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PROPERTIES OF WMA–FOAM MIXES BASED ON MAJOR MECHANICAL TESTS

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Abstract. One of the main advantages of warm mix asphalt (WMA) used as an alternative to conventional hot mix asphalt (HMA), is to reduce mixing and compaction temperatures. This laboratory study was conducted with the aim of determining physical properties of WMA mixes produced using foam bitumen technology (WMA–Foam), while applying different mixing and compaction temperatures. The effect of laboratory compaction method on mix properties was also investigated.

WMA–Foam mixes were produced, adding a soft bitumen to coarse aggregate particles at the first stage, then a hard bitumen, transformed into foam bitumen using a laboratory foam making device, was directly added to aggregates at the next stage. Compaction was performed separately applying both Marshall and gyratory compactors (GC) at different temperatures. Marshall Stability and void contents of the samples were determined as two major parameters for characterizing WMA–Foam mixes. Moisture susceptibility and rutting potential of WMA–Foam samples were evaluated using indirect tensile strength (ITS) and wheel tracking tests. In addition, separate samples were prepared, in which hydrated lime powder was added as an anti-stripping agent to improve adhesion properties of the mixes.

Comparing the results of WMA–Foam mixes with control HMA of the same content, resulted in mixes with similar properties of the control HMA, with appreciably lower production and compaction temperatures of the former. It was also resulted that mixes compacted with gyratory compactor were less sensitive to temperature variations than those compacted with Marshall Hammer.

Keywords: WMA–Foam, HMA, mix design, foam bitumen, compaction, moisture susceptibility, rutting, ITS.

1. Introduction

Warm Mix Asphalt (WMA) can be produced applying different methods, namely, using additives, bitumen emulsion or foam bitumen. Hurely and Prowel (2006), Borleo *et al.* (2008) and Su *et al.* (2009) used organic additives or waxes. Chemical additives were tested by Barreto *et al.* (2008). Hydrophilic materials, such as zeolite, added to bitumen, were tested by Devivere *et al.* (2003), Hurely and Prowel (2006) and Wasiuddin *et al.* (2007). Hurely and Prowel (2006) also used bitumen emulsion for preparing WMA mixes. Larsen and Robertus (2005), Johnston *et al.* (2006), Romier *et al.* (2006) and Wielinski *et al.* (2009) converted bitumen into foam to prepare WMA–Foam mixes.

All the above mentioned technologies are applied in order to reduce bitumen viscosity at lower temperatures (normally 30 to 50 °C lower than the case of conventional HMA mixes). WMA characteristics vary appreciably in accordance with the adopted technology that is used to produce these (Angelo *et al.* 2008; Vaitkus *et al.* 2009) and also manufacturing technology of asphalt production (Sivilevičius and Šukevičius 2009).

Research results of Kvasnak *et al.* (2009) and Schmitt *et al.* (2009) proved that WMA allows also reducing field compaction temperatures. According to Prowell and Hurely (2007), a reduced temperature should also be applied in the laboratory for mix design. Previous researches showed that laboratory compaction method also affects the results. The latter methods showed that some of the laboratory compactors, including gyratory compactor (GC), are not sensitive enough to temperature variations.

Radziszewski (2007) showed that resistance to permanent deformation depends on the kind of asphalt mixture and binder applied. However, Qin *et al.* (2009) recognized that a reduction in WMA production temperature will result in reducing aging of the mix bitumen. As Su *et al.* (2009) showed this could result in increased rutting susceptibility of WMA mixes. Diefenderfer *et al.* (2007) showed that laboratory tensile strength testing (ITS) indicated lower TSR values for WMA mixes. This could be related to the reduced aging of bitumen in WMA. Researches of West (2009) also indicated that lowering compaction temperature adversely affects moisture susceptibility and rutting potential of WMA mixes.

WMA–Foam process uses two-stage addition of two bitumens to the mix, (i.e. soft and hard bitumen). The resulting blend is used to produce the desired bitumen penetration. The soft bitumen typically represents 20 to 30 percent of the total bitumen. It should be emphasized that in WMA–Foam processing, these minimum levels for soft binders should be kept firm. In fact, a minimum percentage of soft bitumen is required for coating coarse aggregate

particles. With this method of processing, the absorption demand of the aggregate particles will be fulfilled as it was worked out by Larsen and Robertus (2005).

Foaming process is performed by adding water at ambient temperature at the rate of 2 to 5 percent by mass to the hard bitumen. Bitumen temperature should be kept within 160–180 °C, using a laboratory foaming device (Prowell and Hurley 2007). This will result in bitumen-water combination to expand approximately 15 times its original volume.

In this research (performed in TM University by the author in 2009 and 2010 as a part of the Ph.D. research project), Laboratory WLB10 Wirtgen foam making unit was used to produce foam bitumen. By following Marshall Mix design method, an HMA dense graded hot mix was designed. Using the same aggregates and bitumen contents, WMA–Foam mix samples were produced at lower production and compaction temperatures. This was performed by the means of adding two bitumens, namely soft and hard bitumen in two stages. The soft bitumen was blended with coarse aggregates and the hard bitumen, after converting this into foam, was added to the mix. The two binders were added at the amounts required to correspond to the same penetration grade of HMA bitumen.

Different samples were prepared using both Marshall Compaction and GC at various temperatures in order to compare WMA–Foam and conventional HMA mixes. Evaluation of rutting potential and moisture susceptibility of WMA–Foam mixes was performed by the application of wheel tracking and ITS tests.

