Construction and Building Materials 126 (2016) 108–118

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Moisture resistance and compactibility of asphalt concrete produced in half-warm mix asphalt technology with foamed bitumen

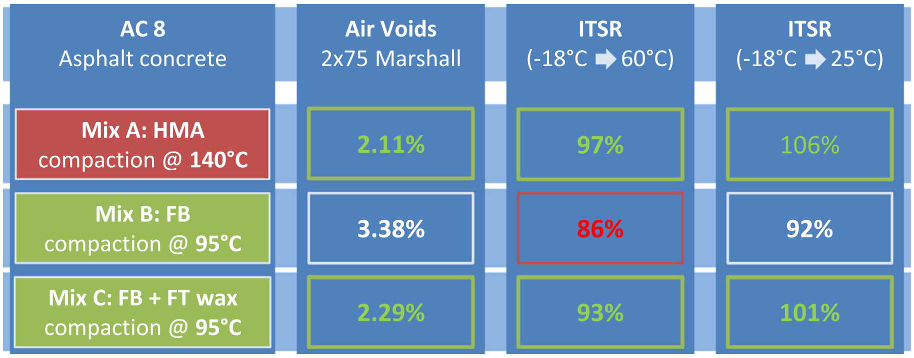
Anna Chomicz-Kowalska [a],*, Władysław Gardziejczyk [b], Mateusz M. Iwański [a]

[a] Department of Transportation Engineering, Faculty of Civil Engineering and Architecture, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
[b] Department of Transportation Engineering, Faculty of Civil and Environmental Engineering, Białystok University of Technology, Ul. Wiejska 45A, 15-351 Białystok, Poland

HIGHLIGHTS

- We evaluated a fine asphalt concrete mix with foamed bitumen compacted at 95 °C.
- The foam mix with 2.5% Fischer-Tropsch wax performed similarly to HMA.
- Moisture resistance testing procedure was significant to obtained results.
- The air void content had an effect on all of the measured properties of the mixes.

GRAPHICAL ABSTRACT



AC 8 Asphalt concrete	Air Voids 2x75 Marshall	ITSR (-18°C ➡ 60°C)	ITSR (-18°C ➡ 25°C)
Mix A: HMA compaction @ 140°C	2.11%	97%	106%
Mix B: FB compaction @ 95°C	3.38%	86%	92%
Mix C: FB + FT wax compaction @ 95°C	2.29%	93%	101%

ARTICLE INFO

Article history:
Received 16 June 2016
Received in revised form 30 August 2016
Accepted 2 September 2016
Available online 14 September 2016

Keywords:
Half-warm mix asphalt
HWMA
HMA
Foamed bitumen
Moisture resistance
Asphalt concrete
Fischer-Tropsch (FT)
Synthetic wax

ABSTRACT

Current regulations regarding emissions, as well as the efforts focused on reducing energy intensity of building materials production create a need for implementing new road construction technologies. Particular attention is being paid to the lowering of asphalt concrete production temperature, which is about 160 °C. In response to this need warm mix asphalt (WMA) technologies have been developed which allow producing asphalt mixes at temperatures about 20–30 °C lower than those of conventional methods. However, it was only after half warm mix asphalt (HWMA) was introduced that the mixing temperature of asphalt concrete with foamed bitumen could be reduced by as much as 60 °C. Asphalt pavements constructed with HWMA may have a reduced service life and lower resistance to environmental factors (e.g. water). This paper presents the results from the tests with one freeze cycle and from the moisture sensitivity analysis conducted for the low-temperature asphalt concrete (AC 8) with foamed bitumen and the control mix produced according to conventional hot mix asphalt technology. It was found that the modification of 50/70 bitumen (before foaming) with the addition of 2.5% *FT* synthetic wax had a beneficial effect on the properties of asphalt concrete mixes under investigation. The *ITSR* indices were compared having been determined in accordance with procedures based on European and AASHTO standards that are widely used in Poland. The analysis was extended to include the compactibility evaluation of low-temperature bituminous mixes and the impact of air voids on the mechanical parameters. The foamed asphalt concrete modified with 2.5% *FT* wax was found to satisfy the requirements for moisture resistance determined during the test with one freeze cycle.

---

* Corresponding author.

E-mail addresses: akowalska@tu.kielce.pl (A. Chomicz-Kowalska), w.gardziejczyk@pb.edu.pl (W. Gardziejczyk), matiwanski@tu.kielce.pl (M.M. Iwański).

http://dx.doi.org/10.1016/j.conbuildmat.2016.09.004
0950-0618/© 2016 The Author(s). Published by Elsevier Ltd.

1. Introduction

The reduction in energy intensity of technological processes and the lowering of greenhouse gas emissions produced during these processes are the key element of the environmental protection policy. In the road paving industry, HMA (Hot Mix Asphalt) mixtures production is one of such processes. HMA mixtures are manufactured at temperatures of about 170–180 °C, depending on the type of bitumen used. The use of low viscosity modifiers, such as Fischer-Tropsch (FT) synthetic wax, allows production and placement of mixtures at temperatures about 20–30 °C lower [1], with a beneficial effect on the change in rheological characteristics of binders [2]. The reduction in energy required to produce a mineral-bitumen mix with Fischer-Tropsch wax is similar to that coming from the incorporation of reclaimed asphalt pavement in the mix [3]. These eco-friendly mixtures, which are produced in WMA (warm mix asphalt) technology require that aggregates making over 90% of the mixture composition, have to be subjected to the same thermal treatment as in the standard hot mix technology as this is the only way to remove a thin water film from the aggregate surface. The water has to be removed to ensure proper adhesion between bitumen and the aggregate surface, thus providing the mixture with adequate resistance to moisture – the most deleterious factor affecting road pavement quality [4]. The effect of water on bituminous mixtures (and asphalt pavements) is complex and dependent on several factors, which include aggregate type [5,6], bitumen type [7,8], adhesion promoters and bitumen ageing retarders [8–10]. They all have a substantial influence on the thickness of the binder film forming on the aggregate particles [11]. A significant part is also played by the structure of the pavement layer, characterized by air void content [12] dependent on the compaction temperature. Production and paving temperatures can be considerably reduced by applying HWMA (half-warm mix asphalt) technology, in which foamed bitumen is used as a binder [13]. Foamed bitumen allows manufacturing bituminous mixtures at temperatures less than 100 °C. In this technology, aggregates do not have to be completely dry as the thin water film on their surface has a beneficial effect on the additional foaming process [14]. Energy used in the drying process is reduced substantially as the temperatures used are lower than those of HMA or WMA mixtures production. These lower temperatures may have a negative effect on the formation of the film on the aggregate surfaces. Also compaction at temperatures lower than 100 °C may lead to an excessive content of air voids. As a result, the layer may not obtain the required moisture resistance and be susceptible to damage. One of the methods applied to prevent these negative effects is to use foamed bitumen with high expansion ratio (*ER*) and half-life (*HL*) obtained as a result of pre-foaming bitumen modification with the use of low viscosity modifiers, for example, *FT* wax [15].

The issue of water susceptibility of bituminous mixtures is particularly important in moderate climate regions, including Poland. Water susceptibility accompanied by low temperatures in the winter season may cause a failure of the surface course in the pavement. Due to complexity of the process, laboratory evaluations of the mixture's resistance to these environmental factors are difficult and studies are being conducted to develop a procedure that will best simulate real field conditions. The indirect tensile strength ratio (*ITSR*) is the popular assessment criterion used to determine moisture resistance of mineral-bitumen mixes [16], however the methodology for water susceptibility evaluation has changed over the last years and, as shown in Table 1, it varies even throughought the EU and member states of the European Committee for Standardisation (CEN).

Poland, compared with other European countries, has the most severe requirements for water resistance indicated by the highest required *ITSR* values along with the use of wet conditioning with one freeze cycle. Besides Poland, freeze cycles are used in Turkey (AASHTO T283 [19]) and Finland (10 freeze–thaw cycles).

