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Effects of zeolites and hydrated lime on volumetrics and moisture resistance of foamed warm mix asphalt concrete

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Abstract. The paper concerns the utilization of hydrated lime and zeolites as additives in warm mix asphalt produced with foamed bitumen. The mentioned additives were added to the mixtures in exchange for specific quantities of mineral filler, which amounted to 0.4% and 1.2% of hydrated lime or 0.4% of water-modified and 1.0% of air-dry zeolites in mineral mix. The study investigated warm-produced mixtures with 4.5% and 4.8% binder content and production and compaction temperatures set at 120ºC and 100ºC respectively. Additionally, reference hot and warm mixtures were evaluated. The testing included: air void content, indirect tensile strength in dry state and after one freeze-thaw cycle as well as the resulting resistance to moisture and frost damage index. The mixtures incorporating hydrated lime and lower bitumen content of 4.5% exhibited increased air voids and mostly unchanged mechanical performance when compared to the reference warm mix. Increased bitumen content has resulted in significantly improved performance in moisture resistance and compactability which could be compared to that of the reference hot-produced mixture. On the other hand, the incorporation of zeolites in the foamed bitumen mixtures resulted in all cases in increased air void content in the samples. This has apparently led to decreased indirect tensile strength, in both the dry state and after the freeze-thaw cycle. Based on the results it was concluded that the production temperature of the zeolite-bearing mixtures was too low for the zeolite water to significantly improve the mix' workability and therefore positively affect its mechanical parameters.

Key words: WMA; foamed bitumen; zeolite; hydrated lime.

1. Introduction

Construction of bituminous pavements is a highly energy consuming process, mostly due to the fact that the commonly used hot mix asphalt (HMA) technique utilizes high processing temperatures. Typically, the constituents of asphalt mixtures, i.e., aggregates and bitumen, must be heated to high temperatures, with the mixing temperature reaching up to 160–190°C, depending on the mix and binder used. Such high temperatures are needed to dry the aggregates, to ensure their adequate coating with the bituminous binder and to provide sufficient workability during mixing, paving and compaction. This has given rise to a number of warm mix asphalt (WMA) techniques enabling the reduction of processing temperatures, including the use of proprietary WMA additives, processes, and bitumen foaming. The two most often used methods for producing foamed warm mix asphalt is the utilization of mechanical water foaming and the addition of zeolites to the asphalt mix, which in addition of releasing foaming water, act as a filler.

Mechanical water foaming is usually conducted through direct injection of atomized water into the hot binder. The sudden expansion of water turning into steam upon contacting hot bitumen, results in the formation of bitumen foam with greatly increased volume and surface area, decreased viscosity and enhanced coating abilities. These effects in conjunction with adequate aggregate selection and temperature, permit production of high-quality asphalt mixtures, with properties adequate for recycled base courses and asphalt concrete mixtures for upper pavement layers in cold, half-warm and warm processes [1–8]. The typically used foaming water content in foam-WMA's range between 1% and 3% per bitumen mass, depending on the bitumen foaming performance and mix workability [8–11].

Zeolites are crystalline micro-porous solids, hydrated aluminosilicates of alkali elements [12]. Their crystalline network creates channels, big enough to enable diffusory permeation of not only single atoms, but whole chemical compound particles without changing the volume of the crystal structure. Thanks to their properties, zeolites became widely used in the global economy as sorbents in the environmental protection, household chemical products, in the cement concrete technology and also as WMA additives [13–15]. The research conducted by Lai et al. [16] showed that synthetic zeolites gradually release water over time and more zeolite water is released, the higher the mixture temperature. The optimal temperature required for effective asphalt foaming amounts to 110–120°C, and the improvement of the asphalt mixture's workability takes place after a minimum of 20 minutes from the introduction of zeolites to the mixture. Similar results were obtained by Woszuk et al. [17–20], who obtained optimum results with 0.4% of water soaked and 1.0% of dry zeolites by the asphalt mix mass and reported an improvement in the resistance to permanent deformation of the mixture.

The experiences in warm mix asphalt with foamed bitumen have shown that the decreased processing temperatures may

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cause a number of issues in WMA's, such as undercompaction, decreased moisture resistance and underdevelopment of aging processes in the bituminous binder resulting in decreased resistance to permanent deformation [21], all of which are significant factors in long term pavement performance [22]. To counter these effects, some specific additives may be used, such as adhesion promoters [23–25], waxes (e.g. Sasobit, Montan Wax) [1, 26, 27], fluxing agents [28], zeolites [11, 18, 23] hydrated lime [23, 29] and fiber reinforcement [30].