2. Materials

2.1. Aggregates

Aggregates with properties summarized in Tables 1 and 2 were taken from a typical HMA production plant in Tehran. HMA and WMA–Foam mixes were selected from a dense graded wearing course grading as shown in Fig. 1.

2.2. Bitumen

For HMA mixes a 60/70 pen bitumen with properties reported in Table 3 was used. For WMA–Foam, a 40/50 pen bitumen was used as the hard binder, while a Vacuum Bottom (V. B.) bitumen was used as the soft binder. General properties of these are reported in Tables 3 and 4.

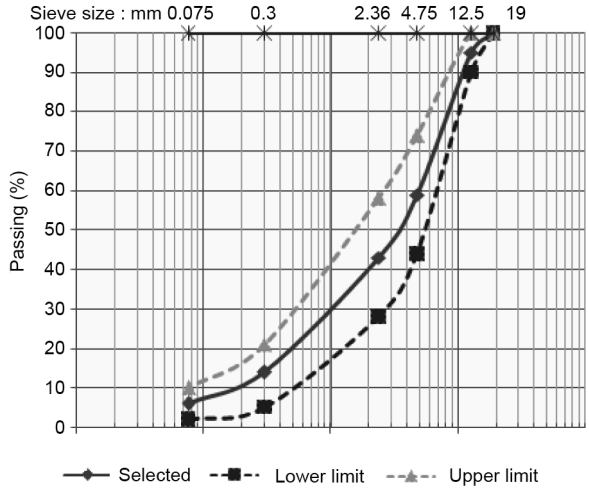

Fig. 1. Aggregates grading curve

For comparison purposes, specific amounts of the two binders should be selected for WMA mix production. This is performed in such order that the final binder has almost the same target 60/70 pen of the bitumen of the control HMA. Table 5 reports the results of these blends. The addition of 15% of the soft and 85% of the hard bitumens resulted in the same 60/70 pen consistency of the HMA. In the next step, coarse aggregates (i.e. particles greater than 4.75 mm) were coated with the soft bitumen. Coating of the particles was controlled by visual inspection.

Foam bitumen

Foam bitumen process is characterized by the following two primary properties (Asphalt Academy 2002):

Expansion Ratio: a measure of foam viscosity that determines how well the foam bitumen will be dispersed in a mix. It is calculated as the ratio of maximum volume of foam relative to its original volume.

Half life: a measure of the foam stability. This provides an indication of the rate of collapse to half of its maximum volume.

Table 6 reports foam bitumen characteristics at different water contents. In the whole production process, the temperature of foam production was kept 170 °C constant.

Table 1. Physical properties of aggregates

Test method	Standard	Specification*	Results
Los Angeles Abrasion Value	AASHTO T–96	Max. 30%	14%
Soundness weight loss ($NaSO_4$)	AASHTO T–104	Max. 12%	Fine particles: 0.5%
		Max. 8%	Coarse particles: 0.3%
Fractured particles in coarse aggregates (two sides)	ASTM D5821	Min. 90%	97%
Coating of bitumen aggregate mixture	AASHTO T–182	Min. 95%	More than 95%
Sand equivalent (SE)	AASHTO T–176	Min. 50%	60%

*Iranian Technical Specifications for Asphalt Pavements (2003).

Table 2. Densities and water absorption of aggregate particles

Aggregate size	Density		Water absorption (%)
	Apparent	Bulk	
Retained on sieve # 8	2.52	2.65	2.54
Passing sieve # 8 and retained on sieve # 200	2.51	2.65	3.14
Passing sieve # 200	2.69		
Total density	2.53		

Table 3. Physical properties of the penetration grade binders

Standard	Test		Bitumen Type	
			60/70	40/50
ASTM D5	Penetration		60	44.1
ASTM D36	Softening point		50	53.9
ASTM D70	Specific gravity at 25 °C		1.017	1.02
ASTM D92	Flash point		319	319
ASTM D113	Ductility		100<	100<
ASTM D2170	Viscosity (St)	100 °C	3082	------
		110 °C	837.1	------
		135 °C	396.3	------
ASTM D1754	TFOT	Retained penetration	40	38.3
		Weight loss	0.02	0
ASTM D1872	RTFOT	Weight loss	0.3	------

Table 4. Testing results of the Vacuum Bottom bitumen

Test	Standard	Bitumen V.B.	
Penetration	ASTM D5	260	
Softening point	ASTM D36	39.5	
Viscosity (St)	ASTM D2170	130 °C	81.7
		120 °C	226
		110 °C	380
		100 °C	667.9

Table 5. Penetration of the soft and hard bitumen blends

Soft bitumen (wt)%	Hard bitumen (wt)%	Penetration of blended bitumen
30	70	86
15	85	62

Table 6. Foam bitumen characteristics at different water contents

Water (with respect to bitumen weight %)	Expansion Ratio	Half life (second)
1.5	8	36
2.0	19	28
2.5	20	25
3.0	22	16
3.5	23	13

With reference to Table 6, considering the two parameters of expansion ratio and half life time together, the optimum water content of the foam bitumen corresponded to 2% of the total bitumen weight.

3. Mix design

3.1. Hot mix asphalt

Marshall Design Method with 75 blows compaction level was followed for HMA mix design. The optimum binder content was selected as 5.8% of the total weight of the mix. Table 7 shows the volumetric properties of the designed HMA. The void content was 4.3% at this bitumen level. The production and compaction temperatures of HMA samples were 150 and 145 °C respectively.

