



ANALYSIS AND EVALUATION OF POSSIBILITIES FOR THE USE OF WARM MIX ASPHALT IN LITHUANIA

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Abstract. Production of hot mix asphalt (HMA) requires a lot of consumption of energy, exhaustion of CO₂ and other environment unfriendly materials. The fumes of HMA are injurious for roadmen and asphalt plant workers. The use of warm mix asphalt (WMA) allows reducing the HMA production temperatures at which the material is mixed and laid on the road. WMA helps to reduce the working temperature of asphalt up to 30 °C. This article presents the overview of different technologies of WMA production, advantages and disadvantages of these technologies. The laboratory research includes research of physical and mechanical properties of WMA produced with different technologies and different amount of additives for temperature lowering. Two different kinds of asphalt were tested in the laboratory. The chemical additives and chemical and natural zeolite were used for WMA production in the laboratory.

Keywords: warm mix asphalt (WMA), low temperature asphalt, hot mix asphalt (HMA), zeolite, chemical additives.

1. Introduction

At the beginning of 19th century due to the expanding economic activities the structure of the atmosphere has started to slowly change. The amount of carbon dioxide in the atmosphere has started to rapidly increase. Climate warming is caused by different gases exhausted into the environment. The countries having signed the Kyoto Protocol entered into commitment to reduce by various measures the amount of hazardous gases exhausted into the atmosphere. One of these measures – to promote reforms in economic sectors, where greenhouse gases are emitted and to reduce emissions. This measure is also aimed at the road building sector and production of asphalt mixtures. Construction of asphalt roads is divided into three stages related to the use of asphalt: production of asphalt mixture, placement and compaction. The largest amount of hazardous materials is emitted into the environment during asphalt production: solid particles, carbon monoxide, nitrogen oxides, sulphur dioxide, formaldehyde, vanadium pent oxide and volatile organic compounds. The amount of hazardous emissions is directly related to the asphalt mixture production temperature and the fuel consumed by the plant to reach the required asphalt temperature.

Discussions on the reduction of asphalt production temperature as of the measure to save energy and reduce the amount of hazardous materials are not new. The idea to save energy and reduce emissions in asphalt industry has

been discussed for decades. In 1956, Dr. Ladis H. Csanyi, Professor of the Iowa State University realized a potential of foam bitumen for the production of cold mix asphalt (CMA) binders. The company *Mobil Oil Australia* acquired patent rights to the Csanyi's invention and modified the original process by replacing fumes with cold water. From then the process of foam bitumen became more practical (Muthen 1998). Jenkins *et al.* (1999) introduced a new process – the use of half warm mix asphalt (HWMA) with foam bitumen. They discussed and investigated possible advantages of heating aggregates to the temperature, higher than the ambient but lower than 100°C before adding foam bitumen (Jenkins *et al.* 1999). Europe and Australia called their attention to the warm mix asphalt (WMA) mixtures in 2000. Several years later the North America also became interested in the WMA mixtures.

Functionality of the WMA technology is based on the reduction of asphalt binder viscosity within the limits of certain temperature. A lower viscosity allows to fully coat aggregates with bitumen at a lower temperature than needed for mixing the hot mix asphalt (HMA) mixtures. There are different technologies and different additives for the production of WMA mixtures. The number of investigations to put different technologies into practise is also different. Some technologies (additives) have been studied very thoroughly, they are used in commerce, whereas the others have got no comprehensive data. In recent years many experimental laboratory