One of the first uses of hydrated lime in HMA was reported in the United States [31, 32] and research carried out over consecutive decades has proven the positive role of hydrated lime in this technique [33, 34]. Hydrated lime has shown to increase moisture and frost resistance [35, 36] as a result of improving the bitumen-aggregate adhesion [36–39]. Its positive effects in increasing the pavement rutting resistance caused by repeated traffic loading have also been reported [38, 39]. The use of hydrated lime in hot mix asphalt is well documented, and although its use in foamed bitumen mixtures produced at lowered temperature has been proven promising [29, 40], more investigations in this field are needed.

Although the overall performance of a pavement system relies heavily on its design and viscoelastic properties, the structural requirements for the materials have to be met first [41]. As it has been presented, the utilization of hydrated lime has been proven effective in enhancing the properties of regular HMA, while zeolites are primarily used to improve workability and permit decreased processing temperatures of asphalt mixtures. However, zeolites are also capable of improving the high temperature performance of asphalt mixtures, in similar manner to hydrated lime. Both additives can be easily utilized in most asphalt mixing plants, but their effects were not extensively studied when used in conjunction with foamed bitumen and decreased processing temperatures. Based on the aforementioned premises, the aim of this paper was to investigate the effects of zeolites and hydrated lime in warm mix asphalt mixtures with foamed bitumen on the volumetric and design properties of an AC 16 asphalt concrete mixture produced at approx. 120°C.

2. Design of experiment

2.1. Experimental program. The experiments were set up to assess the effects of incorporating hydrated lime and natural zeolites into warm mixtures with foamed bitumen produced at temperatures approx. 120°C. The focus of the investigation was aimed at volumetric, basic mechanical properties and moisture resistance of these mixtures produced with different contents of bituminous binder and the considered additives. Asphalt concrete AC 16 binder course mixture was selected for the experiments. The reference mix was designed in accordance to EN-13108-1 [42] and Polish technical requirements WT-2 [43] for a traffic load of 2.5–7.3 million 100 kN equivalent single axle loads – ESALs. This mixture was a basis for the experimental mixtures which differed in the addition of hydrated lime and zeolites in exchange for the portion of limestone dust filler.

The experiments utilized a reference mixture produced as traditional hot mix asphalt and as warm mix asphalt with foamed bitumen denoted as HMA_{Ref} and WMA_{Ref} respectively, with 4.5% bitumen content each. The experimental warm mixtures with foamed bitumen containing hydrated lime and zeolites were denoted as WMA_{HL} and WMA_{NZ}. The HMA mixtures were produced at approx. 165°C and compacted at 145°C, while all WMA mixtures with foamed bitumen were produced at approx. 120°C and compacted at approx. 100°C. The designs of the experiments are shown in Fig. 1.

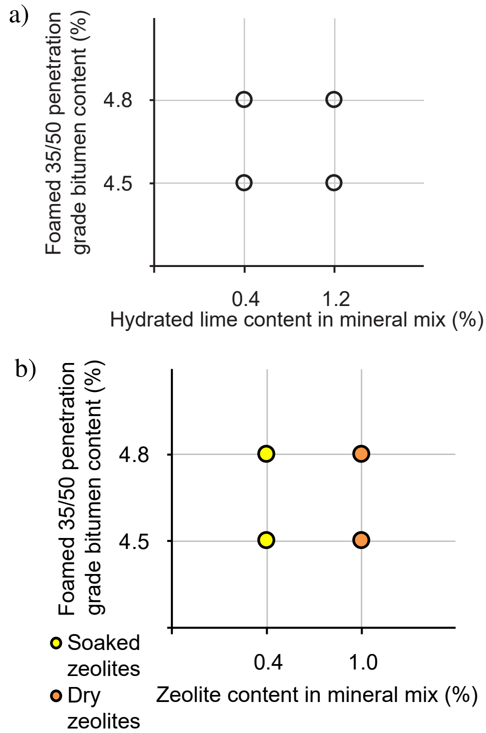

Fig. 1. The experimental program

As shown in Fig. 1, the experimental WMA's were produced with two bituminous binder contents of 4.5% and 4.8% by mixture weight to counteract possible stiffening effects of the additives [40]. Additionally, the amount of the additives also varied. The mixtures with hydrated lime contained 0.4% and 1.2% of hydrated lime in relation to the mineral mix, which in turn amounted to 10% and 30% of the total amount of added filler, respectively. On the other hand, the mixtures with zeolites contained either 0.4% of water-modified (soaked to 20% moisture content) or 1.0% of air-dry zeolites. The dosages of hydrated lime and zeolites were based on the literature provided in the introduction [16–19, 23, 29, 40]. Additionally, the moisture content and amount of zeolites were adjusted to equalize the amount of total zeolite foaming water in the zeolite bearing mixtures.

