors that may be grouped by three stages of pavement life-cycle: construction of asphalt pavement, maintenance and repair, cold milling of asphalt pavement or crumbling of debris.

The initial inhomogeneity of a newly laid asphalt pavement is exposed to the effects of climate and weather and axial load of transport means and this leads to the decrease in the value of strength coefficient. This variable impact contributes to the wear of asphalt pavement and the occurrence of damages on pavement surface course. The elimination of these defects requires the use of different additional materials and technologies. These additional materials get into the recycled asphalt granules (Fig. 1).

The average content of bitumen (%) in milled RAP granules ($\overline{B}_{RA}$) is generally higher than in virgin HMA pavement ($\overline{B}_{HMA}$). The increase of bitumen content in RAP by an average value ($\overline{B}_{MRM}$) is explained by a higher average content per mass unit of road pavement of bitumen materials consumed during the maintenance and repair works:

$$\overline{B}_{RA} = \overline{B}_{HMA} + \overline{B}_{MRM} . \quad (1)$$

The homogeneity of RAP is estimated based on the variation parameters of each selected quality indicators: variance σ^2 or standard deviation σ. The total variance of ready-for-use RAP i component content or its property indicator (σ^2_{iRA}) is calculated by the following additive model:

$$\sigma^2_{iRA} = \sigma^2_{i1} + \sigma^2_{i2} + \sigma^2_{i3}, \qquad (2)$$

where σ^2_{i1} stands for the variance of i component in the new RAP; σ^2_{i2} refers to the variance of i component increased due to the use of additional repair materials, changing the componential structure of asphalt, and due to the ageing of bitumen at the end of RAP operation period; σ^2_{i3} means the variance of i component increased due to the fact that RAP removed from pavements of different roads and streets is stored unsorted in a single stockpile and also due to its segregation.

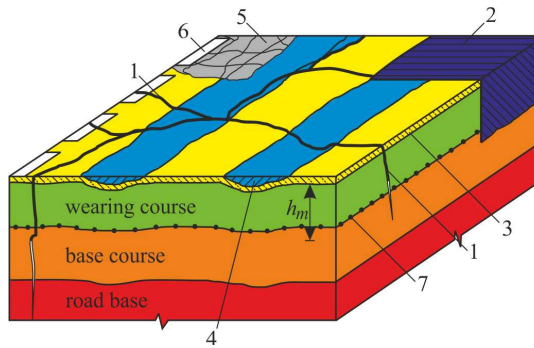

Fig. 1. Fragment showing the distribution of additional materials used for increasing the homogeneity of RAP, improving its surface texture and repairing damages: 1 – paste, emulsified asphalt or bitumen for filling cracks; 2 – asphalt mixture and bitumen priming for filling pot-holes; 3 – bitumen binder and mineral aggregates of surface coating; 4 – asphalt mix or sluri seal for filling ruttings; 5 – layer of emulsified asphalt and filler for sealing the net of cracks; 6 – horizontal pavement marking materials; 7 – geogrid or geotextile with emulsified asphalt; h_m – average depth of milling (normally from 40 to 100 mm)

The actual homogeneity of ready-for use RAP added in producing HMA mixture depends on the above-mentioned factors, the actual parameters whereof are of a stochastic nature and may substantially vary. Therefore, the actual values for the content of RAP components as well as for the variances of their

properties and standard deviations will be determined based on the experimental data rather than using theoretical models.

During the recycling process, the properties of aged bitumen (viscosity, chemical composition, adhesion, and cohesion) can be restored to the initial level or a level near it. The granulometric composition of RAP is also occasionally improved. During the recycling of RAP granules, only additional materials can be added, yet no components of RAP granules can be withdrawn.

A liquid rejuvenating material is poured to the heated mixing RAP granules; it turns from bulk condition into films coating all of the mineral particles. It is necessary to make sure that all particles of different sizes are coated with continuous films of the required thickness.

The proportion between the aged and virgin binder can be estimated by using viscosity mixing rule (Arrenius 1887), so that the resultant mix achieves the target viscosity at the reference temperature:

$$\ln(\eta_{mix}) = x \cdot \ln(\eta_1) + \cdot \ln(\eta_2) + x \cdot (1 - x) \cdot G_{12}\,, \tag{3}$$

where η_{mix} is the viscosity of the mixture; η_1 and η_2 – viscosity of binder 1 and 2 respectively; x is the volume percentage of binder 1 and G_{12} an interaction factor between binder 1 and 2 (for mixtures of bitumens G_{12} was close to zero, whereas mixtures of bitumen and highly aromatic rejuvenators rendered G_{12} values as low as – 10).