The experiences with HMA under moisture resistance tests is well documented and means to achieve adequate performance of mineral-bitumen mixtures are well understood and established. On the other hand, the emerging technologies of low temperature mixes, including HWMA with foamed bitumen require intensive investigations in this field.

While assessing the feasibility of any bitumen modification in HWMA technology, the economic calculation has to include all possible aspects of the production and service the final mix. The investigated asphalt mixes include an AC 8 HWMA wearing course mix based on a 50/70 bitumen, that is modified by the addition of 2.5% of Fischer-Tropsch wax (by bitumen mass). In this example, the increase in the cost of the mix constituents due to the incorporation of *FT* wax varies greatly depending on the constantly changing price of bitumen. However a rough calculation can be made. Taking into account the present (July, 2016) low oil and bitumen prices, the *FT* wax modification increases the cost of bituminous binder by ca. 31% and material costs of the whole mix by ca. 12% (any increase in bitumen prices will decrease this figure). On the other hand, the lowered HWMA processing temperatures can potentially lead to significant economic savings and ecological benefits, which are mostly related to the lower processing and paving temperatures. While it is claimed that the WMA technology, in most favourable conditions, permits the reduction in CO_2 emissions even by 40% and volatile organic compound emissions even by 50% [20], it is reasonable to say that the use of HWMA techniques will yield similar decrease in emissions easily. As the CO_2 is mostly produced in the process of heating the bitumen and aggregates up to the processing temperatures, the relative reduction in CO_2 emissions is directly proportional to the reduction in fuel consumption at the mixing plant and it relates to decreased asphalt production cost. Additionally, the *FT* wax modification allows the bitumen processing temperatures before foaming to be lowered by approx. 20 °C, as the decreased viscosity of *FT* modified bitumen allows the bitumen temperature to be decreased from 170 °C to 150 °C [15]. Taking into account the aforementioned benefits of the HMWA technology and possible positive effects of *FT* wax modification on the durability of the produced mixes, the material costs of introducing Fischer-Tropsch wax to HWMA mixes may eventually become insignificant.

This paper presents results of moisture resistance tests using two slightly different procedures with one freeze cycle. The tests were conducted on HWMA mixtures produced with foamed bitumen and on a control HMA mix. The investigations focused on the susceptibility of the HWMA mixture to the thermal shock during wet conditioning of Marshall samples, but the testing programme included also the analysis of compactibility and the evaluation of the effects of air void content on strength parameters.

2. Tested materials and methodology

2.1. Experimental program

The performance of the HWMA mixes was evaluated by testing the following parameters of Marshall compacted samples:

- air void content (V_m) to EN 12697-8:2005 [21], after 35, 50 and 75 blows per sample face,
- moisture resistance based on the evaluation of:
  - indirect tensile strength for a set of wet specimens ($ITS_{w(A)}$, $ITS_{w(B)}$) conditioned according to procedures specified in p. 2.3, as well as a set of dry specimens (ITS_d),
  - indirect tensile strength ratio ($ITSR_{(A)}$, $ITSR_{(B)}$).

Table 1
HMA requirements with respect to *ITSR* in selected CEN member states [17].

Country	EU (Y/N)	Required minimum values of the indirect tensile strength ratios (*ITSR* categories) (%)			Freeze cycle (Y/N)
		Surface course	Binder course	Base course	
Belgium	Y	ITSR$_{70}$; ITSR$_{80}$ (SMA)	ITSR$_{60}$; ITSR$_{80}$ (EME)	ITSR60, ITSR80 (EME)	N
Finland	Y	ITSR$_{80}$ (AC, SMA); ITSR$_{60}$ (PA)	ITSR$_{NR}$	ITSR$_{NR}$	Y
France	Y	Duriez$_{70}$; Duriez$_{80}$ (BBTM, PA)	Duriez$_{70}$	Duriez 70	N
Spain	Y	ITSR$_{85}$ (AC, PA); ITSR$_{90}$ (BBTM)	ITSR$_{80}$	ITSR$_{80}$	N
The Netherlands	Y	ITSR$_{80}$	ITSR$_{70}$	ITSR$_{70}$	N
Germany	Y	ITSR$_{NR}$	ITSR$_{NR}$	ITSR$_{NR}$	N
Norway	N	ITSR$_{70}$	ITSR$_{70}$	ITSR$_{70}$	N
Poland	**Y**	**ITSR$_{90}$**	**ITSR$_{80}$**	**ITSR$_{70}$**	**Y**
Slovakia	Y	ITSR$_{80}$	ITSR$_{80}$	ITSR$_{80}$	N
Slovenia	Y	ITSR$_{NR}$	ITSR$_{NR}$	ITSR$_{NR}$	N
Sweden	Y	ITSR$_{75}$	ITSR$_{75}$	ITSR$_{75}$	N
Turkey	N	ITSR$_{80}$	ITSR$_{80}$	ITSR$_{80}$	Y

Y – Yes, N – No, Duriez – method B according to EN 12697-12 [18].

The experimental programme was set out to investigate moisture resistance of half-warm mix asphalt concrete with foamed bitumen, in accordance to two different procedures. Formerly, the tests specified in national technical guidelines [22] for assessing moisture resistance of asphalt concrete in Poland were based on the AASHTO T 283-89 [19] and EN 12697-12:2008 [18] procedures. This procedure introduced severe thermal shock to the samples by requiring a direct transfer of the frozen samples at −18 °C to a water bath at a temperature of 60 °C. With the introduction of the recent national guidelines in 2014 [23], the thermal shock was reduced by decreasing the final water bath temperature to 25 °C. The tests with a freeze cycle aimed to compare the moisture resistance of surface course HWMA mixtures with foamed bitumen and HMA mixtures under different testing procedures, specifically in terms of the thermal shock during the wet sample conditioning.

Since there is a risk that HWMA mixtures can be insufficiently compacted due to low processing temperatures, a fine graded asphalt concrete AC 8 was selected for the research.

The following denotation of the mixtures, split by the production technology, was adopted further in the article:

- Mix A (Hot mix asphalt – reference mix),
- Mix B (half warm mix asphalt with foamed bitumen),
- Mix C (half warm mix asphalt with foamed bitumen modified with 2.5% Fischer-Tropsch synthetic wax).

The HMA samples were compacted at 140 °C, whereas the HWMA samples with foamed bitumen were compacted at 95 °C. The production temperature was 20 °C higher than the compaction temperature in the case of HMA and 10 °C higher in the case of HWMA with foamed asphalt. These temperatures were to correspond to the real conditions of production and placement of bituminous mixtures.

The test samples were produced in accordance with EN 12697-30 [24] and compacted by using Marshall hammer. To establish the air void content, the samples were compacted in the Marshall compaction apparatus with the use of 35, 50 and 75 impact blows per face. To determine the indirect tensile strength and calculate the *ITSRs*, the samples were compacted with 35 impact blows per side. All parameters were determined on 9 samples that satisfied the assumed requirements with respect to physical and geometric characteristics.

Comprehensive evaluation of the results included the inference about the significance of the differences between the means of the independent variables being considered (V_m, ITS_d, $ITS_{w(A)}$, $ITS_{w(B)}$, $S_{m(+25^\circ C)}$) in three independent sets, that is, Mix A, Mix B and Mix C. The selection of the tests was dependent on the variable under analysis. When a significant test result was obtained, the *post hoc* comparison was applied to estimate detailed significance of the differences between the sets and to check which particular means differ from one another.

2.2. Air void content (V_m)

The air void content is the volume of void space in the bituminous mixture sample expressed as percentage of the overall volume of the sample. This parameter was determined to EN 12697-8:2005 [21] based on the following formula:

$$V_m = \frac{\rho_{m-}\rho_b}{\rho_m} \cdot 100\%(v/v) \tag{1}$$

where V_m – void space content in the sample (% volume v/v); ρ_m – density of the bituminous mixture (kg/m^3); ρ_b – bulk density of the bituminous mixture (kg/m^3).