2.2. Materials. The asphalt concrete mixtures utilized a 35/50 penetration grade road paving bitumen in accordance to EN 12591 [44], commonly used in mid-eastern Europe for producing binder courses in pavements under medium traffic loads. The bituminous binder was supplemented with an adhesion promoter, which was added to bitumen typically in amounts of 0.3% by mass for the hot mix asphalt (HMA_{Ref}). Based on the previous experiences [5, 40], the amount of adhesion promoter (WBE) was increased in all of foamed WMA mixtures up to 0.6% by mass of the bitumen.

The foaming water content used for producing warm mixtures was set to 3.0% which resulted in obtaining considerable expansion ratio of $ER_m = 12.0$ while maintaining long half-life of $HL = 25.0$ s. The basic properties of the 35/50 binder with the addition of the WBE adhesion promoter are presented in Table 1. As mentioned before, the investigated asphalt concrete mixes were designed with compositions identical to the simultaneously evaluated reference mixes, with changes only in the amounts of the mineral filler (limestone dust), and hydrated lime or natural zeolite added.

The framework composition of all mineral mixtures (mm) and asphalt mixtures (am) is given in Table 2. Table 3 represents the grading of the mineral mix constituents. All of the utilized

Table 1
Basic properties of 35/50 asphalt binders with different surfactant

Variable	WBE percentage (%)	Descriptive Statistics					
		Valid *N*	Mean	Min.	Max.	Std. Dev.	CV (%)
Penetration in 25°C (Pen_{25}) (0.1 mm)	0.0	10	36.6	35.0	38.0	1.17	3.21
	0.3 (HMA)	10	40.8	38.3	43.6	1.59	3.90
	0.6 (WMA)	10	41.5	40.3	43.2	0.95	2.30
Softening point ($T_{R\,\&\,B}$) (°C)	0.0	4	54.3	53.8	54.6	0.36	0.66
	0.3 (HMA)	4	53.9	53.8	54.1	0.13	0.23
	0.6 (WMA)	4	53.7	53.6	53.8	0.08	0.15
Fraass breaking point (T_{Fraass}) (°C)	0.0	3	–13.7	–14.0	–13.0	0.58	4.22
	0.3 (HMA)	3	–13.3	–15.0	–12.0	1.53	11.46
	0.6 (WMA)	3	–12.7	–13.0	–12.0	0.58	4.56

Table 2
The composition of mineral mix in the investigated AC 16 asphalt concrete mixtures

Component	Type of mixture				
	HMA_{Ref} WMA_{Ref}	$WMA_{HL0.4\%,B4.5\%}$ $WMA_{HL0.4\%,B4.8\%}$	$WMA_{HL1.2\%,B4.5\%}$ $WMA_{HL1.2\%,B4.8\%}$	$WMA_{NZ0.4\%S,B4.5\%}$ $WMA_{NZ0.4\%S,B4.8\%}$	$WMA_{NZ1.0\%D,B4.5\%}$ $WMA_{NZ1.0\%D,B4.8\%}$
	Percentage (% m/m)				
Limestone dust	4	3.6	2.8	3.6	3.0
Hydrated lime	–	0.4	1.2	–	–
Natural zeolites	–	–	–	0.4	1.0
0/2 mm (limestone)	15	15	15	15	15
0/4 mm (limestone)	15	15	15	15	15
2/5 mm (quartzite)	12	12	12	12	12
5/8 mm (quartzite)	12	12	12	12	12
8/16 mm (quartzite)	42	42	42	42	42
Total	100	100	100	100	100

Table 3
Grading of the constituents of the mineral mix in the AC 16 asphalt mixes

Component	Particle size # (mm)											
	16	11.2	8	5.6	4	2	1	0.5	0.25	0.125	0.063	< 0.063
Limestone Filler	0	0	0	0	0	0	0	0	0.8	2.3	4.8	92.1
Hydrated lime	0	0	0	0	0	0	0	0	0	0.9	4.2	94.9
Natural Zeolite	0	0	0	0	0.1	0	0	0	0.9	1.2	5.9	92.0
0/2 mm (limestone)	0	0	0	0	0.1	9.2	25.9	19.8	16.7	16.4	8.3	3.5
0/4 mm (limestone)	0	0	0	2.4	13.3	29.0	20.6	11.1	6.7	3.8	2.7	10.4
2/5 mm (quartzite)	0	0	0	11.0	31.9	45.9	8.4	0.7	0.1	0.2	0.4	1.4
5/8 mm (quartzite)	0	0	8.2	64.5	16.5	6.8	1.2	0.3	0.2	0.3	0.5	1.5
8/16 mm (quartzite)	6.8	42.3	40.8	7.0	0.5	0.2	0	0	0	0.1	0.2	2.0

mineral materials fulfilled the requirements stated in appropriate technical documents [44, 45] regarding their use in binding and basecourses in pavements.