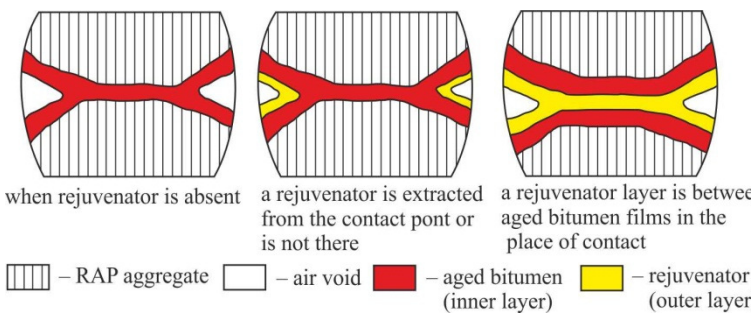

Fig. 2. The structure of the bitumen film in the place of the contact of two adjacent particles in the RAP

Actually, during the recycling process particles of the RAP granules with an aged bitumen film and rejuvenators are mixed and not the two viscous materials. The structure and properties of old bitumen, coating the particles of the mineral

materials and virgin bitumen spread within thin films above the old bitumen or any other rejuvenator, which is affected by absorption in a bitumen line layer, change due to the power field of mineral material. A two-layer binder system, interacting during the recycling of the RAP granules and after the process, is formed.

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 that may be in the place of the contact between the two pressed particles of the compacted asphalt pavement layer (Fig. 2).

The process of diffusion takes place in the layers of old and virgin bitumens, in which atoms and molecules of rejuvenating materials penetrate to the old viscous and solid bitumen. The process of diffusion is described by Fick's second law, the mathematical expression of which is provided in the formula (5) and indicates the expression of c concentration, following the theory of Crank (1956):

$$\frac{\partial c}{\partial t} = D \cdot \frac{\partial^2 c}{\partial x^2}, \tag{4}$$

where t is time; x – position; D – diffusion quotient, m^2/s.

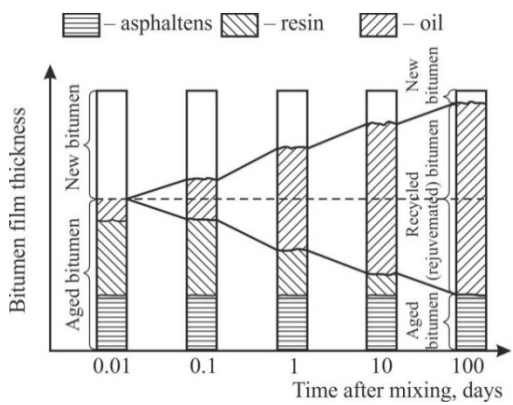

Fig. 3. The dynamic model of mixing the aged and virgin bitumen layers which coat the aged particle of the recycled asphalt

The equation (5) stands for the simplification of the more general theory of the influence of chemical potential on diffusion. Fick's law assumes constant pressure and temperature throughout the sample and no long-range electrostatic interactions. Particle diffusion in the media takes place in the direction of the decrease of their density. Within the liquid (in bitumen), diffusion occurs with molecules leaping from one balance condition to the other. Within the liquid, the diffusion quotient increases along with the increase of temperature, while the number of leaps per unitary duration increases respectively.

Films of aged and newly recycled HMA bitumens have a layer structure with an amount of components dominating within the layers (Fig. 3). Bitumen can be classified into four groups: asphaltenes, resins, aromatics and saturates. Asphaltenes are more viscous than resins and oils, respectively. Therefore, the rejuvenating material hardly gets into their layer.

After the recycling technological process, new and old bitumen layers get mixed due to the diffusion. It is expected that atoms and molecules of rejuvenating material (virgin bitumen) hardly get into a solid layer of asphaltenes.

3. Experimental analysis of RAP granules and of recycled HMA mixtures

According to the statistical data provided by Lithuanian asphalt mixture manufacturing companies and the EAPA, the amount of annually milled RAP in European countries in the years 2004–2009 amounted to about 50 million tons. The percentage of RAP used in the production of HMA mixture has increased from 30 % to 48 %. In Lithuania the use of RAP also increases each year, which shows the advantage of the application of asphalt recycling technologies.

In order to determine and to evaluate the componential composition, properties and homogeneity of the milled RAP stored by the Lithuanian asphalt manufacturing companies, samples have been taken from three stockpiles and were tested in the laboratory. Experimental data has demonstrated that the statistical indicators for the amount of granule size moisture, amount of bitumen and granulometric composition of mineral material from individual RAP samples differ.

The original method provided is meant for comparing RAP homogeneity of size difference of the largest particles and unequal granuliometric composition of the mineral materials, according to the correlation of the arithmetic mean of complete passages through the meshes $\overline{p}$ and standard deviation s_p.

For example, RAP-3 sampled from a stockpile of material prepared for recycling kept at the open storage facility of an AMP (sample size n=43).

$$s_p = \sqrt{2.81 \times 10^{-5} \times \overline{p}^{2.587} \left(100 - \overline{p}\right)^{1.041}} \ , \ R^2 = 0.993 \, . \tag{6}$$

Curve of correlative dependence (Fig. 4) is drawn according to the regression equation (6).

The maximum s_p values of the three individual RAP samples have been compared by applying the Bartlett's criterion and it has been determined that standard deviations s_p are equal statistic wise, and the homogeneity of RAP is the same.