ry researches have been carried out and the test sections have been constructed by using the WMA technologies. In 2008, in Omsk (Russia) an experimental research was implemented with the aim to reduce the compaction temperature of asphalt mixtures. To lower the production and laying temperature of asphalt mixtures the chemical additives Cecabase RT Bio and Cecabase RT 945 were used (Nekrasova *et al.* 2008). Hurley and Prowell (2006) made a laboratory research to reduce the production temperature of HMA with the help of Aspha-min, Sasobit and Evotherm asphalt additives (Hurley, Prowell 2006). In his scientific study Kristjansdottir (2006), has generalized possibilities of laying the WMA mixtures under cold climatic conditions. Between the most suitable Icelandic conditions the following technologies (additives) were mentioned: WAM Foam, Aspha-min and Sasobit (Kristjansdottir 2006). Tušar *et al.* (2008) have generalized the results of the research of test sections constructed from lower temperature HMA mixtures in Slovenia. The research was focused on the road sections where asphalt pavement layers were laid from the WMA mixtures produced using Aspha-min and Sasobit technologies (Tušar *et al.* 2008). Brosseau and Saint Jacques (2008) have described the use of asphalt mixtures of lower working temperatures in France. They singled out the HWMA and WMA production technologies (Brosseau and Saint Jacques 2008; Harder *et al.* 2008). The use of WMA additives Sasobit, Evotherm and Aspha-min and their effect on asphalt properties have been analyzed by many scientists (Butz 2008; You, Goh 2008; Hurley, Prowell 2008). On the basis of the research of Diefenderfer *et al.* (2008) it is stated that the physical and mechanical properties of WMA with Sasobit additive are better than with Evotherm additive and are close to the properties of HMA (Diefenderfer *et al.* 2007, 2008). In his research Butz (2008) has determined that Sasobit additive up to 3% by mass of bitumen is suitable to reduce the production temperature of crushed stone mastic and mastic asphalt mixtures. This amount of additive does not increase bitumen sensitivity to cold (Butz 2008). Many of scientific investigations conclude that the use of WMA technologies apparently reduces emissions of greenhouse gases and bitumen fumes. Scientists are looking forward for new durable road building materials and their mixes (Čygas *et al.* 2008, Radziszewski *et al.* 2007) and analyze depth of frozen ground affected by road climatic conditions and their changes (Juknevičiūtė, Laurinavičius 2008). Now there is a demand on WMA research in Lithuania.

2. Classification of asphalt mixtures according to the production temperature

Asphalt mixtures according to their mixing temperature and energy consumed for the heating process of materials are divided into:

- cold mix asphalt (CMA) – asphalt mixture produced at an ambient temperature using bitumen emulsion or foam;
- half warm mix asphalt (HWMA) – asphalt mixture produced at a temperature below water vaporization;
- warm mix asphalt (WMA) – asphalt mixture produced at a temperature range of 120°C to 140°C;

– hot mix asphalt (HMA) – asphalt mixture produced at a temperature range of 150°C to 180°C in relation with the used bitumen.

According to Asphalt Institute in USA, WMA is a modified HMA mixture that is produced, placed and compacted at a 10–40°C lower temperature than the conventional HMA mixture. WMA could be described as the asphalt mixture produced at a 20–40°C lower temperature than the HMA but at a higher temperature than the water boiling temperature (D'Angelo *et al.* 2008). Technologies used to reduce the mixing temperature of HMA mixtures from 20°C to 40°C in Europe are used to be called Warm Mix Asphalt (WMA). For the description of WMA the term “Low Temperature Asphalt” is sometimes used.

Conventional HMA mixtures are mixed at a temperature range of 140°C to 180°C and compacted from 160°C to 120°C. Temperature of the HMA has a direct impact on binder viscosity as well as compaction. With the decreasing temperature of HMA mixture the binder of asphalt mixture becomes thicker, more resistant to deformation and, thus, more poorly compacted. Finally, the binder becomes so hard that compaction is impossible. For the HAM this temperature is about 80°C.

3. Warm mix asphalt (WMA) technologies

There are four world-wide WMA production technologies. The comparison data is given in Table 1:

- 1) foam bitumen technology when bitumen foam is caused by water. Foamed bitumen is produced by spraying water into the heated bitumen or by adding moist fine mineral aggregate into asphalt mixture: WAM-Foam; Terex WMA System; Double-Barrel Green; LEA – Low Energy Asphalt; LEA-CO; EBE; EBT; LEAB; Ultrafoam GX; Lt Asphalt;
- 2) foam bitumen technology when bitumen foam is caused by adding natural or synthetic zeolite into the asphalt mixture during asphalt production: Aspha-Min – synthetic zeolite; Advera WMA Zeolite – synthetic zeolite; natural zeolite – a mineral sold in many countries of the world;
- 3) technology of organic additives to reduce bitumen viscosity. Additives are introduced into the asphalt mixer together with mineral materials: Sasobit – Fischer-Tropsch synthesis wax; Asphaltan B; Licomont BS 100 – Fatty Acid Amides;
- 4) technology of chemical additives to reduce bitumen viscosity. Additives are mixed with bitumen before batching the bitumen into the asphalt mixer: Iterlow T; Rediset; Cecabase RT; Evotherm; Revix or Evotherm 3G.