3.2. Compaction with gyratory compactor

In order to determine the design number of gyrations in GC, HMA samples were compacted at different gyration levels and their densities were determined. The number of gyrations that results in achieving the required densities can be determined from Fig. 2.

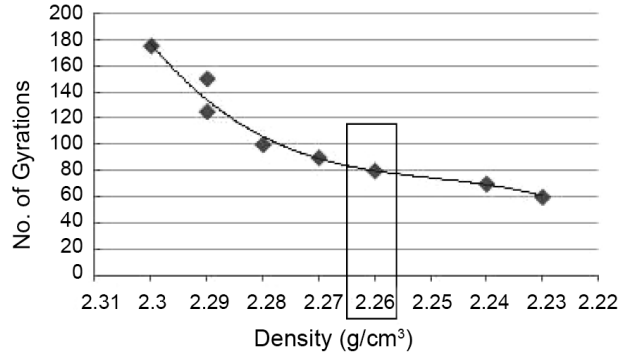

Fig. 2. Number of gyrations versus samples density in gyratory compactor

Table 7. Volumetric properties of HMA

Mixing temperature	Bulk specific gravity	Air void (%)	VMA* (%)	VFB* (%)	Stability (kN)	Flow (1/10 mm)	OBC* (%)
HMA, 150 °C	2.26	4.3	15.6	73.6	12.9	35	5.8
Specification limit**	–	3–5	Min. 13	65–75	≥8.0	20–35	–

* VMA = Void in Mineral Aggregate, VFB = Void Filled with Bitumen, OBC = Optimal Bitumen Content.

** Iranian Technical Specifications (2003) for asphalt pavements.

The samples compacted at 80 gyration levels showed densities corresponding to the densities of the samples compacted with 75 Marshall Hammer blows. Therefore, for compacting HMA and WMA samples using GC, 80 gyrations were considered as the optimum number of gyrations.

3.3. WMA–Foam samples preparation

WMA–Foam samples were prepared with the same bitumen content of HMA mixes (i.e. 5.8% of total weight of the mix). The V.B. bitumen, at 15% level of total bitumen content was mixed with the coarse aggregates at different mixing temperatures. The 40/50 pen hard bitumen at 85% of the total bitumen of the mix was transformed into foam and was mixed with coated and uncoated aggregates at selected mixing temperatures. Compaction was performed at the same level as HMA samples (i.e. 75 blows of Marshall Hammer and 80 gyrations in gyratory compactor). In order to determine the optimum mixing and compaction temperatures of WMA, different WMA–Foam samples were prepared at various mixing temperatures. The samples were compacted at different temperatures using both GC and Marshall Compactors.

For comparison purposes, some WMA samples were prepared at the same mixing and compaction temperatures of WMA–Foam, using the same 60/70 penetration grade bitumen. Mixing time of the foam bitumen mixes were kept 1 minute constant for all the samples (i.e. almost two times that of half life time of foam bitumen).

4. Results

4.1. WMA–Foam mix design

Figs 3 to 8 report the summary results of the major laboratory tests. According to Table 7, minimum accepted level for Marshall Stability was 8 kN while the accepted range for air voids was between 3–5%.

With reference to Figs 3 and 4, it can be seen that WMA–Foam mixes have greater stability values and less void contents than control WMA mixes. Compaction temperature was mostly depended to the adopted compaction method. Based on the specification limits for Marshall Stability and voids content (Table 7), GC WMA–Foam mixes can be compacted at 80 °C in order to achieve the required limits. Unlike these, the samples compacted with Marshall Hammer should be compacted at 90 °C in order that the specification limits are achieved.