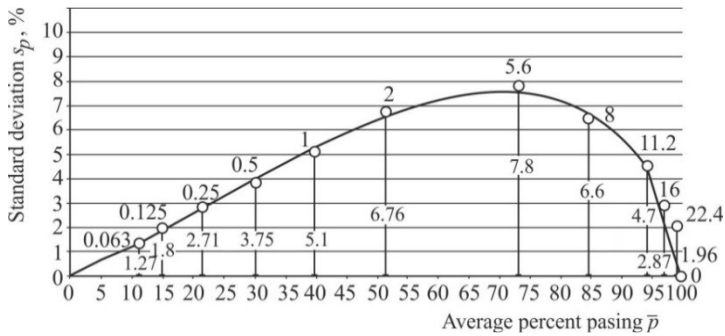

Fig. 4. Correlation between the parameters of milled RAP agregate gradation variation (s_p) and position ($\overline{p}$) determined for the following samples

During another experiment, RAP granules were rejuvenated by adding different types (50/70, 70/100, 100/150 and 160/220) virgin bitumen at different percentages (0.5 %, 1.0 %, 1.5 %, 2.0 %, 4.0 % and 6.0 %). Marshall specimens have been formed from 18 different compositions of the rejuvenated RAP mixture, which reflects the adhesive properties of the total bitumen. Residual air voids content (V_m) of samples, Marshall stability (*S*), flow (F) and Marshall Quotient (S/F) have been determined. After the recycling process, soluble bitumen was extracted from specimens and was separated from a solvent in a rotary evaporator. The following properties were identified: penetration Pen_{25} , 0.1 mm; softening point T_{SP} , °C; Frass breaking point T_{FBP} , °C. Penetration index I_p was calculated as well.

Marshall specimens of AC 11 VL brand asphalt concrete have been manufactured with almost identical granulometric composition and with the same amount of bitumen, yet changing the percentage of RAP granules (0 %, 10 %, 20 %, 40 %, 60 %, 80 %, 100 %) and tested. Flat specimens have been also manufactured from these mixtures (with RAP 0 %, 20 %, 60 %, and 100 %) and tested by using the wheel-tracking test method in compliance with the

requirements of LST 12697-22 and the influence of the percentage of RAP granules on the development of rutting has been determined (Fig. 5).

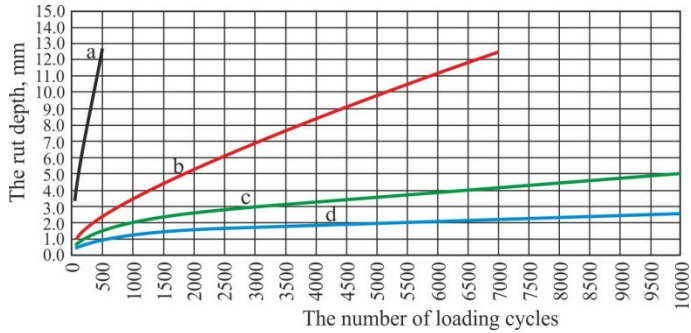

Fig. 5. Distribution of graphs from data recieved a – RA0, b – RA20, c – RA60, d – RA100 mixture

Experimental data has demonstrated (Fig. 5) that by increasing the percentage of RAP granules in the recycled HMA mixture, the rutting resistance has increased as well. The decrease of the rut depth was determined by the increase of the percentage of old viscous bitumen.

4. Optimization of component composition of recycled hot-mix asphalt

Having determined the homogeneity of different RAP samples (RAP-1, RAP-2 and RAP-3) in compliance with the methodology of TRA ASFALTAS 08, the maximum allowed dosage of RAP while manufacturing a recycled HMA mixture has been calculated for all the components (Table 1).

The maximum allowed dosage of RAP in individual samples is different in the case of each property of RAP.

By using stochastic modeling, the influence of variation of granulometric composition of RAP mineral materials to the variation of quantity of recycled HMA mixture components has been determined. During the modeling, completely homogeneous mineral materials for the final dosage have been taken (imported filler reclaimed dust and hot aggregate fraction size 0/2 mm, 2/5 mm, 5/8 mm, 8/11 mm, 11/16 mm), as well as mean values of arithmetic averages of complete RAP percentage passing the sieves $\bar{x}_{RAP}$ and standard deviations s_{RAP}. A stochastically modeled variation of the amount of mineral filler (<0.063 mm particles) of recycled HMA mixture, and its compliance with the job mix formula (JMF) is displayed in Fig. 6.

Table 1. The most content of RAP (percentage mass) allowed for proportion in recycled HMA mixtures corresponding to RAP homogeneity by its componential structure and the type of asphalt mixture

RAP component	Sample	Experimentally determined value, mass %			Estimated % of RAP mass K_i in recycled HMA mixtures used in		
		$x_{i,\max}$	$x_{i,\min}$	range a_i	road base courses	wearing-base course	bin and surface course
Bitumen	RAP-1	6.58	4.39	2.19	27.4	22.8	15.1
	RAP-2	8.22	4.99	3.23	18.6	15.5	10.2
	RAP-3	5.43	3.66	1.77	33.9	28.2	18.6
Filler (<0.063 mm)	RAP-1	17.1	10.8	6.3	79.4	47.6	31.4
	RAP-2	17.5	7.8	9.7	51.5	30.9	20.4
	RAP-3	14.2	8.4	5.8	86.2	51.7	34.1
Fine aggregate (0.063–2 mm)	RAP-1	45.1	30.1	15.0	53.3	53.3	35.2
	RAP-2	44.9	25.0	19.9	40.2	40.2	26.5
	RAP-3	52.1	19.1	33.0	24.2	24.2	16.0
Coarse aggregate (>2 mm)	RAP-1	56.5	41.7	14.8	60.8	54.0	35.7
	RAP-2	63.6	40.6	23.0	39.1	34.8	23.0
	RAP-3	70.9	33.7	37.2	24.1	21.5	14.2