2.3. Indirect tensile strength (ITS) and indirect tensile strength ratio (ITSR)

For each of the three mixes (A, B and C) a set of 9 Marshall specimens was selected to evaluate the moisture resistance. All the specimens intended for the indirect tensile strength tests were compacted using a Marshall hammer with 35 blows per face. Within each set, the specimens were split into three subsets with similar mean densities determined using a hydrostatic balance: one dry subset and two wet subsets. Dry specimens were conditioned by storing them on a flat surface at room temperature (20 ± 5 °C). Wet specimens were conditioned in accordance with the procedures A and B described below:

Stage I: the specimens are submerged in distilled water at (20 ± 5)°C and placed inside a vacuum chamber; a vacuum of 6.7 ± 0.3 kPa is reached within 10 ± 1 min and maintained for (30 ± 5) minutes; the atmospheric pressure is gradually restored and the specimens are kept under water for another (30 ± 5) minutes and then inspected for increase in volume (2% margin);
Stage II: the specimens are placed in a water bath at 40 ± 1 °C for 68 to 72 h;
Stage III: the specimens removed from the bath are separately wrapped in a plastic "stretch" foil and put into plastic bags containing 10 ± 1 ml of water. The bags with the specimens are stored in a freezer at (−18 ± 3 °C) for 16 h;
Stage IV: the frozen specimens are placed in a water bath at a temperature of (60 ± 1) °C in procedure A and (25 ± 1) °C in procedure B for (24 ± 1) hours; the plastic foil and bags are removed immediately after placement in the bath.

After conditioning, the specimens were tested for the indirect tensile strength in the Marshall tester. Based on the maximum stress value at failure, the *ITS* of the specimen is calculated from:

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot H} \tag{2}$$

where *ITS* – indirect tensile strength of the specimen (kPa); *P* – maximum compressive force (kN); *D* – specimen diameter (mm); H – specimen height (mm).

The ability of particular mixtures to resist moisture damage (*ITSR*) was quantified based on the ratio of the strength (*ITS*) of wet and dry subsets according to the formula:

$$ITSR_{(A/B)} = 100 \cdot \frac{ITS_{w(A/B)}}{ITS_d} \tag{3}$$

where $ITSR_{(A/B)}$ – the ratio of the indirect tensile strength calculated for the specimens conditioned in accordance to procedure A or procedure B (%); $ITS_{w(A/B)}$ – averaged indirect tensile strength for wet specimens conditioned n accordance to procedure A or procedure B; ITS_d – averaged indirect tensile strength for dry specimens.

2.4. Materials and mix design procedure

As regards the grading, aggregate type and the amount and type of the bitumen binder, the asphalt concrete mixture was designed based on the national requirements for AC 8 mixtures used for surface courses of pavements with medium traffic load of $0.03 \times 10^6 < ESAL_{100kN} \leqslant 7.30 \times 10^6$ during a 20 year design life [22,23,25].

Framework compositions of the mineral mixture and bituminous mixture are summarised in Table 2. Fig. 1 is a graphical representation of the grading of the designed asphalt concrete mineral mixture.

Table 2
Composition of AC mineral mixture AC 8.

Materials	Mineral mixture (% m/m)	Bituminous mixture (% m/m)
Filler (limestone aggregate)	7.0	6.6
Crushed fine continuously graded aggregate 0/2 mm (limestone)	37.0	34.8
Coarse aggregate 2/5 mm (gabbro)	16.0	15.1
Coarse aggregate 4/8 mm (gabbro)	40.0	37.7
Paving bitumen 50/70	-	5.8
Sum	100	100

For the study, the hot mix asphalt concrete mixture intended for the surface course was produced with 5.8% (by mass) of 50/70 bitumen in accordance with requirements set forth in [22,23,25]. For the first HWMA batch, the bitumen was unmodified and for the second the *FT* wax was added in amounts of 2.5% by the mass of the binder. In both instances the bitumen was eventually subjected to the foaming process with water. *FT* wax is an odourless, milk-white granular material with solidification point ranging from 70 to 100 °C [26]. Its properties allow producing low temperature asphalt concrete and it also contributes to the improved resistance to water damage and improved adhesion in WMA mixtures [27].

Results from the tests of selected properties of 50/70 neat and modified bitumen are summarized in Table 3. Fig. 2 shows the foaming characteristics of those binders.

The optimum foaming water content (*FWC*) was established based on the characteristics above:

for neat 50/70 bitumen: *FWC* = 2.5%, *ER* = 11, *HL* = 10 s,
for 50/70 bitumen + 2.5% FT: *FWC* = 2.0%, *ER* = 18, *HL* = 18 s.

3. Test results and analysis

3.1. Physical parameters

3.1.1. Air void content

Air void content was used as a compaction measure for bituminous mixture samples. Adequate level of this parameter in laboratory-prepared samples and in the pavement layer is a major factor ensuring resistance to the action of environmental and traffic-related factors. If the amount of air voids is too low, the mixture may quickly develop substancial amounts of permanent deformation, whereas too high amount of air voids may additionally lead to decreased water and frost resistance of the mixture. In HWMA technology with foamed bitumen it is essential that optimum compaction or density is obtained to protect the pavement layer against deleterious effects of water ingress.

Values of the basic statistical measures obtained in theses tests are shown in Table 4. Fig. 3 summarizes air void content mean values obtained for asphalt concrete specimens compacted with the use of 75 blows per face, split by production technology.

Analysis of the results indicates that the Mix B, i.e. half-warm mix asphalt concrete with foamed bitumen had the highest air void content (V_m = 3.4%). On the other hand, the amount of air voids in the *FT* wax modified HWMA mixtures with foamed bitumen was comparable to the control mixture produced in the conventional

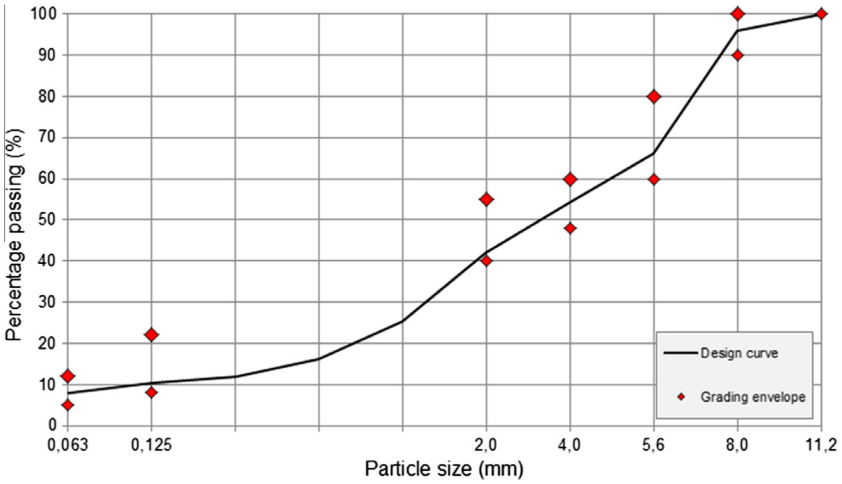


Fig. 1. Grading curve of AC 8 mineral mix with limiting points as in Polish requirements.

Table 3
Properties of neat 50/70 bitumen and 50/70 bitumen with 2.5% *FT* wax content.