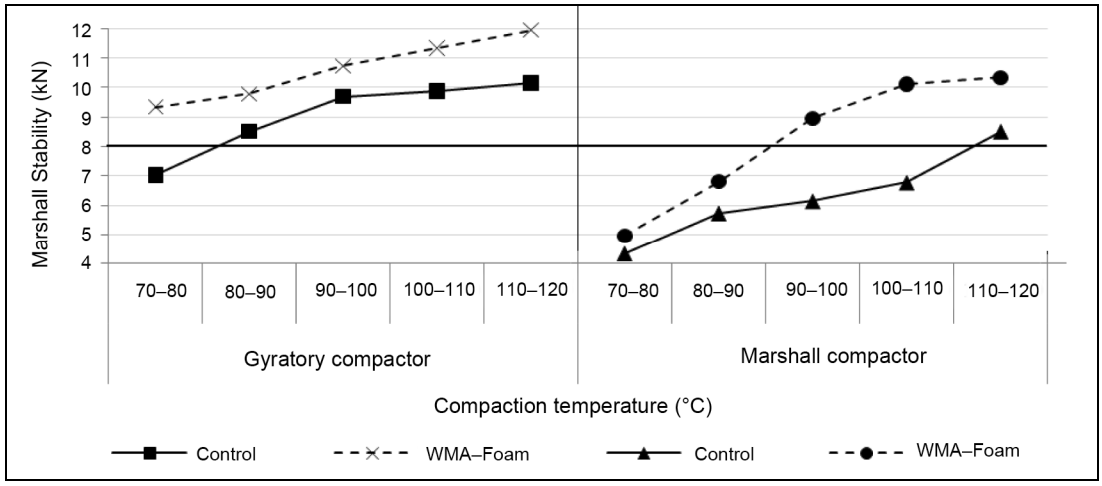

Fig. 3. Marshall Stability of samples prepared at mixing temperature of 130 °C

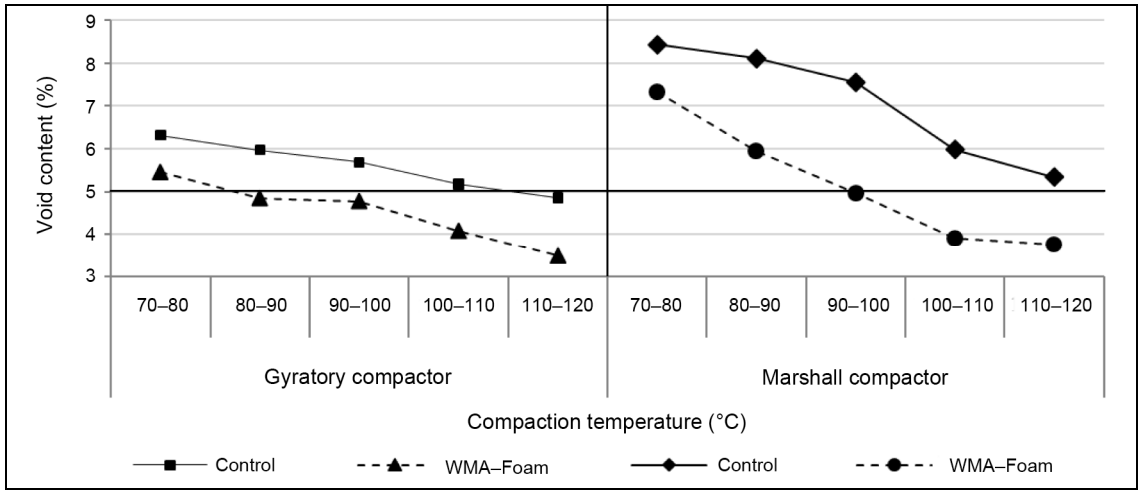

Fig. 4. Void contents of samples prepared at mixing temperature of 130 °C

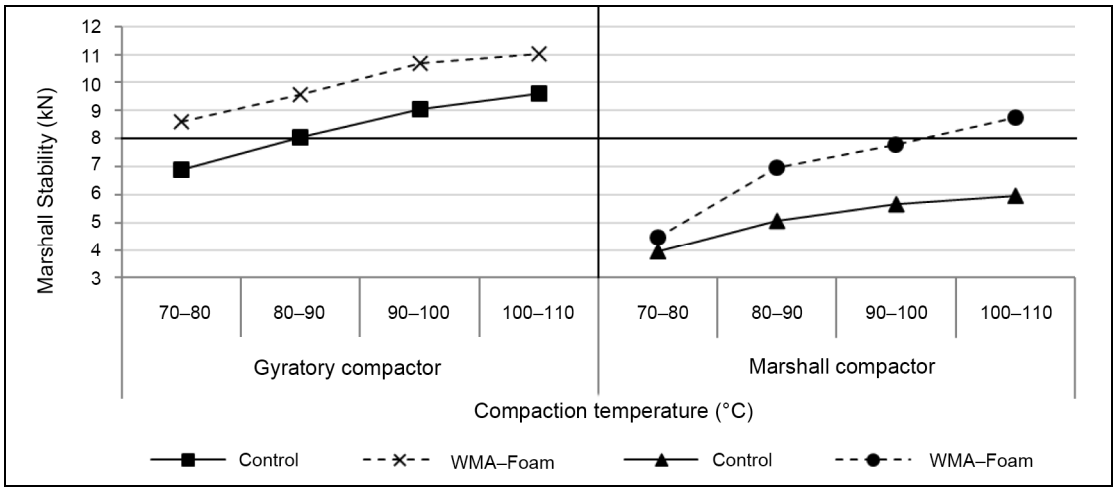

Fig. 5. Marshall Stability of samples prepared at mixing temperature of 120 °C

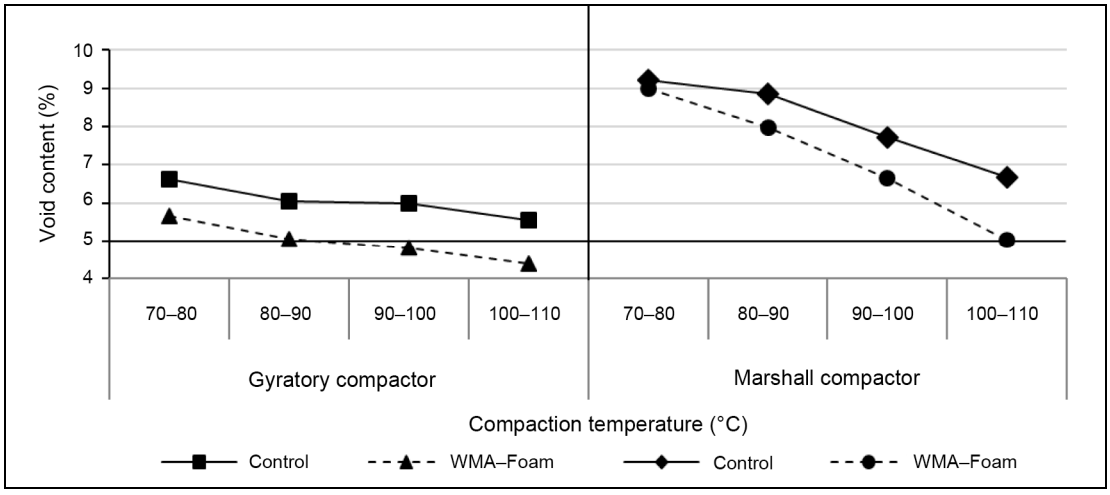

Fig. 6. Void contents of samples prepared at mixing temperature of 120 °C

With reference to Figs 5 and 6, it can be noticed that at mixing temperature of 120 °C, compaction temperature of WMA–Foam mixes compacted by GC could be reduced to 80 °C. In contrast, the samples compacted with Marshall Compactor should be compacted at 100 °C as the lowest temperature. At equal compaction temperatures, Marshall Stability of the GC compacted samples were greater than those compacted using Marshall Hammer.

Figs 7 and 8 show that at mixing temperature of 110 °C, samples compacted with gyratory compactor at 80 and 90 °C, had void contents slightly greater than the required specification limits. However, their Marshall Stabilities were within the limits.

The samples compacted with Marshall Hammer had less stabilities and more void contents than the required limits. Hence, a mixing temperature of 110 °C was considered to be unacceptable when Marshall Compaction was used.

From the above results, it can be concluded that the samples compacted with Marshall Hammer were more sensitive to compaction temperature variations, compared with those compacted with gyratory compactor. In fact, laboratory compaction method had great influence on choosing mixing and compaction temperatures.

4.2. Moisture susceptibility

ITS (Modified Lottman Test–AASHTO T283) was performed on HMA samples and according to the specification; the minimum accepted value for TSR (Tensile Strength Ratio) should be 80%. WMA specimens were prepared at different mixing and compaction temperatures. The results are reported in Table 8. It can be resulted from this table that TSR values were lower for WMA samples. In addition, a reduction in mix and compaction temperatures affects ITS values appreciably. Dry ITS values of HMA samples were greater than WMA–Foam samples. It can be seen from Table 8 that neither HMA nor WMA samples met the minimum required TSR value. Hence the above tests were repeated for HMA and WMA samples containing 2% hydrated lime powder. The results are reported in Table 9.