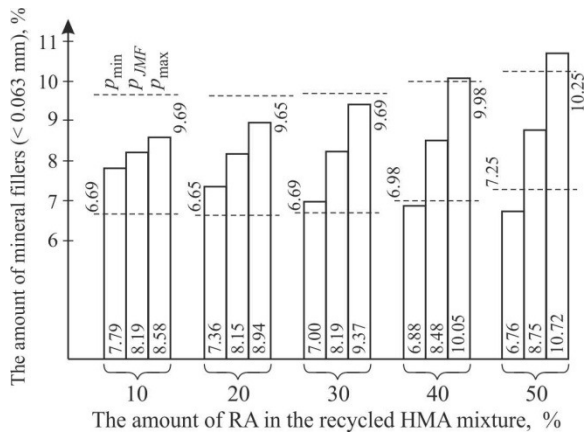

Fig. 6. Variation of cumulative percent passing through a 0.063 mm sieve, depending on the quantity of RAP in recycled HMA

While comparing minimum $p_{\min}$, maximum $p_{\max}$, and JMF p_{JMF} values of the complete percentage of recycled HMA passing through the sieve with statistical tolerance limits, calculated for mineral-filler, when sample size $N \geq 20$, it can be seen that by increasing RAP percentage from 10 % to 50 %, individual values $p_{\min}$ and $p_{\max}$ approach the tolerance limits and exceed them

when the amount of RAP makes more than 40 %. Analogous tendencies have been reported for the quantity of the coarse aggregate and fine aggregate components in the recycled HMA mixture.

General conclusions:

1. Up to present, asphalt as well as the majority of other construction materials has been used only once (one-cycle of exploitation period) as road or other transport infrastructure construction and repair material. This material can be rejuvenated by applying the scientific principles systemized in this work, provided models of component interaction and the data obtained from the experimental tests. The conducted research reveals that the structure and properties of RAP granules have a decisive influence on the physical and mechanical parameters of the recycled HMA mixture. They are unpredictable, since they are determined by a number of initial factors of stochastic nature (the properties of a new pavement), the service life period of the road and recycling technological process factors. Ageing process greatly affects the properties of RAP bitumen, yet the granulometric composition stays the same.

2. The changed composition, structure and properties of old RAP bitumen are rejuvenated during the recycling process by adding rejuvenators, among them is virgin bitumen with lower viscosity. The processes of the mechanical and diffusive mixing of old and virgin bitumens within two-layer films coating mineral particles of various sizes are different between air voids of particles and in the place of contact of particles. It was determined that the mixing time and the effectiveness of the rejuvenation depend on the temperature, pressure, properties of bitumen (diffusion quotient, thickness of films and percentage ratio) and are defined by Fick's law.

3. Given the amount of available and recycled asphalt (about 112 thousand tons per year) used in Lithuanian road construction and maintenance companies, it can be said that the use of asphalt recycling technology is popular not only in economically developed countries, but is increasingly gaining popularity in Lithuania. It requires scientific substantiation, which would allow the effective use of RAP granules in the recycled HMA mixture. Experimental studies on the properties of RAP granules have showed that they are heterogeneous considering the componential composition and properties of aged bitumen. It is determined that mathematical models (regression equations) for the interaction of arithmetic average and standard deviation of complete passages through sieves, allowing comparison of RAP granules of different granulometric composition and sample size in accordance with the Bartlett's criterion, are universal.

4. The effectiveness of virgin bitumen (rejuvenator), which is added to RAP granules at different percentages and of different type, is different in the

case of both physical recycled HMA mixture and mechanical Marshall Parameters. It is not also the way it is expected to be due to unfinished diffusion of the total bitumen and practical possibility of incomplete separation of bitumen during the extraction and recycling by a rotary evaporator. By applying the Marshall Method to determine the optimal composition of the recycled HMA mixture, the resistance to rutting is not always guaranteed. The amount of RAP granules, determined by using the wheel-tracking test method, is final and demonstrates that by increasing the mass of RAP granules, the rutting resistance of the HMA mixture increases. However, the resistance to crack and corrosion (the effect of frost) has not need studied.

5. By annually increasing the amount of milled RAP, its usage has to be adequate; therefore, the percentage of RAP granules in the recycled HMA mixture should be increased or they can be inefficiently used in the construction of road base layers or for pavement strengthening on local roads. It is rational to use the highest quality RAP granules milled from highways to produce HMA mixture for the upper and lower pavement courses. In compliance with LTS EN standards, the maximum allowed average amount of RAP granules cannot exceed 10–20 %, yet it has to be specified for each component considering the homogeneity of granules and the intended use and type of HMA mixture. In order to achieve not only the required componential composition of the recycled HMA mixture, but also low variance, it is rational to apply an optimal composition design method based on the principles of stochastic modeling.

List of Published Works on the Topics of the Dissertation

In the reviewed scientific periodical publications

Mučinis, D.; Sivilevičius, H.; Oginskas, R. 2009. Factors determining the inhomogeneity of reclaimed asphalt pavement ant estimation of its component content variation parameters, The Baltic Journal of Road and Bridge Engineering 4(2): 69–79. doi:10:3846/1822-427X.2009.4.69-79 (IF=2,06; AIF=1,324).