Property		Unit	Testing method	Bitumen	
				50/70	50/70 + 2.5FT
Penetration at 25 °C		0.1 mm	EN 1426 [24]	65.9	44.3
Softening point		°C	EN 1427 [28]	50.4	63.3
Fraass breaking point		°C	EN 12593 [29]	-15.1	-12.8
Plasticity range		°C	–	65.5	76.1
Penetration Index		–	EN 12591 [30]	−0.6	1.4
Dynamic viscosity	60 °C	Pa·s	EN-13302 [31]	372.9	613.7
	90 °C	Pa·s	EN-13302 [31]	14.0	16.9
	135 °C	Pa·s	EN-13302 [31]	0.649	0.522 l

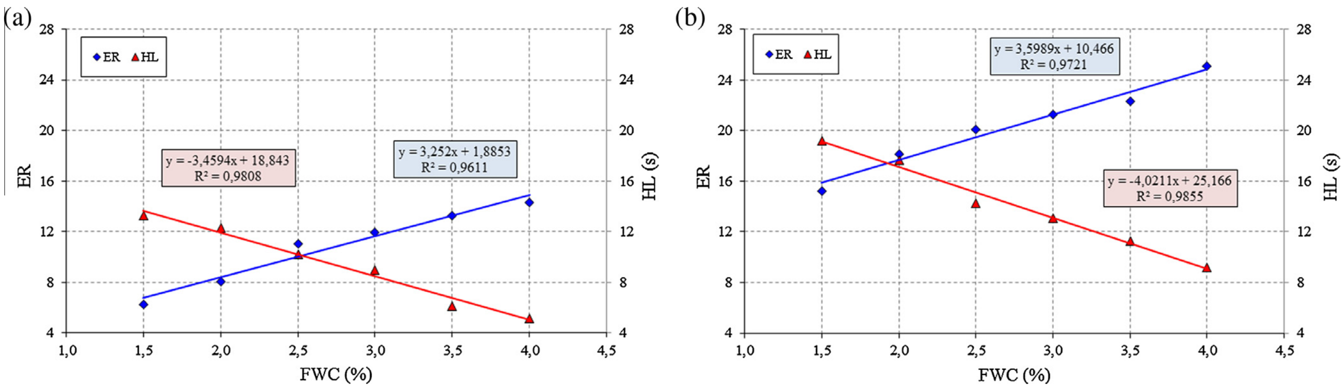


Fig. 2. Characteristics of foamed bitumen produced with neat 50/70 bitumen (a) and 50/70 bitumen with 2.5% *FT* wax content (b).

Table 4
Basic statistical quantities determined for characteristic V_m.

Feature	Breakdown table of descriptive statistics								
	Type of the mix	Means	N	Std. Dev.	Variance	Coef. Var.	Std. Err.	Minimum	Maximum
V_m (%)	Mix A	2.111	9	0.15366	0.024	7.27859	0.05122	1.90	2.40
	Mix B	3.378	9	0.23863	0.057	7.06471	0.07954	3.10	3.70
	Mix C	2.289	9	0.25712	0.066	11.23343	0.08571	2.00	2.70

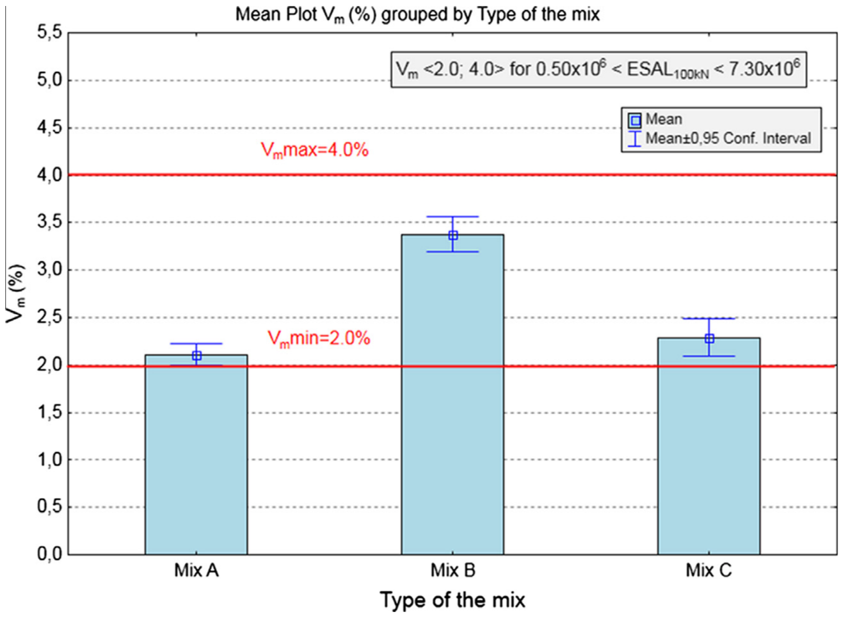


Fig. 3. Summary of average air void contents in HMA and HWMA mixtures with foamed bitumen (with and without the addition of *FT* wax).

Table 5
Results from the analysis of variance for characteristic V_m.

Effect	One-way ANOVA (Analysis of Variance) Marked differences are significant at $p < 0.05$ (bold)							
	SS Effect	Df Effect	MS Effect	SS Error	df Error	MS Error	F	p
V_m (%)	8.4652	2	4.2326	1.1733	24	0.0489	86.5758	0.000000

Table 6
Results from Duncan's multiple comparison test used to analyse variations in the effect of the factor under investigation (*Type of the mix*) on characteristic V_m.

Feature	Duncan test; Variable: ITSM (MPa) Marked differences are significant at $p < 0.05$ (bold), M – mean value			
	Type of mix	(1) M = 2.1111	(2) M = 3.3778	(3) M = 2.2889
Vm (%)	(1) Mix A		0.000065	0.101150
	(2) Mix B	0.000065		0.000152
	(3) Mix C	0.101150	0.000152	

HMA procedure with the difference of only 0.2%. This was a result of the improved mix compactibility due to the reduction of binder viscosity resulting from the addition of the wax. For all mixtures investigated, the air void content was within the range of 2.0% to 4.0% required for the AC 8 mixture intended for the surface course designed for medium traffic volumes ($0.50 \times 10^6 < \text{ESAL}_{100\text{kN}}$ - $\leqslant .30 \times 10^6$ in accordance with the Polish handbook [25]).

To evaluate the differences between the mixtures in terms of the production method (factor: *Type of the mix*), the significance test for independent samples was used. Since the variable V_m was normally distributed for all three independent groups (Mix A, Mix B, Mix C) and since the homogeneity of variance assumption was satisfied, the *F* parametric test (Fisher-Snedecor test) was used. Results from the *F* test allow concomitant comparison of several means without indicating which group means differ for other group means. If the differences between the means appear to be significant, the only information obtained from this test is that at least one mean value varies from the others. Therefore, when a significant result was obtained in the general *F* test, the *post hoc* comparison was used for estimation of detailed significance of the differences between the groups to see which specific means are different from one another.

Results from the significance evaluation of the effect of *Type of the mix* factor on characteristic V_m are shown in Table 5.

As shown in Table 5, production technology (Mix A, Mix B, Mix C) had a significant effect on the V_m variable. In this case, the hypothesis assuming equality of the means should be rejected because the level of assumed test probability *p-value* was <0.05, that is, less than the assumed significance level. The analysis of variance indicated that there were at least two groups of significant variation. The results for the characteristic under investigation were the basis for conducting multiple comparison *post hoc* tests (Table 6).

No statistically significant differences were found in the Duncan *post hoc* test (Table 6) (*p-value* = 0.10115 for V_m) while comparing the HMA mixture with the HWMA mixture containing foamed bitumen and *FT* wax. It can thus be stated that the addition of the synthetic wax improved workability of the mixture at the compaction temperature of 95 °C and contributed to the air void level comparable with that obtained for HMA mixture compacted at temperature 45 °C higher than the compaction temperature of HWMA mixtures. The remaining pairs varied significantly at the assumed significance level of $\alpha = 0.05$.

3.1.2. Compactibility of the asphalt concrete produced at lowered temperatures

The term "compactibility" is understood as a change in physical and mechanical characteristics due to an increase in the degree of compaction [32]. The compactibility evaluation was conducted with the use of a Marshall compactor. This method is a basic, simple and widely used method of preparing cylindrical bituminous specimens for the determination of their physical and mechanical properties. The physical parameters, such as bulk density and air void content in the specimen are the basic characteristics taken into account during the mix design phase and during the evaluation of the correctness of pavement layer compaction.