The chemical composition of the natural zeolites used in the experiments is given in Table 4 and its microscopic image is depicted in Fig. 2. The EDX (energy-dispersive X-ray spectroscopy) was used to validate the composition of the zeolites [46]. The analysis using standardless ZAF quantification method in the Quanta Feg 250 Scanning Electron Microscope has shown that the dominant elements of natural zeolite were O, Si and Al, which corresponded to the chemical composition specified by the manufacturer. The analyzed sample demonstrated additional presence of potassium, calcium, iron and trace amounts of magnesium and sodium.

Table 4
Results of EDX analysis using standardless ZAF quantification method of the natural zeolite using the Quanta Feg 250 SEM

Elem.	Wt. %	At. %	*k*-ratio	Z	A	F
O K	41.18	56.15	0.1245	1.0310	0.2931	1.0005
Na K	0.07	0.06	0.0003	0.9649	0.4611	1.0059
Mg K	0.55	0.49	0.0034	0.9891	0.6209	1.0119
Al. K	7.68	6.21	0.0564	0.9600	0.7513	1.0183
Si K	42.02	32.64	0.3230	0.9880	0.7772	1.0010
K K	4.00	2.23	0.0333	0.9374	0.8848	1.0043
Ca K	2.92	1.59	0.0254	0.9596	0.9063	1.0007
Fe K	1.59	0.62	0.0137	0.8718	0.9928	1.0000

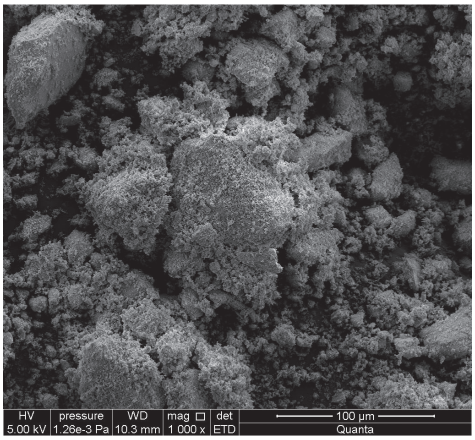

Fig. 2. Scanning electron microscope image of the natural zeolite (Quanta Feg 250 SEM)

2.3. Methods for asphalt concrete testing. The testing methods employed focused on the assessment of volumetric properties and moisture resistance of the investigated AC 16 mixtures:

- density (ρ_{mv}) in acc. to EN 12697-5:2010 – 3 replicates,
- bulk density (ρ_{bssd}) in acc. to EN 12697-6:2012 – 10 replicates,
- air void content (V_a) in acc. to EN 12697-8:2005 – 10 replicates,
- indirect tensile strength (ITS_{dry}) in air-dry condition and ($ITS_{freeze\text{-}thaw}$) after one freeze-thaw cycle with 8 replicates in each group,
- resistance to moisture and frost damage ITSR in acc. to EN 12697-12:2008 and to WT-2 [43] – procedure was described in detail in [1] (procedure B, p. 2.3).

2.4. The method of multivariate optimization. To distinguish the best performing WMA asphalt concrete mixture with the considered additives and to compare the performance of the investigated mixtures, a multivariate optimization approach employing desirability functions and desirability index in accordance to the methodology laid out in [47] was adopted. Linear desirability functions assessing the measured properties of the asphalt concrete mixtures were defined with the specification limits given in Table 5.

Table 5
Specification limits used in the multivariate optimization

Measured property	Lower specification limit (*Desirability* = 0)	Upper specification limit (*Desirability* = 1)
V_a (%)	7	4
ITS_{dry} (kPa)	90%·min (ITS_{dry})	max(ITS_{dry})
ITSR (%)	70	100

The specific limits regarding air void contents (V_a) and resistance to moisture and frost damage (*ITSR*) were derived from the domestic requirements laid out in Polish specifications [43] for binding and base courses. The limits for indirect tensile strength were based on minimum and maximum recorded values of ITS_{dry}. This approach permitted that all mixes could be evaluated using a final desirability index in the range of $DI \in \langle 0, 1 \rangle$, where *DI* is defined as a geometric mean of partial desirability (1):

$$DI = \left(\prod_{i=1}^{k} d_i \right)^{1/k} \tag{1}$$

where: *DI* – desirability index, d_i – partial desirability assessing the mix performance calculated using the chosen properties (V_a, ITS_{dry}, *ITSR*), k – number of the evaluated properties.

3. Results

The results of air void content and the mechanical performance measured in the investigated mixtures are presented as bar plots in Figs. 3–5. The error bars shown in Figs. 3–4 represent the reported ±1 standard deviation from the mean, showing the variability in air void content and indirect tensile strength data. The data presented in Fig. 5 show the ITSR indices calculated the ratio of adequate mean values of $ITS_{freeze\text{-}thaw}$ and ITS_{dry} and therefore cannot be characterized statistically by indicating standard deviation.