Čygas, D.; Mučinis, D.; Sivilevičius, H.; Abukauskas, N. 2011. Dependence of the recycled asphalt mixture physical and mechanical properties on the grade and amount of rejuvenating bitumen, *The Baltic Journal of Road and Bridge Engineering* 6(2): 124–134. doi:10.3846/bjrbe.2011.17 (IF=2,436; AIF=1,479).

In the other editions

Mučinis, D.; Čygas, D.; Oginskas, R. 2008. The possibility of using reclaimed asphalt pavement (RAP) in hot mix asphalt in Lithuania, in *Proc of the 7th International Conference "Environmental Engineering": selected papers*, vol. 3. Ed. by Čygas, D.; Froehner, K. D. May 22–23, 2008, Vilnius, Lithuania. Vilnius: Technika, 1199–1203.

Oginskas, M.; Mučinis, D.; Sivilevičius, H. 2009. Research the homogeneity of reclaimed asphalt pavement used in Lithuania, in *II International Conference Environmentally Friendly Roads „enviroad 2009". Pavement Design and Construction*, 15–16 X 2009. Warszawa: 1–9.

About the author

Darjušas Mučinis was born on the 24th of April 1974 in Vilnius.

In 1996 he receives the Bachelor's degree in Civil Engineering at Vilnius Gediminas Technical University, Faculty of Environmental Engineering. In 1997 he receives the Degree in Road and Railway Engineering at Vilnius Gediminas Technical University, Faculty of Environmental Engineering. In 1999 he receives the Master's degree in Civil Engineering at Vilnius Gediminas Technical University, Faculty of Environmental Engineering. Since 1997 he works in SE "Problematika", Engineer. Since 1999 he works in SE "Problematika", Head of Department. Since 2006 he works in SE "Problematika", Director of the company. Since 2011 he works in JSC "Problematika", Deputy Director. During 2006-2011 years – doctoral studies at Vilnius Gediminas Technical University.

KARŠTAI REGENERUOTO ASFALTO MIŠINIO KOMPONENTŲ SĄVEIKOS MODELIAVIMAS IR JO NAUDOJIMO KELIŲ DANGOS KONSTRUKCIJOJE TYRIMAS

Mokslo problemos aktualumas. Judėjimo laisvė yra viena iš pagrindinių žmonijos vertybių, kuri įgyvendinama plėtojant transporto sistemą. Daugiausiai keleivių ir krovinių vežama kelių transportu, kurio efektyvumas priklauso nuo automagistralių ir kelių asfalto dangos eksploatacinių savybių. Veikiant destruktyviems veiksniams asfalto dangos savybės blogėja, o jų atstatymo taikomi metodai ir technologijos ne visada leidžia gauti stiprų ir ilgaamžį regeneruotą dangos sluoksnį. Tai nelemia ir senų bei naujų medžiagų sąveikos procesų nepakankamas ištyrimas, jai įtakos turinčių veiksnių variavimas, priklausantis nuo konkrečių iš anksto nenuspėjamų sąlygų.

Iki šiol Lietuvoje įprastas asfalto dangos vienacikliškumas netenkina dabarties ir ateities visuomenės ir kelių tiesėjų poreikius, brangstant ir senkant naftos bei iškasamų mineralinių medžiagų ištekliams, iš naftos išskiriant vis daugiau komponentų degalams ir cheminėms medžiagoms gaminti, saugant aplinką nuo panaudotų medžiagų trąšos, siekiant ekonominės naudos, ieškoma būdų eksploatuotų asfalto dangos medžiagų kartotiniam naudojimui, t. y. regeneravimui.

Tyrimų objektas. Eksploatuoti netinkančios asfaltinės dangos granulių vienalytiškumas; jų sąveika su atstatančiosiomis medžiagomis; regeneruoto

karštai maišyto asfalto mišinio fizinės-mechaninės savybės; regeneruoto KMA mišinio atsparumas vėžėms; minimalus leidžiamas dozuoti naudoto asfalto (RA) granulių kiekis gaminant KMA mišinį.

Darbo tikslas ir uždaviniai. Darbo tikslas – pateikti moksliškai pagrįstą komponentų sąveikos dinamikos modelį bei jos rezultatus, leidžiančius projektuoti ir gaminti kokybiškus karšto maišymo asfalto (KMA) mišinius su Lietuvos kelių dangos naudoto asfalto (RA) granulėmis. Siekiant nusibrėžto tikslo, buvo sprendžiami šie uždaviniai:

1. Išanalizuoti pasaulinėje mokslinėje literatūroje su asfalto dangos regeneravimu susijusias problemas ir jų sprendimo būdus; asfalto dangos irties veiksnius ir jų įtaką naudotam asfaltui; senų bei naujų medžiagų sąveiką; regeneruoto asfalto mišinio savybes; regeneravimo proceso technologijas.
2. Sumodeliuoti naudoto asfalto (RA) homogeniškumą nulemiančius veiksnius.
3. Sumodeliuoti dviejų rūšių sumaišyto bitumo ar kitos atstatančiosios medžiagos teorinę klampą ir seno bei naujo bitumų maišymosi dėl difuzijos dvisluoksnėje plėvelėje dinamiką.
4. Pateikti susistemintuosius asfalto dangos regeneravimo mokslinius principus.
5. Ištirti RA naudojimo užsienio šalyse ir Lietuvoje kiekio dinamika.
6. Ištyrinėti Lietuvos keliuose ir miesto gatvėse frezuoto bei išlaužto ir sutrupinto RA granulių komponentinę sudėtį ir savybes.
7. Nustatyti pridedamo atnaujinančio bitumo rūšies ir procentinio kiekio įtaką regeneruoto KMA mišinio fiziniams ir mechaniniams Maršalo rodikliams, taip pat regeneruoto suminio bitumo savybes.
8. Nustatyti su skirtingu RA granulių kiekiu regeneruoto KMA mišinio atsparumą vėžių susidarymui.
9. Pateikti deterministinio ir stochastinio modeliavimo naujus metodus, tinkančius nustatyti RA granulių kiekio ir savybių įtaką regeneruoto KMA mišinio komponentinei sudėčiai ir jos vienalytiškumui.

Tyrimų metodai. Darbe naudojami šie tyrimo metodai: matematiniai analiziniai, grafinio ir matematinio modeliavimo, matematinės statistikos; eksperimentiniai laboratoriniai, stochastinio modeliavimo; eksperimentiniai natūriniai (naudoto asfalto savybių kelių dangoje).

Mokslinis naujumas

1. Iškelta hipotezė, kad eksploatuoti netinkančias kelio ar kito transporto infrastruktūros elemento (aerodromo riedėjimo tako, automobilių stovėjimo aikštelės) asfalto dangos pasenusi medžiaga gali būti daugiaciklio (kartotinio) naudojimo, jei atkuriamos jos pakitusios savybės iki artimų KMA mišinio, pagaminto vien iš naujų medžiagų, savybių, reglamentuotų šalies norminiuose dokumentuose.

2. Pirmą kartą susisteminti ir sumodeliuoti veiksniai, nulemiantys RA granulių nevienalytiškumą, nustatytas jų stochastinis pobūdis ir įtakos vienalytiškumui išankstinis nenuspėjamumas.

3. Sumodeliuotas RA esančio seno bitumo ir jį atnaujinančio naujo rišiklio mechaninio bei difuzinio maišymosi ir suminio bitumo klampos mineralinius grūdelius gaubiančiose dvisluoksnėse plėvelėse procesas.

4. Susisteminti asfalto dangos regeneravimo moksliniai principai, leidžiantys taikant teorines nuostatas praktikoje gauti geriausios struktūros ir savybių regeneruotus karšto maišymo asfalto mišinius.

5. Pirmą kartą surinkti duomenys RA granulių gavybos ir panaudojimo Lietuvos kelių tiesybos įmonėse, leidžiantis matyti, kad šios medžiagos kiekiai kaip ir kitose šalyse pakankamai dideli ir kiekvienais metais turi tendenciją didėti.

6. Eksperimentais iš reprezentatyvių imčių nustatytas ir statistiškai įvertintas RA granulių komponentinis vienalytiškumas, pateikta originali granuliometrinės sudėties dispersijų lyginimo metodika.

7. Ištyrinėta skirtingos rūšies ir kintančio kiekio atnaujinančio naujo bitumo įtaka regeneruoto KMA mišinio fiziniams ir mechaniniams rodikliams, juos nustatant pagal Maršalo metodiką.

8. Nustatyta nauju (atnaujinančiu) bitumu atkurtų savybių seno bitumo, esančio RA, standartinių rodiklių priklausomybė nuo atnaujintojo procentinio kiekio ir rūšies, leidusi įvertinti regeneravimo proceso veiksmingumą.

9. Su skirtingu RA kiekiu pagaminus vienodos granuliometrinės sudėties ir optimaliu suminio bitumo kiekiu plokščiuosius bandinius ir juos išbandžius įvažinėjimo ratu, nustatyta RA įtaka regeneruoto KMA mišinio atsparumui vėžėms.

10. Pateiktas RA granulių maksimalaus leidžiamo kiekio nustatymo regeneruojamame KMA mišinyje būdas, pagrįstas deterministiniu ir stochastinio modeliavimo metodais, jas taikant gautos praktiškai rekomenduojamos RA kiekio atskirų komponentų diferencijuotos pagal mišinių rūšis bei paskirtį skaitinės vertės.

Praktinė vertė. Darbe pasiūlytos šios moksliškai pagrįstos priemonės Lietuvoje gaminamų KMA mišinių su naudoto asfalto (RA) granulėmis kokybei gerinti:

1. Įrodyta, kad RA granulės turi būti taip frezuojamos, kraunamos, vežamos ir sandėliuojamos, kad dėl regeneruoti paruošta medžiaga būtų maksimaliai homogeniška, į ją nepatektų kritulių vanduo ir kaitinant saulės spinduliams nesuliptų į sunkiai išardomus luitus. Skirtingų kelių išfrezuotas RA granules būtina sandėliuoti atskirose krūvose, o tai padaryti neturint galimybės – jas homogenizuoti specialiu įrenginiu ar maišant krautuvu.