Analysis of compactibility of the asphalt concrete mixtures was performed based on the determined air void contents in the specimens compacted using 35, 50 and 75 blows per side, in compliance with EN 12697-8 [21].

The relationship shown in Fig. 4 between the number of blows and the air void content in the laboratory specimens was used to analyze the HWMA mixture compaction effectiveness. These mixtures are compacted at substantially lower temperatures and thus they are exposed to compaction deficiency, which may lead to a decline in their water and frost resistance. The result obtained by the HMA mixture compacted at 140 °C was taken to be a reference value of V_m. The low temperature compaction tests (95 °C) aimed at establishing feasibility of using *FT* synthetic wax in bituminous mixtures with paving bitumen. The overall objective of this study was to check whether it is possible for the HWMA mixtures to obtain the reference level of compaction. The results confirmed that it is possible when the addition of 2.5% *FT* wax is used. With known characteristics of compactibility from the low temperature asphalt concrete mix design phase, indications about possibilities of placing mixtures at temperatures substantially lower, 45 °C in this case, relative to the conventional hot mix asphalt were obtained.

The results from the compactibility tests revealed high effectiveness of *FT* wax at the lower temperatures of asphalt concrete production. Air void content in the Mix C specimens was comparable to that obtained for the reference HMA mixture. The obtained air void values indicate that the behaviour of the HWMA mixes during compaction is similar to that of conventional HMA mixtures. It was observed that in all studied mixes the decrease in air void content due to increasing number of Marshall hammer blows was similar, resulting in an approximately perpendicular progression of the compactibility characteristics. In mixes A, B and C the increased number of blows from 35 to 50 resulted in approx. 1% air void content decrease and further compaction with 75 blows decreased the air voids by approx. 0.9%. The compactibility curve of the Mix B was significantly shifted compared to the characteristics of mixes A and C. This means that the HWMA mix without FT wax modification obtained significantly higher air void contents than the reference Mix A and HWMA Mix C with FT wax

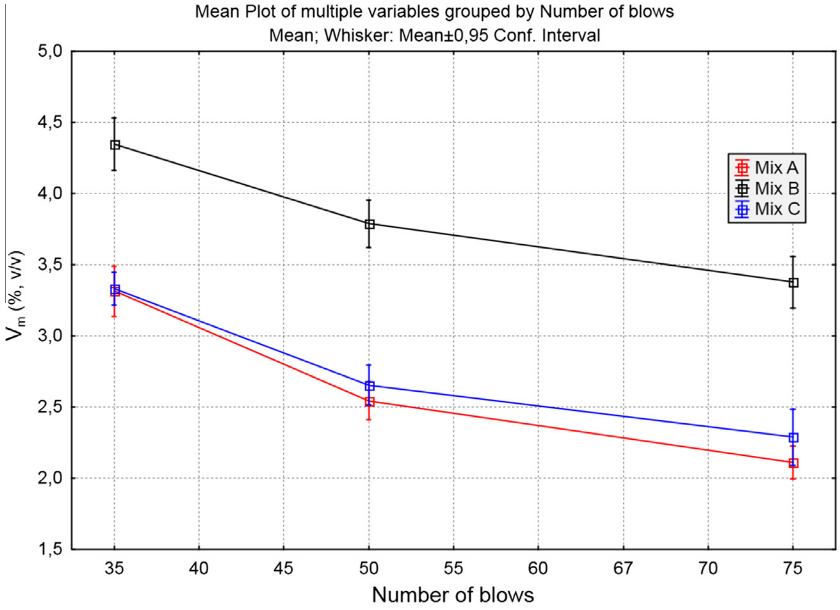


Fig. 4. Relationship between air void content and number of Marshall hammer blows.

Table 7
Descriptive statistics for ITS_d, $ITS_{w(A)}$ and $ITS_{w(B)}$.

Feature	Breakdown table of descriptive statistics								
	Type of the mix	Means	N	Std. Dev.	Variance	Coef. Var.	Std. Err.	Minimum	Maximum
ITS_d (kPa)	Mix A	1052.350	9	75.57764	5711.979	7.181794	25.19255	945.76	1169.11
	Mix B	844.704	9	73.02260	5332.299	8.644759	24.34087	759.20	970.80
	Mix C	1144.847	9	33.26479	1106.546	2.905610	11.08826	1094.88	1187.01
$ITS_{w(A)}$ (kPa)	Mix A	1024.011	9	51.27174	2628.791	5.006951	17.09058	928.80	1107.90
	Mix B	727.622	9	48.98150	2399.187	6.731721	16.32717	663.30	827.90
	Mix C	1069.511	9	36.07965	1301.741	3.373471	12.02655	1013.70	1111.10
$ITS_{w(B)}$ (kPa)	Mix A	1118.734	9	38.65593	1494.281	3.455328	12.88531	1055.20	1179.49
	Mix B	774.057	9	20.28012	411.283	2.657998	6.76004	736.10	801.22
	Mix C	1161.823	9	30.88122	953.6499	2.619977	10.29374	1114.50	1198.10

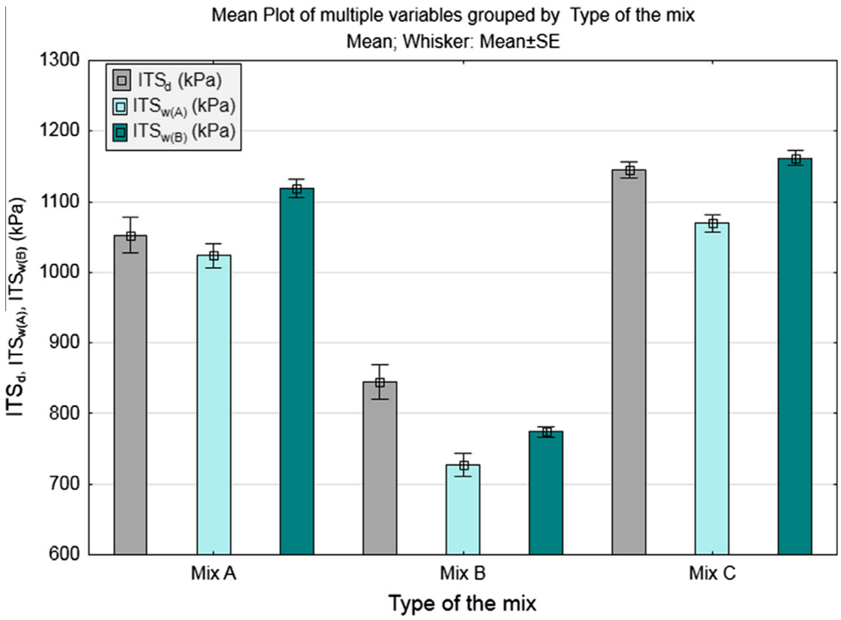


Fig. 5. Indirect tensile strengths for the specimens from the dry subset (ITS_d) and wet subsets of AC 8 mixtures.