3.1. Air void content (V_a). The assessment of air voids presented in Fig. 3 shows that both, the asphalt concrete production technique (HMA, WMA with foamed bitumen) and composition of the warm mixtures had major impact on the compactability of the investigated mixes. The reference foamed warm mixture has obtained 5.61% air void content, while the hot mix reached significantly lower $V_a = 4.40\%$.

In the warm mixes, the additives in the filler fraction and the bitumen content significantly affected the measured volumetrics. The addition of 0.4% of hydrated lime in the mixture with bitumen content of 4.5% resulted in an increase in air voids from 5.61% (WMA_{Ref}) to 6.47%, and further increase in hydrated lime content to 1.2% resulted in 6.76% of air voids measured. On the other hand, the combined addition of hydrated lime with the increased bitumen content in the $WMA_{HL0.4\%,B4.8\%}$ has resulted in significantly decreased air void content, amounting to 4.60%, which can be regarded as similar to the reference hot mixture. The increased hydrated lime content in the $WMA_{HL1.2\%,B4.8\%}$ mix has again resulted in elevated air void content amounting to 5.10%.

Similarly, the addition of natural zeolites has significantly affected the measured air void contents in the investigated foamed warm mixtures. The addition of zeolites in the filler fraction of the mixtures resulted in increased V_a values. This effect in mixtures with bitumen content of 4.5% was similar to that observed in mixtures with hydrated lime, resulting in air void contents of 6.35% and 6.68% in $WMA_{NZ0.4\%,B4.5\%}$ and $WMA_{NZ1.0\%,B4.5\%}$ mixtures respectively. Increasing the bitumen content up to 4.8% had lesser effect on decreasing the air void contents than it was seen in mixtures with hydrated lime. The resulting V_a values amounted to 5.89% in the $WMA_{NZ0.4\%,B4.8\%}$ mix and 6.16% in the $WMA_{NZ1.0\%,B4.8\%}$ mix.

3.2. Indirect tensile strength (ITS_{dry}, $ITS_{freeze\text{-}thaw}$). The indirect tensile strengths of the samples produced form the investigated mixtures are presented in Fig. 4. Here it can be seen that the highest values of indirect tensile strength were attained by the reference hot mix asphalt with $ITS_{dry} = 1453$ kPa and $ITS_{freeze\text{-}thaw} = 1255$ kPa. The reference foamed warm mix registered a significantly lower indirect tensile strengths by 227 kPa and 233 kPa in the case of dry and freeze-thawed samples respectively.

The performance of the foamed warm mixtures with hydrated lime in the filler fraction was very similar to the refer-

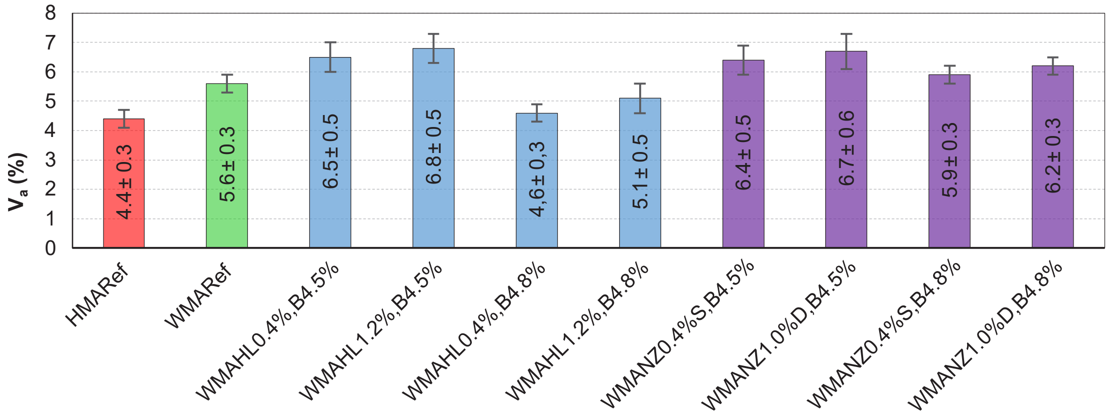

Fig. 3. Results of air void contents (V_a) measured in Marshall samples produced from the AC mixtures