4. Experimental laboratory research of WMA mixtures

Experimental research of WMA mixtures was carried out in summer 2008 by the Road Research Laboratory of Dept of Roads of Vilnius Gediminas Technical University. Two-type asphalt mixtures were selected for the research purposes. To reduce the asphalt mixture production temperature two technologies were used: foam bitumen where bitumen foam is caused by adding natu-

Table 1. Comparison data of the WMA technologies

Technology or additive	Manufacturer	Amount of additive	Asphalt production temperature (or reduction ranges), °C
Foam bitumen technology, when bitumen foam is caused by water			
WAM Foam	Shell (UK) and Kolo-Veidekke (Norway)	2–5% water by mass of hard binder	100–120
Terex WMA system	Terex (USA)	~ 2% water by mass of bitumen	130
Double – Barrel Green	Astec Industrines (USA)	~ 2% water by mass of bitumen	116–135
LEA – Low Energy asphalt	LEA-CO (France)	3% water introduced with fine sand	<100
LEAB	Royal BAM Group (Netherlands)	Foam bitumen with a special additive (0.1% by mass of bitumen)	90
LT Asphalt (Nynas Low temperature asphalt)	Nynas (Netherlands)	Foam bitumen with hydrophilic additive the amount of which 0.5–1.0% by mass of bitumen	90
Foam bitumen technology, when bitumen foam is caused by adding natural or synthetic zeolite			
Aspha-Min	Eurovia GmbH (Germany)	0.3% by mass of the mixture	(20–30)
Advera WMA Zeolite	PQ Corporation (USA)	0.25% by mass of the mixture	120
Technology of organic additives to reduce bitumen viscosity			
Sasobit	Sasol Wax International	2.5–3.0% by mass of bitumen	(20–30)
Asphaltan B	Romonta GmbH (Germany)	2.0–4.0% by mass of bitumen	(20–30)
Licomont Bs 100	Clariant (Switzerland)	3.0% by mass of bitumen	(20–30)
Technology of chemical additives to reduce bitumen viscosity			
Iterlow T	Iterchimica (Italy)	0.3–0.5% by mass of bitumen	120
Rediset	Akzo Nobel (Netherlands)	2% by mass of bitumen	(30)
Cecabase RT	CECA (France)	0.3–0.5% by mass of bitumen	(30)
Evotherm	MeadWestvaco (USA)	0.5% by mass of bitumen emulsion Emulsion contains 70% of bitumen	115
Revix or Evotherm 3G	MeadWestvaco (USA)	–	(30–40)

ral or synthetic zeolite into the asphalt mixture during its production (Aspha-min zeolite and natural zeolite) and chemical additives to reduce bitumen viscosity (Iterlow T, Cecabase RT Bio chemical additives). Asphalt mixtures for the laboratory research were selected in a way that one of them would represent the mixtures used for roads with normal load, the other – with heavy (special) load. For the roads with heavy load the asphalt mixture AC 11 VS was selected produced from granite materials. For the roads with normal load the asphalt mixture AC 16 PD was selected produced from crushed dolomite and gravel. The aim was to evaluate the dependency of physical and mechanical properties of the same grade asphalt mixture, produced from different mineral materials, on the additive used. All the mixtures were produced from the bitumen 70/100. Chemical additives were added to improve cohesion properties between mineral materials and bitumen. For producing the asphalt mixture AC 16 PD (with crushed gravel) the cohesion additive Gripper L was used, for the mixtures AC 11 VS (with crushed granite) and AC 16 PD (with crushed dolomite) – Iterlene IN/400L. Of each grade of asphalt mixture 8 mixtures of identical grading and bitumen content were mixed with a different amount of additives. The reference asphalt mixture (without additives) was mixed and compacted at 150°C and 120°C. Asphalt mixtures with additives were mixed and compacted

at 120°C. Based on TRA ASPHALT 08 the compaction temperature of the asphalt samples AC 16 PD and AC 11 VS (bitumen 70/100) is $145 \pm 5^\circ\text{C}$. Systemized data of experimental laboratory research is given in Table 2. The following physical and mechanical properties of asphalt mixtures were identified:

- flow and stability (LST EN 12697–34+A1:2007);
- asphalt max density (LST EN 12697–5+A1:2007);
- asphalt bulk density (LST EN 12697–6+A1:2007);
- air voids content (LST EN 12697–8:2006).

Analysis of the research results showed that there is no clear dependency between the amount of additives and the physical and mechanical properties of asphalt mixture. Having studied how the stability index of asphalt mixtures varies depending on the amount of additive and the compaction temperature, one could notice that a lower scattering of results is between 0.2% and 0.3% of additive. Stability of the asphalt mixture AC 16 PD with Aspha-min and natural zeolite at 120°C is significantly increasing, when the amount of additive is 0.3% by mass of the mixture. In this case, stability is higher than that of the reference asphalt mixture compacted at 150°C. The highest stability of the asphalt mixture AC 16 PD with Cecabase RT Bio additive is also reached, when the amount of additive is 0.3% by mass of bitumen. Stability of the asphalt mixture AC 11 VS compacted at

Table 2. Systemized data of experimental laboratory research of asphalt mixtures.

Asphalt mixture	Bitumen	Additive for cohesion	WMA additive	Amount of WMA additive in bitumen (in mix), %						Mixing temperature, °C		
AC 11 VS (granite)	70/100	Iterlene IN/400L	Iterlow T			0.0				150	120	
				0.1	0.2	0.3	0.4	0.5	0.6		120	
			Cecabase RT Bio			0.0				150	120	
				0.1	0.2	0.3	0.4	0.5	0.6		120	
AC 16 PD (dolomite)				Iterlow T			0.0			150	120	
					0.1	0.2	0.3	0.4	0.5	0.6		120
			Cecabase RT Bio			0.0				150	120	
					0.1	0.2	0.3	0.4	0.5	0.6		120
AC 16 PD (gravel)		Gripper L				(0.0)				150	120	
			Aspha-min	(0.1)	(0.2)	(0.3)	(0.4)	(0.5)	(0.6)		120	
						(0.0)				150	120	
			Natural zeolite	(0.1)	(0.2)	(0.3)	(0.4)	(0.5)	(0.6)		120	

120°C is decreasing with the increasing amount of both additives Iterlow T as well as Cecabase RT Bio (Fig. 1a).

The identified index of flow of asphalt mixtures depending on the compaction temperature and the amount of additive is the least varying at 0.3% amount of additive. The index of flow of the asphalt mixture AC 16 PD with all the used additives is increasing when the amount of additive exceeds 0.3%. Dependency of the index of flow of the asphalt mixture AC 11 VS on the amount of additive is very similar with both additives Iterlow T and Cecabase RT. The index of flow of this mixture has the nearest value to that of the index of flow of the reference mixture, when the amount of additive varies from 0.2% to 0.3% (Fig. 1b). Distribution of the average bulk density values of asphalt mixtures depending on the amount of additive is given in Fig. 1c.

Analysis of the distribution of the average values of physical and mechanical properties of asphalt mixtures mixed and investigated in the laboratory shows that the most optimum amount of additives allowing to reduce the asphalt production and placement temperature is:

- aspha-min and natural zeolite – 0.3% by mass of the asphalt mixture;
- Iterlow T and Cecabase RT Bio – 0.3% by mass of bitumen.