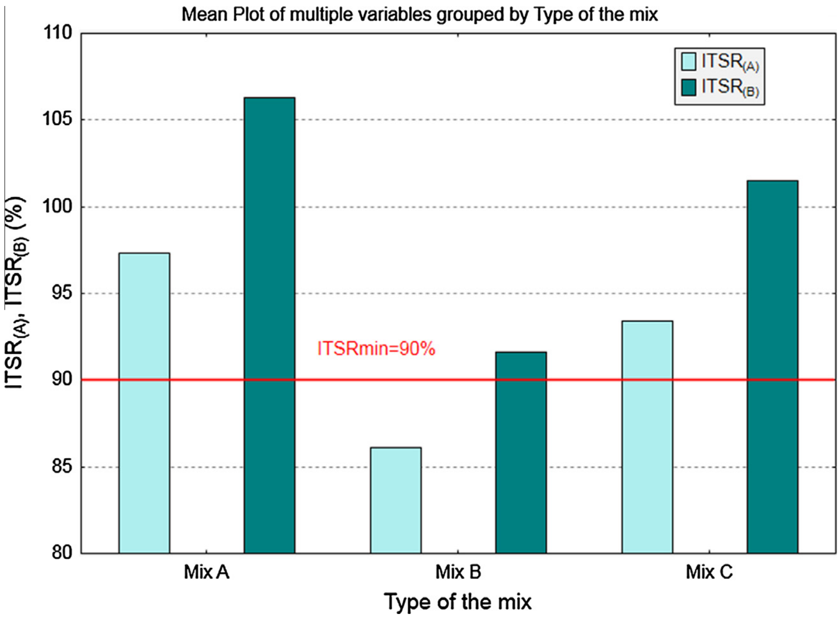


Fig. 6. Indirect tensile strength ratios, *ITSR*, of AC 8 mixtures with a set minimum value of ITSR = 90% as for surface courses in Poland.

modified binder when subjected to any of the analysed number of blows. The results show that the addition of 2.5% synthetic wax resulted in a decrease in air voids by about 2% relative to the HWMA mixture, allowing for compaction potential comparable with the HMA mix at 140 °C.

These results confirm the effectiveness of the synthetic wax, the addition of which allows obtaining the desired compaction level even at 95 °C.

3.2. Comparison of moisture resistance results from the procedure with a single freeze cycle performed on asphalt concrete specimens compacted at 140 °C and at 95 °C

Moisture resistance of asphalt concrete mixes is an important parameter in the design of durable pavement layers in climates like in Poland, where the road surface is exposed to the action of water and multiple cycles of freezing and thawing. The evaluation of moisture susceptibility was performed in accordance with procedures described in p. 2.3. based on European and American standards.

In Poland, the *ITSR* must be determined with respect to bituminous mixtures such as AC, AC-EME, SMA, PA and BBTM, designed and produced in compliance with the European Standards. In the national guidance documents developed based on these standards, the required *ITSR* categories vary depending on for which pavement layer they are intended. Mixes for base courses should be characterized with the *ITSR values* greater than 70%, 80% for the binder courses and 90% for the surface courses [22,23].

The values of the descriptive statistics performed on the obtained *ITS* data from tests on samples from all of the three mixes (A, B and C) are shown in Table 7. Fig. 5 illustrates the results of the indirect tensile strength tests on the AC mix specimens which were dry conditioned (ITS_d) and wet conditioned ($ITS_{w(A)}$, $ITS_{w(B)}$) in compliance with the adopted procedures. Fig. 6 shows the calculated values of moisture resistance ratios (*ITSRs*).

Results of the indirect tensile strength tests revealed similar relationships as those found in air void content tests. The highest absolute indirect tensile strengths were found in the HWMA mixture with *FT* modified foamed bitumen (i.e. Mix C). When compared to other mixes, the *FT* modification resulted in the relatively best indirect tensile performance after all types of conditioning (i.e. dry and both wet procedures). Slightly lower but still comparable values were recorded for the HMA mixture. The asphalt concrete produced without the synthetic wax and compacted at 95 °C returned the lowest values of all parameters (ITS_d, $ITS_{w(A)}$, $ITS_{w(B)}$).

It should be noted that these mechanical parameters were undoubtedly affected by the amount of air voids in the bituminous mixtures. Since the air void content was determined for each specimen used in the strength tests, correlations for dependent variables (i.e., between the V_m characteristic and the investigated mechanical characteristics) could be estimated (Figs. 7 and 8).

The relationships presented in Figs. 7 and 8 confirmed the inversely proportional relationship between the air void content and the indirect tensile strengths in all of the investigated groups. The specimens with the lower air void content had higher values of mechanical parameters. The coefficient of determination $R^2 > 0.7$ indicates that the mathematical models in the form of linear functions explain more than 70% of variability in the results. Thus the amount of air voids in the laboratory specimens of the mixes was proven to be a factor in the indirect tensile strength performance. In addition, the high values of the indirect tensile strengths recorded for Mix C are attributable to the use of synthetic wax, whose presence at processing temperatures reduces the viscosity of the binder and improves workability and compactibility, whereas at service temperatures it contributes to changes in the structure of bitumen and bituminous mixes by increasing stiffness and resistance to permanent deformation [15]. The addition of 2.5% of the *FT* modifier to 50/70 bitumen reduced penetration at 25 °C from 65.9 to 44.3 (0.1 mm), owing to which the recorded indirect tensile strength values in all sets of specimens examined at the same temperature (25 °C) were higher than those of the remaining mixtures.

The highest moisture resistance (*ITSR*) was recorded for the HMA compacted at traditional temperature of 140 °C. Similarly high *ITSR* values (>90%) were recorded for the mixture produced at lower temperatures with foamed bitumen modified with 2.5% *FT* wax content. This mixture yielded the smallest scatter of results

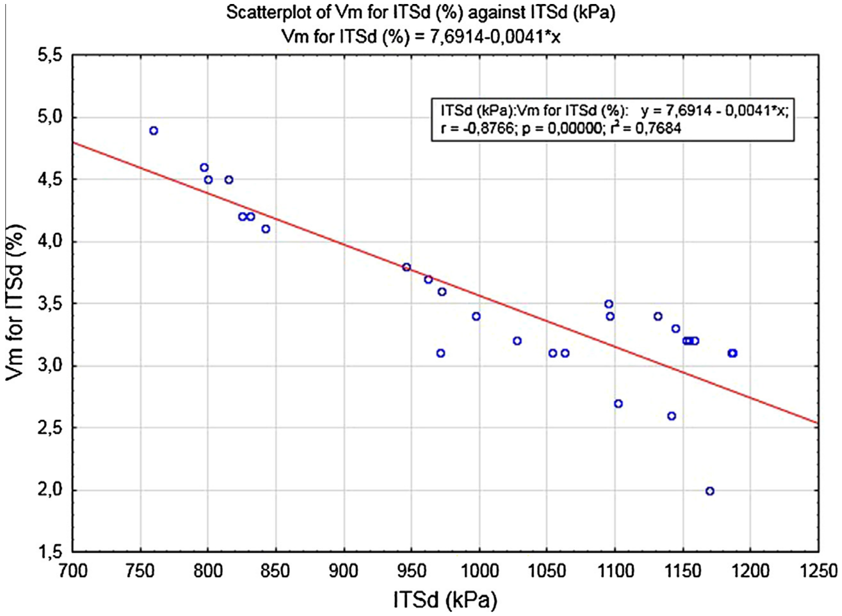


Fig. 7. Correlation between V_m and ITS_d for dependent samples compacted using 35 impact blows per side.

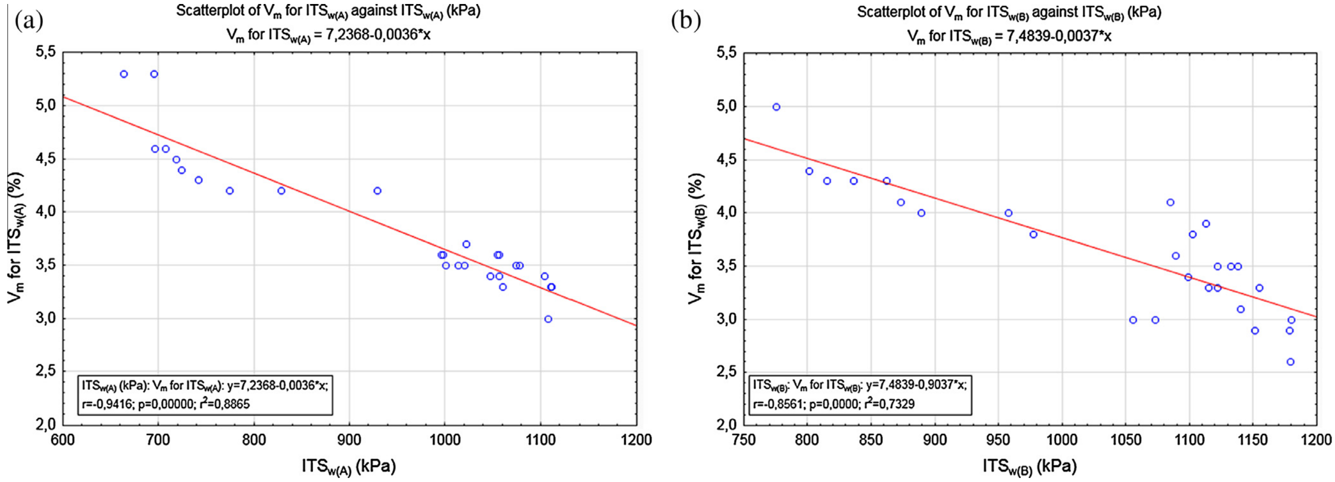


Fig. 8. Correlation between V_m vs. $ITS_{w(A)}$ (a) and V_m vs. $ITS_{w(B)}$ (b) for dependent samples compacted using 35 impact blows per side.