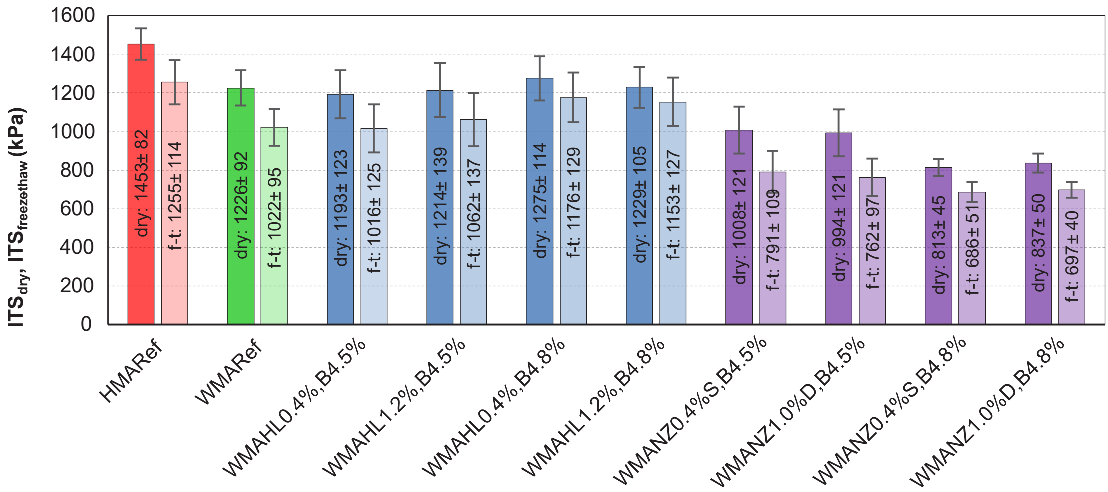

Fig. 4. Results of indirect tensile strengths: ITS_{dry} (denoted as "dry") and $ITS_{freeze\text{-}thaw}$ (denoted as "f–t") measured in Marshall samples produced from the AC mixtures

ence WMA mixture in terms of ITS_{dry} values, which were all in the range from 1193 kPa to 1229 kPa. On the other hand, the mixtures with hydrated lime and increased 4.8% bitumen content, registered $ITS_{freeze\text{-}thaw}$ values amounting to 1176 kPa and 1153 kPa at 0.4% and 1.2% hydrated lime content respectively, which were visibly higher than those obtained by the reference WMA mixture and the hydrated lime mixtures with 4.5% bitumen content.

The addition of natural zeolites in the composition of the foamed warm mix asphalts has brought detrimental effects to their indirect tensile strengths, resulting in ITS_{dry} and $ITS_{freeze\text{-}thaw}$ values significantly lower than in the case of any of the previously mentioned mixtures. At 4.5% bitumen content the mixtures with 0.4% of water-modified zeolites and 1.0% dry zeolites obtained similar ITS_{dry} (1008 kPa and 994 kPa, respectively) and $ITS_{freeze\text{-}thaw}$ (813 kPa and 837 kPa, respectively) strengths. With the increased bituminous binder content, the recorded values of those parameters have dropped. The ITS_{dry} values of the $WMA_{NZ0.4\%,B4.8\%}$ and $WMA_{NZ1.0\%,B4.8\%}$ mixtures were measured ad 791 kPa and 762 kPa, while the $ITS_{freeze\text{-}thaw}$ amounted to 686 kPa and 697 kPa, respectively.

In the presented results it can be seen that the incorporation of hydrated lime in the mixtures has significantly increased the indirect tensile strengths of the samples subjected to a freeze-thaw conditioning, when the increased (+0.3%) binder content was utilized. On the contrary, the addition of natural zeolites to the mixture has caused a decrease in the measured *ITS* values in both modes of dosing (dry and water-modified zeolites).

3.3. Resistance to moisture damage (*ITSR*). The indices of the resistance to moisture damage were calculated based on the results of the aforementioned indirect tensile testing. The results of the *ITSR* indices are presented in Fig. 5.

The results show that the change in the production regime of the asphalt concrete from hot mix to warm mix with foamed bitumen has resulted in its decrease in resistance to moisture damage seen as a minor change in the *ITSR* index from 86.4% to 83.4%. The effects of incorporating the two investigated additives in the warm mixtures were distinct and were influenced by the content of the bituminous binder.

The mixtures with hydrated lime manifested increased resistance to moisture damage with *ITSR* values amounting to 85.7% and 87.4% calculated for the $WMA_{HL0.4\%,B4.5\%}$ and $WMA_{HL1.2\%,B4.5\%}$ mixtures, respectively. The increased amount of the bituminous binder of up to 4.8% has amplified this effect by further increasing the *ITSR* values of those mixtures, resulting in the measured resistance to moisture damage of 93.2% in the case of 0.4% hydrated lime content and 93.8% in the mixture with 1.2% hydrated lime.