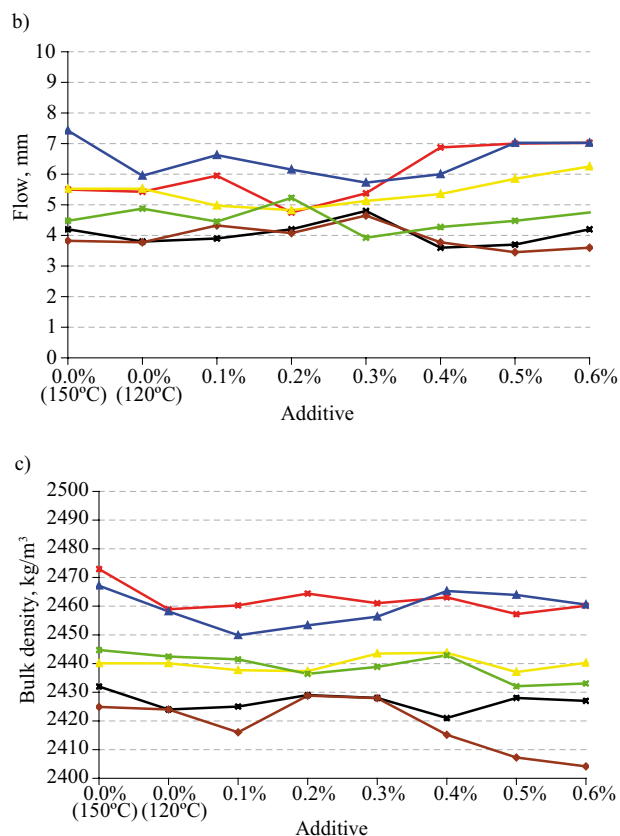
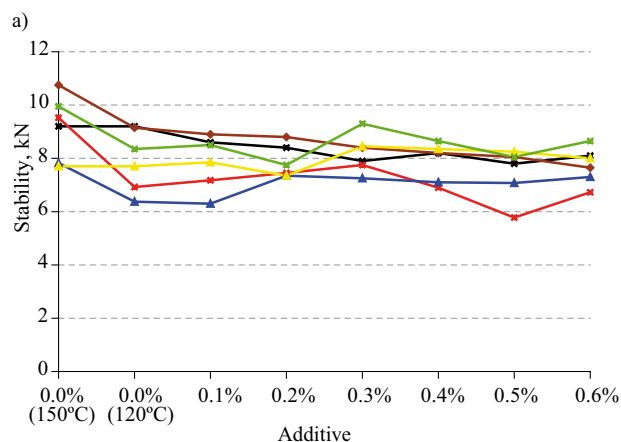


Fig. 1. Distribution of the average stability (a), flow (b) and bulk density (c) values of asphalt mixtures (at 60 °C) depending on the amount of additive:

- × — Cesaba RT AC 11 VS; — × — Cesaba RT AC 16 PD;
- ◆ — Iterlow T AC 11 VS; — ▲ — Iterlow T AC 16 PD;
- ▲ — Aspha-min AC 16 PD; — × — Zeolite AC 16 PD

Analysis of the distribution of the average values of physical and mechanical properties of asphalt mixtures mixed and investigated in the laboratory shows that the most optimum amount of additives, allowing to reduce the asphalt production and placement temperature, is:

– aspha-min and natural zeolite – 0.3% by mass of the asphalt mixture;
 – Iterlow T and Cecabase RT Bio – 0.3% by mass of bitumen.

Further, the dependency is given to physical and mechanical properties of the asphalt mixture AC 16 PD on the type of additive, its amount and the mixing temperature. Distribution of the average stability values of the asphalt mixture AC 16 PD depending on the temperature and the type of additive shows that (Fig. 2a).