With reference to Table 9, it can be concluded that adding 2% hydrated lime will result in achieving greater ITS conditioned values and increased TSRs (exceeding the minimum 80% required). This is for samples that were compacted at above 90 °C. It can also be noticed from Table 9 that by adding 2% hydrated lime powder, even at lower mixing and compaction temperatures, ITS values of WMA–Foam samples were increased. However, the accep-

table TSR values were achieved at the same mixing and compaction temperatures that Marshall Stability and void contents of both Marshall Hammer and gyratory compacted samples were in the specification limits.

From ITS testing results, it can be concluded that lowering mixing and compaction temperatures of all samples (with or without additive) resulted in less ITS and TSR values. It could be related to less bitumen stiffening during mixing and compaction processes.

4.3. Rutting

Wheel tracking test was carried out according to EN 12697–22 standard in order to determine rutting potential of WMA-Foam and control HMA mixes. The test was performed on samples that were prepared at different mixing and compaction temperatures. According to ITS testing results on WMA–Foam samples, since the addition of 2% hydrated lime powder had pronounced effects on increasing ITS values, the rutting test was carried out on samples containing 2% hydrated lime. The results are reported in Table 10.

Comparing results of wheel track testing of HMA and WMA–Foam mixes from Table 10, it can be concluded that lowering mixing and compaction temperatures resulted in greater rut depth values. This could be as a result of less bitumen stiffening in these mixes.

It is resulted from the same Table that rutting values of mixes prepared at mixing temperatures of 130 and 120 °C and compaction temperatures above 105 °C, are comparable with the control HMA specimens. Comparing the recent results with the previous testing results indicated that at the mentioned mixing and compaction temperatures, all WMA–Foam samples had properties within the specification limits, regardless of the adopted compaction method (i.e. from Marshall Stability, void contents and TSR values of the samples).

5. Discussion of the results

Fig. 9 shows Marshall Stabilities of WMA–Foam samples, compacted both with gyratory and Marshall Compactors. As expected, the greater mixing and compacting temperatures, the greater the stabilities (regardless of the applied compaction method). With reference to this figure, it was observed that Marshall Stability of WMA–Foam samples, compacted with GC were greater than those compacted applying Marshall hammer. However,