Unlike in the case of the incorporation of hydrated lime, the added natural zeolites have resulted in a detriment of the moisture resistance of warm mixtures. In relation to the reference WMA asphalt concrete, the $WMA_{NZ0.4\%,B4.5\%}$ mix has obtained decreased *ITSR* which was measured at 78.5%, and the mixture with the addition of 1.0% of dry zeolites exhibited even lower *ITSR* of 76.7%. These mixtures benefited in terms of the moisture resistance from an increase in bitumen content, which resulted in 84.3% and 83.3% *ITSR* values measured for the $WMA_{NZ0.4\%,B4.8\%}$ and $WMA_{NZ1.0\%,B4.8\%}$ mixtures, respectively.

These results show, that even at the base 4.5% bitumen content, the warm mix asphalt concrete with foamed bitumen and 1.2% of hydrated lime in the mixture obtained *ITSR* results superior to the reference hot mix. On the contrary, the incorporation of natural zeolites has decreased the resistance to moisture damage of these mixtures and only at higher bitumen content of 4.8% their *ITSR* indices were similar to those of the reference warm mixture.

3.4. Results of the multivariate optimization. The results of the conducted multivariate analysis showing the respective types of investigated mixtures and their performance is presented in Table 6.

The analysis has shown that the compound multivariate performance measured by the means of the desirability index (*DI*) differed significantly depending on the mixture production process and its composition. The highest desirability score, calculated as 0.76, was attained by the reference hot mix asphalt HMA_{Ref} due to its lowest air void content and ITS_{dry} scores and one of the highest *ITSR* results. The desirability index of the reference warm mix asphalt was significantly lower, at only 0.26.

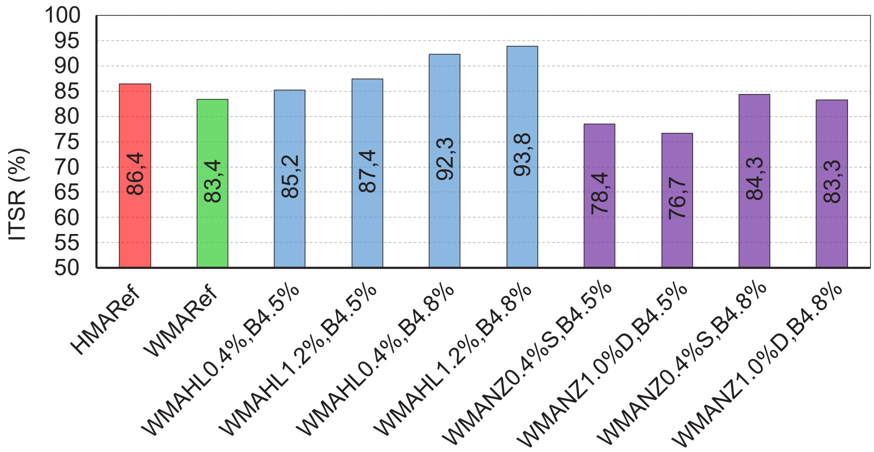

Fig. 5. Values of resistance to moisture and Frost damage (*ITSR*) of the AC 16 mixtures

Table 6
The results of the multivariate optimization of the composition of the investigated asphalt concrete mixes

Type of mix	Measured mean values			Partial desirability values d_i			Desirability index DI
	V_a (%)	ITS_{dry} (kPa)	$ITSR$ (%)	V_a	ITS_{dry}	$ITSR$	
HMA_{Ref}	4.41	1453	86	0.86	1.00	0.69	0.76
WMA_{Ref}	5.61	1226	83	0.46	0.69	0.56	0.26
$WMA_{HL0.4\%,B4.5\%}$	6.47	1193	85	0.18	0.64	0.64	0.10
$WMA_{HL1.2\%,B4.5\%}$	6.76	1214	87	0.08	0.67	0.73	0.05
$WMA_{HL0.4\%,B4.8\%}$	4.58	1275	92	0.81	0.75	0.93	0.59
$WMA_{HL1.2\%,B4.8\%}$	5.13	1229	94	0.62	0.69	1.00	0.43
$WMA_{NZ0.4\%,B4.5\%}$	6.35	1008	78	0.22	0.38	0.35	0.06
$WMA_{NZ1.0\%,B4.5\%}$	6.68	994	77	0.11	0.36	0.28	0.03
$WMA_{NZ0.4\%,B4.8\%}$	5.89	813	84	0.37	0.11	0.60	0.04
$WMA_{NZ1.0\%,B4.8\%}$	6.16	837	83	0.28	0.15	0.56	0.03

This was mostly to its decreased compactability and indirect tensile strength.