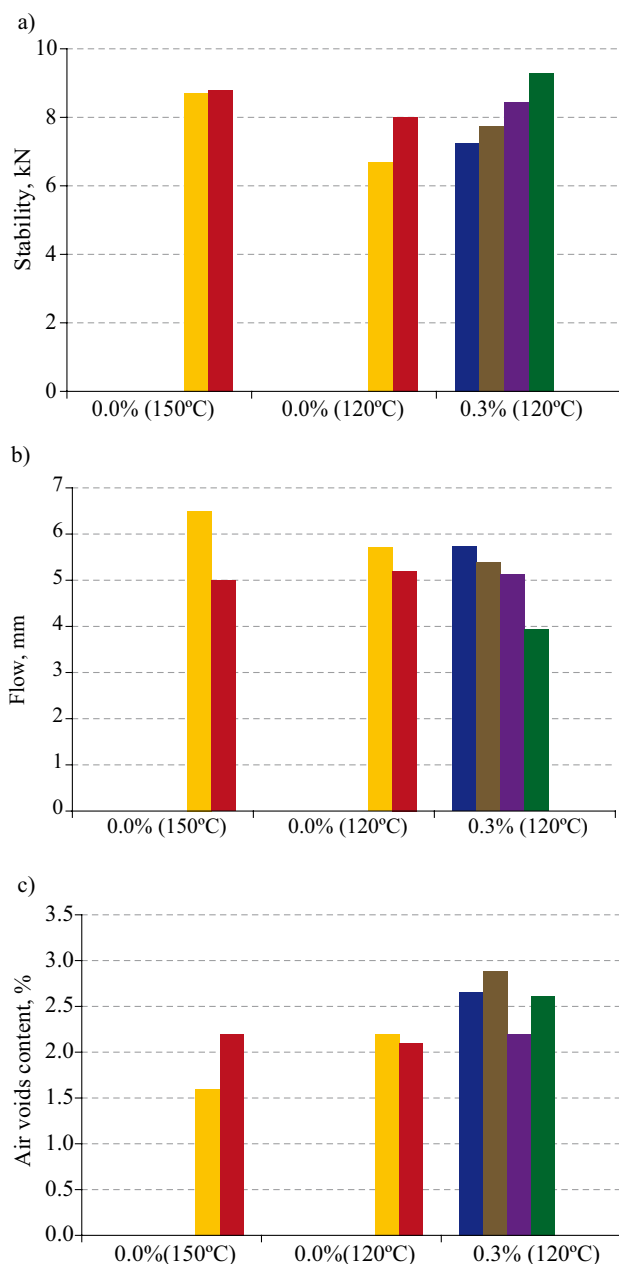


Fig. 2. Distribution of the average stability (a), flow (b) and air voids content (c) values of the asphalt mixtures AC 16 PD depending on the temperature and the type of additive:
 ■ – Interlow T AC 16 PD; ■ – Zeolite AC 16 PD;
 ■ – Aspha-min AC 16 PD; ■ – Cecabase RT AC 16 PD;
 ■ – AC 16 PD (gravel); ■ – AC 16 PD (dolomite)

– stability of the asphalt mixture AC 16 PD produced at 120 °C decreases from 10% to 23% if compared to the stability of the mixture produced at 150°C;

– the use of additives to reduce the production temperature of asphalt mixture allows achieving the same stability as of the reference mixture produced at 150°C.

Distribution of the average flow values of the asphalt mixture AC 16 PD, depending on the temperature and the type of additive, shows that the flow of the reference mixture produced at 120°C with and without additives differs only slightly (Fig. 2b). With the exception of the asphalt mixture produced at 120°C with natural zeolite additive the average flow value of which is by 20% lower than of the reference mixture.

Distribution of the average values of air voids content of the asphalt mixture AC 16 PD depending on the temperature and the type of additive shows that the air voids content of this mixture produced at 120°C with and without additives is higher than that of the reference mixture. However, the average values of air voids content do not exceed the limit values of TRA ASPHALT 08 (Fig. 2c).

5. Advantages and disadvantages of the WMA technologies

It could be reasonably stated that in the production process of WMA mixtures emissions of hazardous materials (greenhouse gases) are significantly lower than that in HMA mixtures. Laying of asphalt pavements in half- or fully-closed sites, e.g. in tunnels, makes a negative impact on the road workers' health, since the exhausted smoke and fumes are cleared away much slower than in an open area; thus, concentration of hazardous materials within the working zone increases several times. In these cases, lower emissions of WMA mixtures would be a considerable advantage. On the basis of the analysis of scientific researches here are the expected values for reducing hazardous emissions in the production of WMA mixtures:

- reduction of CO₂ by 30–40%;
- reduction of SO₂ by 35%;
- reduction of VOC (volatile organic compound) by 50%;
- reduction of CO by 10–30%;
- reduction of NO_x by 60–70%;
- reduction of dust by 20–25%.