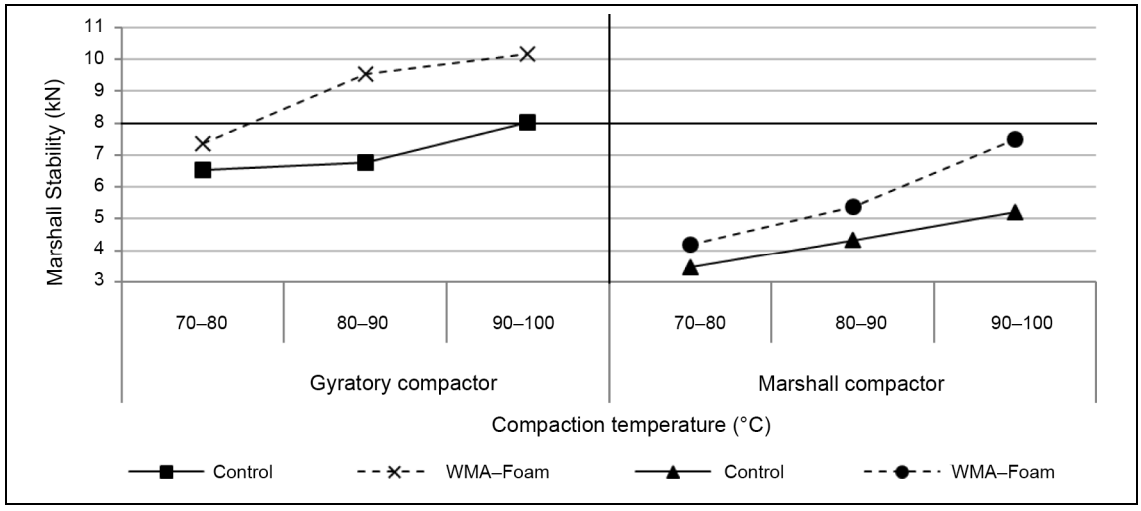

Fig. 7. Marshall Stability of samples prepared at mixing temperature of 110 °C

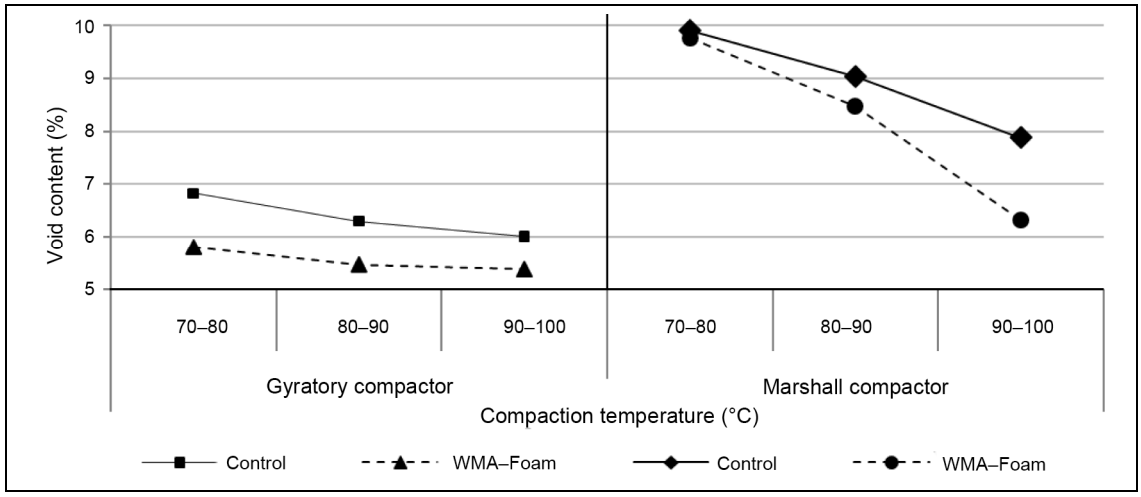

Fig. 8. Void contents of samples prepared at mixing temperature of 110 °C

Table 8. Results of ITS testing on HMA and WMA–Foam samples

Mix type	Mixing temperature (°C)	Compaction temperature (°C)	Average air void contents (%)		ITS (kPa)		TSR (%)
			Dry	Conditioned	Dry	Conditioned	
HMA	150	135	7.03	6.96	980	683	69.63
WMA	130	115	7.07	7.03	860	490	56.99
		105	7.62	7.68	821	424	51.68
		90	7.91	7.88	791	354	44.82
	120	105	7.19	7.22	698	316	45.21
		90	7.19	7.20	698	303	43.33
	110	100	7.16	7.13	546	286	52.33

Table 9. Results of ITS testing on HMA and WMA–Foam samples containing hydrated lime powder

Mix type	Mixing temperature (°C)	Compaction temperature (°C)	Average of air void contents (%)		ITS (kPa)		TSR (%)
			Dry	Conditioned	Dry	Conditioned	
HMA+lime 2%	150	135	7.14	7.18	973	902	92.68
WMA–Foam+ 2% lime	130	115	6.97	7.01	938	929	98.99
		105	7.04	6.98	847	831	98.20
		90	7.48	7.49	839	640	76.26
	120	105	7.29	7.22	829	778	93.84
		90	7.56	7.50	800	611	76.47
	110	100	7.04	6.99	824	670	81.30

Table 10. Results of rutting test on HMA and WMA–Foam samples

Mix type	Mixing temperature (°C)	Compaction temperature (°C)	Rutting (mm)
HMA	150	140	3.60
WMA–Foam (with 2% lime powder)	130	115	3.10
		105	3.60
		90	4.60
	120	105	3.40
		90	5.40
	110	100	4.90

the difference is greater at lower compaction temperatures. According to Fig. 10, this could be due to the increased air void of the samples. Fig. 10 shows also the air voids content variations which are greater in the case of the Marshall compacted samples.

Comparing Marshall stability and void contents of WMA–Foam samples, based on the specification limits of HMA (reported in Table 7), these are met in GC compacted specimens at mixing and compaction temperatures of 120 and 90 °C respectively as the minimum required temperatures. For Marshall hammer compacted specimens, at mixing temperature of 120 °C and compaction temperatures of 100 °C, the air void content is slightly greater than that of control HMA, however, still within the specification limits.

Fig. 11 shows the TSR and rutting values of HMA and WMA–Foam samples produced at different mixing and compacting temperatures.