2. Iš atlikto tyrimo nustačius seno ir naujo regeneruojančio bitumo plėvelių ilgalaikio maišymosi dėl difuzijos dinamiką rekomenduojama mobiliuoju regeneratoriumi sutaisyta kelio asfalto danga neleisti tuoj pat važiuoti transporto

priemonėms, kol suminio bitumo dvisluoksnė plėvelių struktūra priartės prie stabilios sumaišytos būsenos, neleidžiančios atsirasti vėžėms.

3. Komponentinės sudėties optimizavimo deterministiniu ir stochastiniu metodais nustatytos regeneruoto KMA mišinio komponentų kiekio leistinos vertės gali būti panaudotos tobulinant norminius dokumentus, skirtus techniniams reikalavimams, reglamentuojantiems didžiausią leidžiamą RA granulių kiekį.

Ginamieji teiginiai

1. Netinkamos eksploatuoti asfalto dangos medžiaga gali būti kartotinai panaudota gaminant KMA mišinius, jei yra atkuriamos jos savybės iki reikiamo lygmens.

2. Transporto priemonių ir aplinkos veiksnių paveiktos asfalto dangos labiau blogėja ne granuliometrinė sudėtis, bet organinis rišiklis – bitumas, kurį galima atkurti naudojant papildomas minkštinančias ar atstatančias medžiagas, tarp jų ir skystesnį naują bitumą.

3. Nufrezuoto arba sulaužyto ir sutrupinto asfalto dangos sluoksnio granulių didelis komponentinis nevienalytiškumas riboja jų maksimalaus kiekio naudojimo galimybes.

4. Regeneravimo technologiniame procese sąveikauja seno ir naujo bitumų plėvelės, kurių baigiamojo maišymosi dėl difuzijos didelė trukmė nulemia regeneruoto KMA mišinio kintančias laike savybes ir struktūrą.

5. Tinkamai suprojektuoto regeneruoto KMA mišinio Maršalo bandinių ir įvažinėjimo ratu nustatytos stipruminės savybės gali būti ne blogesnės kaip vien tik iš naujų medžiagų pagaminto KMA mišinio.

6. Didinant nehomogeniško RA granulių procentinį kiekį regeneruojamame KMA mišinyje, pastarojo sudėties sklaidos parametrai, nustatyti stochastiškai modeliuojant granuliometrinę sudėtį, proporcingai didėja.

Darbo apimtis. Darbą sudaro įvadas, keturi skyriai, išvados, literatūros sąrašas, publikacijų sąrašas. Bendra disertacijos apimtis – 105 puslapiai, 37 numeruotos formulės, 31 paveikslas ir 9 lentelės

Pirmajame disertacijos skyriuje analizuojami mokslo literatūroje skelbti rezultatai, skirti eksploatuojamos asfalto dangos irties priežastims, veiksnių parametrų įtakai bei dinamikai būsimojo regeneravimo proceso ir jo rezultato kokybei tirti. Taip pat pateikiami RA senų ir naujų medžiagų sąveikos, regeneruoto KMA mišinio ir iš jo įrengtos kelio dangos eksploatacinių ir stiprumo rodiklių tyrimų rezultatai. Glaustai analizuojamos regeneravimo technologijos. Skyriaus pabaigoje formuluojamos išvados.

Antrajame disertacijos skyriuje pateikti teoriniai tyrimai, skirti RA kokybei ir regeneravimo procesams modeliuoti. Čia ištyrinėti RA granulių nehomogeniškumą nulemiantys veiksniai, seno ir naujo sumaišytų bitumų teorinė klampa, jų difuzijos

plėvelėse, gaubiančiose mineralinių medžiagų daleles, procesai. Pateikti susistemintieji asfalto dangos regeneravimo moksliniai principai ir skyriaus išvados.

Trečiajame disertacijos skyriuje atliktas RA naudojimo keliams tiesti išvystytas ekonomikos Europos šalyse ir Lietuvoje bėgant metams tyrimas. Eksperimentais iš reprezentatyvių imčių nustatytas RA komponentinis vienalytiškumas ir jis įvertintas. Ištyrinėta skirtingos rūšies bitumo kintančio kiekio įtaka regeneruoto KMA mišinio fiziniams ir mechaniniams Maršalo rodikliams, įvertintas suminis regeneruotas bitumas. Nustatyta RA kiekio įtaka regeneruoto KMA mišinio atsparumui vėžėms sudaryti, bandant įvažinėjimo ratu. Pateiktos skyriaus išvados.

Ketvirtajame disertacijos skyriuje pateikti maksimalaus leidžiamo dozuoti RA kiekio regeneruotame KMA mišinyje nustatymo deterministiniais metodais tyrimų duomenys, atitinkantys faktinį RA homogeniškumą ir normų reikalavimus. Pasiūlytas naujas stochastinio modeliavimo principais paremtas RA granulių kiekio įtakos regeneruoto KMA mišinio vienalytiškumui nustatymo metodas, kai varijuoja RA granulių ir naujų asfaltbetonio maišytuve (ABMA) baigiamų dozuoti mineralinių medžiagų granuliometrinė sudėtis. Suformuluotos skyriaus išvados.