Reduced fuel consumption is another advantage of WMA mixtures. Measurements of these mixtures show up to 40% lower fuel costs, if compared to HWA mixtures. Reduction of fuel costs is directly dependent on the production temperature of WMA mixtures. The magnitude of this advantage depends on the type of fuel used in the production process and on fuel prices. These prices in Lithuania are relatively high and has been continuously rising, therefore, this advantage could be very important for the Lithuanian road building companies involved in asphalt mixture production. On the basis of the review of scientific investigations it could be stated that lower fuel consumption for producing WMA mix-

tures has not been estimated as one of the main advantages of these mixtures.

Advantages in the production and use of WMA mixtures according to the largest benefit are as follows:

- 1) improvement of working conditions for asphalt workers, reduction in the emissions of fumes;
- 2) reduction in the hazardous emissions (greenhouse gases);
- 3) improvement of asphalt paving conditions:
 - asphalt pavement can be laid at a lower temperature – extended asphalt paving season;
 - asphalt mixture can be transported for longer distances;
 - more easy to mechanically process asphalt pavements and to reach the required compaction degree;
 - more soon opening to traffic – shorter paving time;
- 4) possibility to add to the asphalt mixture by 50% and more of Reclaimed Asphalt Pavement (RAP);
- 5) reduction in fuel consumption.

Disadvantages in the production and use of WMA mixtures are related to an insufficient degree of their investigation and a relatively short duration of its use. Some additional disadvantages could be stated:

- 6) based on the results of many researches, the physical and mechanical properties of WMA mixtures are worse than those of HMA mixtures. The properties of WMA mixtures differ from the technology used;
- 7) rise in the price of asphalt mixture due to the technological costs of WMA;
- 8) longer asphalt mixing cycle due to adding some additives (not for all technologies);
- 9) necessary modification of asphalt plant (not for all technologies);
- 10) insufficient cohesion between bitumen and mineral materials due to an excessive moisture of mineral materials. It is necessary to use additives to improve cohesion between bitumen and mineral materials.

6. Conclusions and recommendations

The recommended optimum amount of additives allowing to reduce the temperature of asphalt production and placement is: Iterlow T and Cecabase RT Bio – 0.3% by mass of bitumen; Aspha-min zeolite and natural zeolite – 0.3% by mass of asphalt mixture. With the use of this amount of additives the best stability of asphalt mixture produced at 120°C was identified.

On the basis of laboratory researches, it could be stated that WMA mixtures produced at a temperature of 120°C with the additives Iterlow T. Cecabase RT Bio. Aspha-min and natural zeolite have a lower stability by Marshall and higher air voids content than HMA mixtures of the same type.

Depending on the technology and output, the use of WMA technologies irrespective of the reduction in energy (fuel) costs rises the price of asphalt mixture from 0.5% to 7.0%, if compared to the production of HMA mixtures.

The WMA technologies allow using the Reclaimed Asphalt Pavement (RAP). The use of RAP for the production of WMA mixtures reduces water sensitivity of mineral materials (mixture) since the particles of RAP are right away coated with bitumen.

It is recommended on the selected roads of Lithuania to construct experimental asphalt pavement sections using the WMA technologies; during construction and after the opening to evaluate physical-mechanical and operational indices of pavements as well as WMA.