From this figure, it can be seen that for mixing and compaction temperatures of 120 and 105 °C (as the minimum temperatures), TSR and rutting values are comparable with those in the control HMA. As it was concluded from the previous results, regardless of the adopted compaction method, the Marshall stability and void contents of WMA–Foam samples were acceptable at these mixing and compaction temperatures. Hence, it could be resulted that for WMA–Foam specimens, produced at minimum mixing and compaction temperatures of 120 and 105 °C respectively, Marshall Stability, air void contents, TSR and rutting values were comparable with the control HMA. In the case of the gyratory compacted samples, based on the results of Marshall Stability and air void contents, compaction temperature could be reduced to 90 °C. However, this temperature reduction was not acceptable based on ITS and wheel track testing results. Hence, it could be concluded that the Marshall Hammer compaction method is a better compaction tool for WMA–Foam mixes than GC.

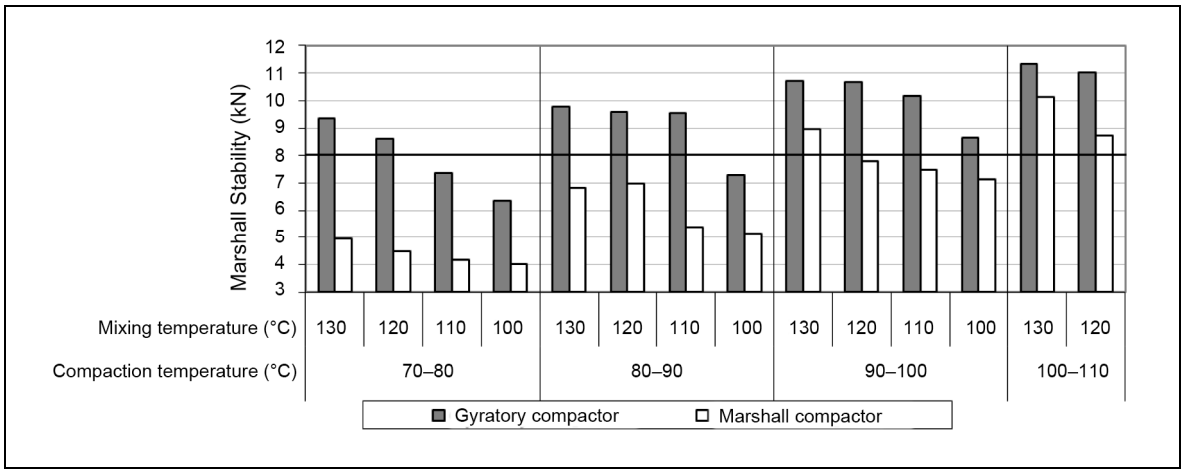

Fig. 9. Marshall Stabilities of WMA–Foam samples compacted by Marshall and gyratory compactors

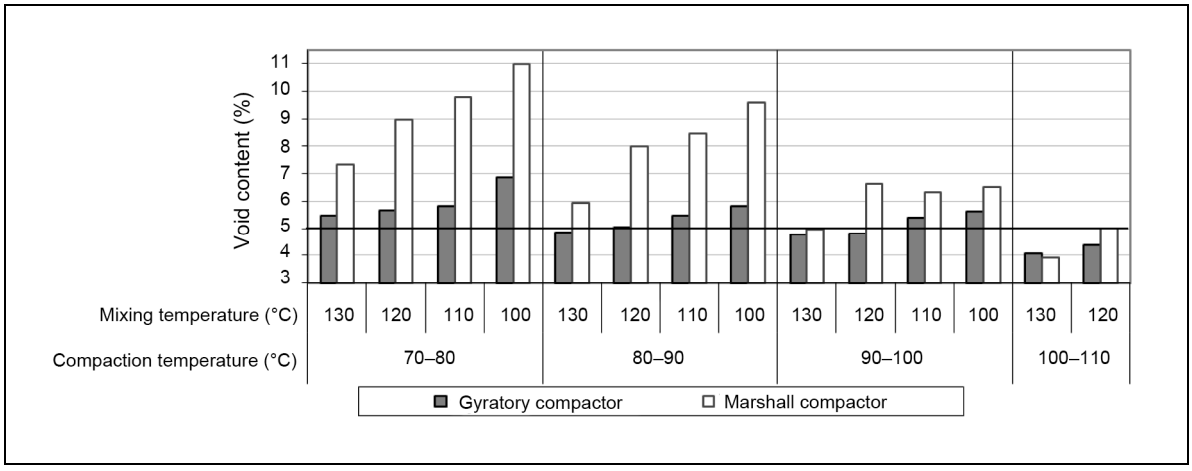

Fig. 10. Void contents of WMA–Foam samples compacted by Marshall and gyratory compactors