for all *ITSR* components investigated, ITS_d, $ITS_{w(A)}$ and $ITS_{w(B)}$ – the calculated values of the coefficients of variability for all mechanical properties were not higher than 3.5%. Considering the variation of the results in the context of the test method, the scatters for $ITS_{w(A)}$ determined on the shock-thawed specimens (with a higher temperature gradient) were larger than in the case of $ITS_{w(B)}$.

It should be noted that Mix B did not satisfy the Polish requirements set for moisture resistance of surface course mixes with the value of $ITSR = 86\% < 90\%$. The remaining mixtures were found to be resistant to the environmental factors under investigation in accordance with Polish technical documents [22,23].

The difference between the values of *ITSR* in terms of the testing procedure used was observed to be about 10% on average in all mixtures. The highest difference ($ITSR_{w(B)} - ITSR_{w(A)} = 10.8\%$) was recorded for the HMA mixture, with the least difference (9.4%) recorded for the Mix C. These differences were attributed to the temperature gradient, which for the specimens conditioned in accordance with procedure A was as high as 78 °C (from −18 °C to +60 °C), being more severe than that specified by AASHTO T 283-89 [19].

An interesting observation was made during the analysis of the results as the *ITSR* of more than 100% was obtained in two cases. The highest increase (ca. 6%) in indirect tensile strength of the specimens after wet conditioning with one freeze cycle was recorded for the HMA mixture. The values of the *ITSR* components may be influenced by a number of factors, such as aggregate parameters (absorption, frost resistance), type and amount of bitumen, presence of adhesive agents, adhesion of the bitumen to aggregate particles, and the type and properties of the bituminous mixture (density, air void content). In this case, identification of the factors that affect the high values of the *ITSRs* is a very difficult task, possible, but providing not necessarily reliable explanation. The tests on a larger number of asphalt specimens, varied in amounts and quality of constituent materials, may show the direction for finding the causes of this phenomenon. It can be said, however, that the higher number of freeze–thaw cycles would not provide the increase in the indirect tensile strength after a destructive action of water and low temperatures (on the specimens conditioned in the air), equal to that obtained after one freeze cycle.

Table 8
Results of the analysis of variance for indirect tensile strength of AC 8 mixtures.

Feature	One-way ANOVA (Analysis of Variance) Marked differences are significant at $p < 0.05$ (bold)							
	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	p
ITS_d (kPa)	425276.4	2	212638.2	97206.60	24	4050.275	52.4997	0.000000
$ITS_{w(A)}$ (kPa)	620413.9	2	310207.0	50637.75	24	2109.906	147.0240	0.000000
$ITS_{w(B)}$ (kPa)	401327.3	2	200663.7	59372.77	24	2473.865	81.1134	0.000000

Table 9
Results from Duncan's multiple comparison test used to analyse variation in the effect of the factor under investigation (*Type of the mix*) on characteristics ITS_d, $ITS_{w(A)}$, and $ITS_{w(B)}$.

Duncan test; Variable: ITSM (MPa) Marked differences are significant at p < 0.05 (bold), M – mean value				
ITSd (kPa)	Type of mix	(1) M = 1052.4	(2) M = 844.7	(3) M = 1144.8
	(1) Mix A		0.000153	0.005254
	(2) *Mix B*	0.000153		0.000065
	(3) *Mix C*	0.005254	0.000065	
$ITS_{w(A)}$ (kPa)	Type of mix	(4) M = 1024.0	(5) M = 727.6	(6) M = 1069.5
	(4) Mix A		0.000152	0.046427
	(5) *Mix B*	0.000152		0.000065
	(6) *Mix C*	0.046427	0.000065	
$ITS_{w(B)}$ (kPa)	Type of mix	(7) M = 1118.7	(8) M = 865.2	(9) M = 1128.6
	(7) *Mix A*		0.000152	0.679052
	(8) *Mix B*	0.000152		0.000065
	(9) *Mix C*	0.679052	0.000065	

It is worth noting that besides Poland and Finland, the *ITSR* is determined without the freeze cycle in the countries-members of the CEN that have similar climate (Slovakia, Germany) [17]. The idea of increasing the number of freeze–thaw cycles [33,34] for the evaluation of the effect of moisture and frost resistance on the durability of bituminous mixtures for road pavements seems justified.

To evaluate the differences between the mixtures in terms of the production technology, as in the case of the V_m characteristic, it was possible to use the *F* test as the assumptions of normal distribution and homogeneity of variance were satisfied. The results from the calculation of the significance of the *Type of the mix* effect on the mechanical properties are shown in Table 8.

The results clearly indicate significant differences between the mechanical parameters of asphalt concrete mixtures as the *p-values* obtained in the *F* test was lower than the assumed significance level ($\alpha = 0.05$). Thus, there were at least two groups, which varied significantly. To find them, Duncan's multiple comparison tests were performed (Table 9).

The Duncan *post hoc* test (*p-value* = 0.679052) found no statistically significant differences only in the case of the indirect tensile strength determined on the specimens cured in accordance with procedure B, while comparing the HMA mixture and the HWMA mixture with foamed bitumen modified with *FT* wax. The other pairs compared differed from one another significantly at the assumed significance level of $\alpha = 0.05$.

4. Conclusions

Based on the analysis of the results obtained from the laboratory tests, the following conclusions can be formulated:

- the addition of 2.5% synthetic wax to bitumen 50/70 resulted in significant changes in the values of basic rheological characteristics, including reduced penetration and increased softening temperature. As a result, stiffer binder could reduce the mix susceptibility to permanent deformation;
- modification of 50/70 bitumen with 2.5% *FT* wax caused changes in the measured physical parameters of the bitumen foam; the volume of the foam (expansion ratio) increased; half-life substantially increased leading to a high level of coating the mixture with the binder, this level being nearly identical with that of the mixture produced in the conventional hot mix asphalt technology;
- modification of 50/70 bitumen considerably improved workability and compactibility of HWMA AC 8 as a result of lowering the viscosity and improving the foaminess of the binder, contributing to the reduction in air void content in the specimens and the increase in their moisture resistance (*ITSR*);
- the HWMA asphalt concrete mixture without the addition of the low viscosity agent (*FT* wax) had insufficient workability and compactibility and as a result, it did not reach the required level of water resistance in the light of the test procedure A;
- high effectiveness of synthetic wax with respect to the improvement of low-temperature mixture compactibility was confirmed as providing adequate compaction at 95 °C, that is, comparable to that of the mixture compacted at 140 °C;
- introduced in Poland in 2010, moisture resistance testing procedure with one freeze cycle, which combines the most adverse conditions of specimen conditioning based on EN 12697-12:2008 and AASHTO T 283-89 standards, is regarded as the most severe testing method used in Europe for determining water resistance of bituminous specimens, more severe than the method recommended by AASHTO.