References

- Brosseau, Y.; Saint Jacques, M. 2008. Warm asphalt mixes: overview of this new technology in France, in *Proc of the Transport Research Arena*. Ed. by Žnidarič, A. April 21–24, 2008, Ljubljana, Slovenia. Ljubljana: ZAG, DDC, DRC. 187 p.
- Butz, T. 2008. *Warm asphalt mix – technologies. Research and experience* [cited 19 December, 2008]. Available from Internet: <<http://www.pkd.org.pl/pliki/referaty/butz.pdf>>.
- Čygas, D.; Laurinavičius, A.; Vaitkus, A.; Motiejūnas, A.; Pervenekas, Z. 2008. Research of asphalt pavement structures on Lithuanian roads (I), *The Baltic Journal of Road and Bridge Engineering* 3(2): 77–83. DOI: 10.3846/1822-427X.2008.3. 77-83.
- D'Angelo, J.; Harm, E.; Bartoszek, J.; Baumgardner, G.; Corrigan, M.; Cowser, J.; Harman, T.; Jamshidi, M.; Jones, W.; Newcomb, D.; Prowell, B.; Sines, R.; Beaton, B. 2008. *Warm-Mix Asphalt: European Practice*, Report No. FHWA-PL-08-007, Federal Highway Administration, Washington DC, 59.
- Diefenderfer, S. D.; Hearon, A. J.; McGhee, K. K. 2008. Installation of warm mix asphalt projects in Virginia [CD-ROM], in *Proc of the TRB 87th Annual Meeting*. 13–17 January, 2008, Washington DC, USA. Washington DC: Transportation Research Board. 15 p.
- Diefenderfer, S. D.; McGhee, K. K.; Donaldson, B. M. 2007. *Installation of warm mix asphalt projects in Virginia*, Research Report VTRC 07-R25, Virginia Transportation Research Council, 29.
- Harder, G.; LeGoff, Y.; Loustau, A.; Martineau, Y.; Heritier, B.; Romier, A. 2008. Energy and environmental gains of warm and half-warm asphalt mix: quantitative approach [CD-ROM], in *Proc of the TRB 87th Annual Meeting*. 13–17 January, 2008, Washington DC, USA. Washington DC: Transportation Research Board. 20 p.
- Hurley, G. C.; Prowell, B. D. 2008. Field performance of warm mix asphalt [CD-ROM], in *Proc of the TRB 87th Annual Meeting*. 13–17 January, 2008, Washington DC, USA. Washington DC: Transportation Research Board. 17 p.
- Hurley, G. C.; Prowell, B. D. 2006. Evaluation of potential processes for use in warm mix asphalt, *Journal of the Association of Asphalt Paving Technologists* 75: 41–90.
- Jenkins, K. J.; Groot, J. L. A.; Ven, M. F. C.; Molenaar, A. A. A. 1999. *Half-warm foamed bitumen treatment, a new process* [cited 12 January, 2009]. Available from Internet: <<http://www.aapa.asn.au/content/aapa/download/AdvisoryNote17.pdf>>.
- Juknevičiūtė, L.; Laurinavičius, A. 2008. Analysis and evaluation of depth of frozen ground affected by road climatic conditions, *The Baltic Journal of Road and Bridge Engineering*

- ing 3(4): 226–232. DOI: 10.3846/1822-427X.2008.3. 226-232.
- Kristjansdottir, O. 2006. *Warm mix asphalt for cold weather paving*, Master thesis. The University of Washington, Washington. 127 p.
- Muthen, K. M. 1998. *Foamed asphalt mixes – mix design procedure* [cited 12 January 2009]. Available from Internet: <<http://asphalt.csir.co.za/foamasph/foamasph.pdf>>.
- Radziszewski, P. 2007. Modified asphalt mixtures resistance to permanent deformation, *Journal of Civil Engineering and Management* 13(4): 307–315.
- Tušar, M.; Zupan, J.; Iljaž, K. 2008. Low temperature asphalt trials in Slovenia and chemical analysis of binders, in *Proc of the Transport Research Arena*. Ed. by Žnidarič, A. April 21–24, 2008, Ljubljana, Slovenia. Ljubljana: ZAG, DDC, DRC. 185 p.
- You, Z.; Goh, S. W. 2008. Laboratory evaluation of warm mix asphalt: a preliminary study, *International Journal of Pavement Research and Technology* 1(1): 34–40.
- Некрасова, О. С. и др. 2008. Использование добавок CECABASE RT BIO и CECABASE RT 945 для снижения температуры уплотнения асфальтобетона [Nekrasova, O. S. et al. Usage additives CECABASE RT BIO and CECABASE RT 945 to reduce temperature consolidation of asphalt concrete]: отчет по научно-исследовательской работе [Research Record]. Omsk. Russia. 26 p.

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