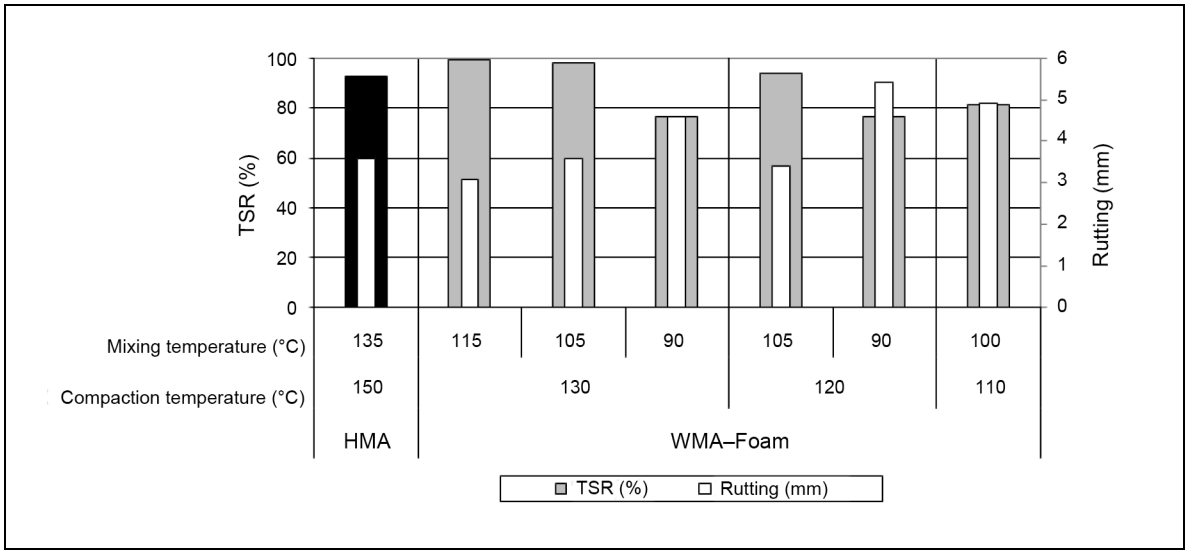

Fig. 11. TSR and rutting values of control HMA and WMA–Foam samples

6. Conclusions

Comparing test results of WMA–Foam and control HMA mixes, the following conclusions could be drawn:

- Preparing WMA–Foam mix, using two bitumen types (i.e. soft and hard, the latter in foam state) resulted in appreciable decreased mixing and compaction temperatures, compared with conventional HMA control mix.
- At various mixing and compaction temperatures, laboratory compaction method affected greatly Marshall Stability and void contents of both WMA–Foam and control HMA mixes.
- In preparing WMA–Foam specimens, greater compaction temperatures are required in the case of Marshall Compaction method, compared with gyratory method.
- The moisture susceptibility of WMA–Foam samples was greater than those of control HMA. The addition of 2% hydrated lime powder was effective in increasing TSR values above the minimum required specification level.
- Rutting values in the wheel tracking test of WMA–Foam samples, containing hydrated lime powder, were comparable with those of the control HMA.
- Based on the laboratory testing results obtained in this research, Marshall Compaction method can be considered a more effective method in compacting WMA–Foam specimens, compared with gyratory compactor.

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ŠILTAI MAIŠYTO ASFALTO MIŠINIŲ, GAMINAMŲ PAGAL PUTOTO BITUMO TECHNOLOGIJĄ (*WMA-Foam*), SAVYBĖS REMIANTIS PAGRINDINIAIS MECHANINIAIS BANDYMAIS

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Santrauka

Pagrindinis šiltai maišyto asfalto mišinių privalumas, lyginant su įprastiniais karštai maišyto asfalto mišiniais, yra galimybė sumažinti asfalto mišinio maišymo ir tankinimo temperatūras. Šio laboratorinio tyrimo tikslas – nustatyti šiltai maišyto asfalto mišinių, gaminamų pagal putoto bitumo technologiją (*WMA-Foam*), fizines savybes taikant skirtingas maišymo ir tankinimo temperatūras. Taip pat buvo tirtas skirtingų laboratorinių tankinimo metodų poreikis asfalto mišinio savybėms.
WMA-Foam technologijos mišiniai gaminti pirmame etape į stambiąsias mineralines medžiagas dedant minkštąjį bitumą, o kitame etape – kietąjį bitumą specialiu laboratoriniu putojimo įrenginiu pavertus putotu bitumu dedant į pirmame etape paruoštas mineralines medžiagas. Tankinta atskirai Maršalo plūktuvu ir giratoriaus presu skirtingose mišinio temperatūrose. Maršalo bandinių pastovumas ir oro tuštumų skaičius buvo nustatyti kaip du pagrindiniai *WMA-Foam* technologijos mišinius charakterizuojantys parametrai. *WMA-Foam* technologijos bandinių jautrumas vandeniui ir atsparumas provėžų susidarymui buvo vertinti pagal netiesioginio tempimo jėgos ir rato riedėjimo vėžės nustatymo bandymus. Keletas bandinių papildomai buvo pagaminti su gesintosiomis kalkėmis, t. y. asfalto mišinio sukibimą gerinančiu priedu.
Lyginant *WMA-Foam* technologijos ir karštai maišyto asfalto mišinių bandymų rezultatus nustatyta, kad identiškos sudėties *WMA-Foam* technologijos mišinių savybės yra panašios į karštai maišyto asfalto mišinių savybes, tačiau jos pasiekiamos pastebimai žemesnėse maišymo ir tankinimo temperatūrose. Taip pat nustatyta, kad asfalto mišinio bandiniai, pagaminti giratoriaus presu, buvo ne tokie jautrūs gamybos temperatūros kitimui, lyginant su bandiniais, pagamintais Maršalo plūktuvu.

Reikšminiai žodžiai: *WMA-Foam* technologija, karštai maišyto asfalto mišinys, mišinio sudėtis, putotas bitumas, tankinimas, jautrumas vandeniui, provėžų susidarymas, netiesioginė tempimo jėga (angl. *Indirect Tensile Strength* – ITS).

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