Bendrosios išvados

1. Asfaltas kaip ir dauguma statybinių medžiagų, iki šiol buvo vienaciklio naudojimo eksploatacijos laikotarpyje suirusias kelio ar kito transporto infrastruktūros tiesinio dangos medžiaga. Ji gali būti atnaujinta taikant darbe susistemintus mokslinius principus, pateiktus komponentų sąveikos modelius bei eksperimentais gautus tyrimų duomenis. Atlikus tyrimus buvo nustatyta, kad RA granulių struktūra ir savybės turi lemiamą įtaką regeneruoto KMA mišinio fiziniams ir mechaniniams rodikliams. Jos nenuspėjamos, nes būna nulemtos daugelio stochastinį pobūdį turinčių pradinių (naujos dangos savybių), kelio eksploatacijos laikotarpio ir regeneravimo technologinio proceso veiksnių. Dėl senėjimo procesų būna iš esmės pakitusios RA bitumo savybės, o ne jų granuliometrinė sudėtis.

2. Regeneravimo procese atkuriant RA seno bitumo pakitusias sudėtį, struktūrą bei savybes naudojamos atstatančiosios medžiagos, iš kurių ir mažesnės klampos naujas bitumas. Seno ir naujo bitumų mechaninio ir difuzinio maišymosi dvisluoksnėse skirtingo dydžio mineralinius grūdelius dengiančiose plėvelėse procesai tarp grūdelinių oro tuštymių ir grūdelių kontakto vietose skiriasi. Nustatyta, kad maišymosi proceso laikas bei atnaujinimo veiksmingumas priklauso nuo temperatūros, slėgio, bitumo savybių (difuzijos koeficiento, plėvelių storio, procentinio santykio) ir aprašomas Fiko dėsniu.

3. Nustatytas Lietuvos kelių statybos ir eksploatavimo įmonėse išgaunamo ir regeneruojamo naudoto asfalto kiekis (apie 112 tūkst. t per metus) leidžia teigti, kad regeneruoto asfalto panaudojimo technologija yra populiari ne tik išvystytos ekonomikos šalyse, jos mastas didėja ir Lietuvoje. Eksperimentiniai RA granulių

savybių kompleksiniai tyrimai parodė, kad jos yra nevienalytės komponentine sudėtimi ir seno bitumo savybėmis. Nustatyta, kad pilnutinių išbirų per sietus aritmetinio vidurkio bei standartinio nuokrypio sąsajos matematiniai modeliai (regresijos lygtys), leidžiantys pagal Bartleto kriterijų lyginti skirtingos granuliometrinės sudėties bei imties didumo RA granules, yra universalūs.

4. Į RA granules skirtingu procentiniu kiekiu ir skirtingos rūšies pridedamo naujo bitumo (atstatymo medžiagos) veiksmingumas regeneruoto KMA mišinio fiziniams bei mechaniniams Maršalo rodikliams skiriasi. Ne visada jis būna toks, kokio tikimasi dėl suminio bitumo nesibaigusios difuzijos ir ne viso bitumo kiekio atskyrimo ekstrahuojant ir regeneruojant sūkiuoju garintuvu praktinės galimybės. Taikant Maršalo metodą regeneruoto KMA mišinio optimaliai sudėčiai nustatyti, ne visada laiduojamas jo atsparumas vėžėms. Įvažinėjimo rato (wheel tracking) metodu nustatytas RA granulių kiekis yra galutinis ir rodo, kad didinant RA granulių masę didėja KMA mišinio atsparumas vėžėms, tačiau atsparumas plyšiams ir korozijai (šalčio poveikiui) nėra ištyrinėtas.

5. Didėjant kiekvienais metais išfrezuoto RA kiekiui, jo sunaudojimas turi būti adekvatus ir todėl reikia didinti RA granulių procentą regeneruotame KMA mišinyje arba neefektyviai jas naudoti kelio dangos konstrukcijos pagrindo sluoksniuose ar vietinės reikšmės kelių dangai stiprinti. Aukščiausios kokybės iš automagistralių frezuotas RA granules racionalu naudoti viršutinio ir apatinio dangos sluoksnių KMA mišiniui gaminti. Pagal LST EN standartus RA granulių didžiausias leistinas vidutinis kiekis negali viršyti 10–20 %, tačiau jis turi būti patikslintas kiekvienam komponentui atsižvelgiant į granulių vienalytiškumą ir KMA mišinio paskirtį bei rūšį. Siekiant ne tik reikiamos regeneruoto KMA mišinio komponentinės sudėties, bet ir jos mažos sklaidos, racionalu taikyti stochastinio modeliavimo principais pagrįstą optimalios sudėties projektavimo metodą.

Trumpos žinios apie autorių

Darjušas Mučinis gimė 1974 m. balandžio 24 d. Vilniuje.

1996 m. įgijo civilinės inžinerijos bakalauro laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. 1997 m. įgijo, kelių ir geležinkelių diplomuoto kelių inžinieriaus laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. 1999 m. įgijo civilinės inžinerijos mokslo magistro laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. Nuo 1997 m. dirbo VĮ „Problematika“ inžinieriaus pareigose. Nuo 1999 m. dirbo VĮ „Problematika“ tarnybos viršininko pareigose. Nuo 2006 m. dirbo VĮ „Problematika“ direktoriaus pareigose. Nuo 2011 m. dirba AB „Problematika“ direktoriaus pavaduotojo pareigose. 2006-2011 Vilniaus Gedimino technikos universiteto doktorantas.