The assessment of the warm mix asphalt concrete produced with the incorporation of hydrated lime in amounts of 0.4% and 1.2% by the mixture mass had detrimental effect on the overall performance of the mixture unless an increased bitumen content was utilized. The $WMA_{HL0.4\%,B4.5\%}$ and $WMA_{HL1.2\%,B4.5\%}$ mixtures attained desirability indices as low as 0.10 and 0.05 respectively, which were significantly lower than the one of the reference warm mixture. This outcome was due to significantly decreased compactability and in spite of the increased resistance to moisture damage. On the other hand, the addition of hydrated lime together with increased bitumen content have resulted in better compaction and even higher *ITSR* values, which in turn resulted in reasonably high scores of $WMA_{HL0.4\%,B4.8\%}$ and $WMA_{HL0.4\%,B4.8\%}$ mixtures (0.59 and 0.43, respectively).

The introduction of natural zeolites in the composition of foamed bitumen asphalt concrete mixtures produced at approx. 120°C was generally in detriment to their overall performance. This was exhibited in very low calculated desirability indices which were in the range of 0.03 to 0.06. The mixtures containing natural zeolites and the lower bitumen content of 4.5% obtained better performance in indirect tensile strength, while the mixtures with 4.8% bitumen content had more desirable compatibility and higher resistance to moisture damage. In all cases, the differences between the type of the zeolites (air-dry, 20% water-soaked) were relatively small, however slightly better performance was seen in the mixtures bearing 0.4% of water modified zeolites. Based on these findings, it was inferred, that in these mixtures the additional foaming water was more readily available and smaller amount of the highly porous zeolites in less pronounced way influenced the optimum bitumen content in the mixtures.

The decreased values of the *ITSR* parameter in the samples that were produced from the asphalt mixtures with zeolites can be partially attributed to the increased air void content and greater bitumen absorptivity of zeolites than in the case of limestone powder (the mineral filler used), as confirmed by other authors [17–20]. This effect could also be partially a result of the increased total foaming water content in the mix (0.135% from direct water injection and approx. 0.08% as zeolite water, approx. 0.215% in mix total), as Newcomb et al. [21] have found that excessive foaming water content may lead to hindered workability and decreased performance of a foamed mix.

4. Conclusions

This research assessed asphalt concrete mixtures produced with foamed bitumen at approx. 120°C utilizing different bituminous binder and incorporation of hydrated lime or natural zeolites in their composition. The analysis of results permitted the formulation of the following conclusions:

- the lowering of production temperature to 120°C and compaction temperature to 100°C has resulted in a significant decrease in compactability, indirect tensile strength and resistance to moisture damage of the foamed warm mix AC 16 asphalt concrete for binder and basecourses,
- the substitution of small fractions of the mineral filler with hydrated lime and natural zeolites had significant impact on the properties of the asphalt mixture and these effects were different depending on the added material and the bitumen content utilized,
- the addition of hydrated lime in the mixtures with base bitumen content (4.5%) has increased the measured air void contents in the samples but at the same time had marginal impact on the indirect tensile strengths and resistance to moisture damage; at increased (4.8%) bitumen content, a significant improvement in overall performance of the mixtures was recorded, making them comparable to reference hot mix asphalt in terms of air void contents and resistance to moisture damage,
- the addition of natural zeolites in the mixtures with base bitumen content (4.5%) has resulted in increased air void contents and a significant decrease in both, the indirect tensile strengths (exceeding 200 kPa) and resistance to mois-

ture damage ($< 80\%$) of the asphalt concrete samples; at increased (4.8%) bitumen content only the compactability and *ITSR* were increased to levels similar to those of the reference warm mixture,
- the effects of the type of the used zeolite (air-dry, 20% water-saturated) on the measured properties (V_a, ITS_{dry}, $ITS_{freeze\text{-}thaw}$, *ITSR*) of the zeolite-bearing warm mix asphalts were regarded as insignificant,
- in regards to a number of CEN member states' [1] requirements towards HMA asphalt concrete mixtures, all investigated mixtures have complied for the use in basecourses, but only the reference mixtures and hydrated lime mixtures with foamed bitumen could be used in binder courses ($ITSR > 80\%$),

In conclusion, it was found that utilization of hydrated lime and zeolites in warm mix asphalt concrete with foamed bitumen is a prospective scope. It was found that in spite of the significant decrease in the production and compaction temperatures, the relatively low bitumen and fines content, the obtained results were satisfactory and could be easily optimized in the production process. Future research should be supplemented with higher production and compaction temperatures of the foamed bitumen mixtures, as the decreased compactability could be a consequence of the adopted very low production temperature. The investigation of the additives showed that their incorporation, hydrated lime in particular, could be beneficial for the stability and load bearing potential of the mixtures if higher processing temperatures are used. The presented findings show that further research concerning the use of hydrated lime as a multi-functional additive for warm mix asphalt should be continued. Additionally, the effects of total foaming water contents in mixtures with zeolites and foamed bitumen should be further investigated. The scope of research should also include the assessment of rutting and low temperature performance.

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