References

[1] Audrius Vaitkus, Donatas Čygas, Alfredas Laurinavičius, Zigmantas Perveneckas, Analysis and evaluation of possibilities for the use of warm mix asphalt in Lithuania, Baltic J. Road Bridge Eng. IV (2) (2009) 80–86, http://dx.doi.org/10.3846/1822-427X.2009.4.80-86.

[2] H.M.R.D. Silva, J.R.M. Oliveira, J. Peralta, S.E. Zoorob, Optimization of warm mix asphalt using different blends of binders and synthetic paraffin wax contents, Constr. Build. Mater. 24 (2010) 1621–1631, http://dx.doi.org/10.1016/j.conbuildmat.2010.02.030.

[3] A. Jamshidi et al., Evaluation of sustainable technologies that upgrade the binder performance grade in asphalt pavement construction, Mater. Des. 95 (2016) 9–20, http://dx.doi.org/10.1016/j.matdes.2016.01.065.

[4] S.G. Jahromi, Estimation of resistance to moisture destruction in asphalt mixtures, Constr. Build. Mater. 23 (2009) 2324–2331, http://dx.doi.org/10.1016/j.conbuildmat.2008.11.007.

[5] G.D. Airey, A.C. Collop, S.E. Zoorob, R.C. Elliott, The influence of aggregate, filler and bitumen on asphalt mixture moisture damage, Constr. Build. Mater. 22 (2007) 2015–2024, http://dx.doi.org/10.1016/j.conbuildmat.2007.07.09.

[6] E. Remišová, Theory and measurements of bitumen binders adhesion to aggregate, Komunikacie 6 (1) (2004) 58–63.

[7] B.V. Kok, M. Yilmaz, The effect of using lime and styrene–butadien–styrene on moisture sensitivity resistance of hot mix asphalt, Constr. Build. Mater. 23 (2009) 1999–2006, http://dx.doi.org/10.1016/j.conbuildmat.2008.08.019.

[8] C. Gorkem, B. Sengoz, Predicting stropping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime, Constr. Build. Mater. 23 (2009) 2227–2236, http://dx.doi.org/10.1016/j.conbuildmat.2008.12.001.

[9] M. Iwański, A. Chomicz-Kowalska, J. Mrugała, Application of the synthetic wax to improve the foamed bitumen parameters used in half-warm bituminous mixtures. 9th International Conference Environmental Engineering. Procedia Engineering, Vilnius, Lithuania, 2014. doi: 10.3846/enviro.2014.154.

[10] S. Hesami, H. Roshani, H.G. Hamedi, A. Azarhoosh, Evaluation the mechanism of the effect of hydrated lime on moisture damage of warm mix asphalt, Constr. Build. Mater. 47 (2013) 935–941, http://dx.doi.org/10.1016/j.conbuildmat.2013.05.079.

[11] B. Sengoz, E. Agar, Effect of asphalt film thickness on the moisture sensitivity characteristics of hot-mix asphalt, Building and Environmental 42 (2007) 3621–3628, http://dx.doi.org/10.1016/j.buildenv.2006.10.006.

[12] M. Iwański, A. Chomicz-Kowalska, Evaluation of the pavement performance, Bull. Polish Acad. Sci. Tech. Sci. 63 (1) (2015) 97–105, http://dx.doi.org/10.1515/bpasts-2015-0011.

[13] K.J. Jenkins, A.A.A. Molenar, J.L.A. de Groot, M.F.C. Van de Ven, Optimization and Application of Foamed Bitumen in Road Building. Vegbouwkundige Werkdagen, Doorwerth, Nederlandes, 2000.

[14] M.F.C. Van de Ven, K.J. Jenkins, J.L.M. Voskuilen, R. Ven den Beemt, Development of (half-) wam foamed bitumen mixes: state of the art, Int. J. Pavement Eng. 8 (2) (2007) 163–175.

[15] M. Iwański, A. Chomicz-Kowalska, K. Maciejewski, Application of synthetic wax for improvement of foamed bitumen parameters, Constr. Build. Mater. 83 (2015) 62–69, http://dx.doi.org/10.1016/j.conbuildmat.2015.02.060.

[16] EN 12697-12. Bituminous mixtures. Test methods for hot mix asphalt. Determination of the water sensitivity of bituminous specimens.

[17] D. Sybilski, et al., Sprawozdanie końcowe z pracy: Weryfikacja i uaktualnienie metody badawczej wodoodporności z cyklem zamrażania mieszanek mineralno-asfaltowych. Temat TN-255. Etap III – Zadanie 7,8. [Final progress report: Verification and updating of water resistance test method with a freeze-thaw cycle of bituminous mixtures]. Road and Bridge Research Institute, Warsaw, 2013.

[18] EN 12697–12:2008. Bituminous mixtures. Test methods for hot mix asphalt. Determination of the water sensitivity of bituminous specimens.

[19] AASHTO T283–89. Standard Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage, Standard Specifications for Transportation Materials and Methods of Sampling and Testing.

[20] J. D'Angelo, et al., Warm-Mix Asphalt: European Practise, Federal highway Administration, Report No.FHWA-PL-08-007.

[21] EN 12697–8:2005. Bituminous mixtures. Test methods for hot mix asphalt. Determination of void characteristics of bituminous specimens.

[22] WT-2. Nawierzchnie asfaltowe na drogach krajowych. Część I. Mieszanki mineralno-asfaltowe. Wymagania Techniczne. [Technical Guidelines 2: Asphalt pavements for national roads. Part I: Asphalt mixes]. General Directorate for National Roads and Motorways, Warsaw, 2010.

[23] WT-2. Nawierzchnie asfaltowe na drogach krajowych. Część I. Mieszanki mineralno-asfaltowe. Wymagania Techniczne. [Technical Guidelines 2: Asphalt pavements for national roads. Part I: Asphalt mixes]. General Directorate for National Roads and Motorways, Warsaw, 2014.

[24] EN 1426:2015 Bitumen and bituminous binders. Determination of needle penetration.

[25] J. Judycki, Katalog typowych konstrukcji nawierzchni podatnych i półsztywnych. [Catalogue of typical flexible and semi-rigid pavements]. General Directorate for National Roads and Motorways, Warsaw, 2014.

[26] J. Król, K. Kowalski, P. Radziszewski, Rheological behavior of n-alkane modified bitumen in aspect of Warm Mix Asphalt technology, Constr. Build. Mater. 93 (2015) 703–710, http://dx.doi.org/10.1016/j.conbuildmat.2015.06.033.

[27] M.R.M. Hasan, Z. You, D. Porter, S.W. Goh, Laboratory moisture susceptibility evaluation of WMA under possible field conditions, Constr. Build. Mater. 101 (2015) 57–64, http://dx.doi.org/10.1016/j.conbuildmat.2015.10.004.

[28] EN 1427:2015. Bitumen and bituminous binders. Determination of the softening point. Ring and Ball method.

[29] EN 12593:2015. Bitumen and bituminous binders. Determination of the Fraass breaking point.

[30] EN 12591:2009. Bitumen and bituminous binders. Specifications for paving grade bitumens.

[31] EN-13302:2010. Bitumen and bituminous binders – determination of dynamic viscosity of bituminous binder using a rotating spindle apparatus.

[32] D. Sybilski, Ocena odporności na koleinowanie mieszanki mineralno-asfaltowej na podstawie badania zagęszczalności i naprężenia ścinającego w prasie żyratorowej. Sprawozdanie z realizacji tematu TN-230. [Evaluation of rutting resistance of bituminous mixtures based on the tests for compactability and shear stress in the gyratory compactor]. Road and Bridge Research Institute, Warsaw, 2004.

[33] P. Jaskula, J. Judycki, Verification of the criteria for evaluation of water and frost resistance of asphalt concrete. Road Mater. Pavement Des. 9(1), 135–162. doi: 10.1080/14680629.2008.9690163.

[34] P. Jaskuła, J. Judycki, Durability of asphalt concrete subjected to deteriorating effects of water and frost. J. Perform. Constr. Facil. 30(1), 2016. doi: 10.1061/(ASCE)CF.1943-5509.0000645.