Asphalt mixture performance and testing

Effects of hydrated lime on the mechanical properties and moisture susceptibility of foamed half-warm mix AC 16 asphalt concrete

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Abstract

The article describes laboratory investigations regarding production and performance of half-warm mix (HWMA) AC 16 asphalt concrete mixes with produced with foamed bitumen and incorporating hydrated lime. The experiments were designed to evaluate the influence of the hydrated lime added in partial substitution of limestone dust in the filler on the properties of the asphalt mixes produced at decreased temperatures. The performed laboratory tests included assessment of two reference asphalt mixtures (HMA and HWMA produced at ca. 120°C and compacted at ca. 100°C) and four HWMA mixes with 10% and 30% of limestone dust substituted for hydrated lime and with typical and increased (+0.3%) bitumen content. The mixtures were evaluated based on the air void content in Marshall samples (Vm) indirect tensile strength of dry and freeze-thawed Marshall samples (ITSdry, ITSfreeze-thaw), resistance to moisture and frost damage (ITSR) and wheel tracking performance (PRDair, WTSair). Additionally, a multivariate optimization of these properties was utilized to distinguish the best performing mixtures and showcase their features. The adopted methodology allowed to evaluate relationships between the investigated properties of the half-warm mix asphalt concrete and its composition in scope of the mix performance and its projected durability.

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1. INTRODUCTION

The idea of using hydrated lime in the technology of bituminous mixtures is not new, as it dates to the first uses of asphalt mixtures in paving technology on an industrial scale over a hundred years ago. One of the first uses of this additive were reported in the United States, where such attempts are dated to the end of the 19th century. A special type of asphalt mix was used to construct structural layers of street surfaces in Washington and Buffalo, containing a 0.3% addition of „air-slacked lime" [1], which task was to remove any residual water on the surface of the aggregates. Other types of technologies with the use of hydrated lime have also developed, which primarily used its strong alkaline properties as an adhesion promoter [2], 3]. At the same time, in Europe, hydrated lime was used in England to increase the resistance of tar mixtures in which soft coal tar was used [4]. The development of the chemical industry and the implementation of new types of adhesion promoters obtained as by-products of the chemical industry have practically ceased the use of lime in asphalt mixtures with bitumen or tar binder. Only to a limited extent have the tests been performed by M. Duriez and J. Arrambide in France's LPCP [5], who positively assessed the effects of lime on the adhesion of mixtures with asphalt or tar binder.

It wasn't until the late 1970s that the energy crisis, related to oil shortage and being the result of armed conflicts, caused renewed interest in lime-based products as modifiers to improve the properties of poor quality of asphalt. In addition, during this period there was a dynamic development of the automotive industry affecting the increase in requirements for road pavements. These two premises caused a increased interest in hydrated lime as an additive to asphalt mixes, providing improved adhesion of the binder to the aggregate and thus their moisture and frost resistance as well as increased resistance to permanent deformation [6], 7].

The use of hydrated lime is particularly beneficial in the presence of acidic aggregates (SiO2> 65%). The mechanism of this interaction is based on the binding of calcium cations with silicon compounds on the surface of this type of aggregates, which results in formation of strong ionic bonds. Calcium cations replace potassium and sodium cations occurring on the aggregate surface and as a consequence, water-insoluble salts are formed. In consequence of this process, a strong bonding at the border of the aggregate grain surface and acidic bitumen is formed [8]. Hydrated lime can also play a very important role in eliminating the adverse effects of clay inclusions on the surface of aggregate grains, which significantly reduce the resistance of the asphalt mix and pavement structural layers to water and frost damage [9], 10].

The action of the hydrated lime on the aggregate surface is often similar to that in the soil stabilization process. It causes flocculation of clay particles, thus preventing the formation of an intermediate layer between the surface of the aggregate grains and the asphalt film, which could result in a significant reduction in adhesion. Another beneficial effect of using hydrated lime in asphalt mixtures is the mechanism of chemical interaction of hydrated lime and asphalt, which first neutralizes the polar asphalt particles and then partially adsorbs them [11]. The remaining polar bitumen particles neutralized by hydrated lime no longer diffuse to the surface of the asphalt-aggregate interface but remain deeper in the binder layer. As a consequence, the adhesion of the asphalt film to the surface of aggregates, especially those with high silica content, is improved due to the presence of a binder of neutral or alkaline nature – depending on the type of bitumen [13].

As a result of the interaction of hydrated lime with the bitumen, the binder's aging resistance also can be improved. Research on the use of hydrated lime as an additive for asphalt mixes carried out in Poland [9, 16, 17, 18, 19] confirmed the effectiveness of this additive in improving water and frost resistance as well as aging performance of hot mix asphalt (HMA) in the demanding conditions of a transition climate.

In the studies carried out so far, the possibility of using hydrated lime as an addition to asphalt mixtures produced in foamed HWMA (Half-Warm Mix Asphalt) process in producing binder and basecourse mixes was yet to be studied. This technique, characterized by low technological temperatures not exceeding 120°C for the production stage and 100°C for compaction of the asphalt concrete mix and use of foamed bitumen as a binder, requires specific investigations of such a a multifunctional additive as hydrated lime. This necessity of incorporating different additives was shown in recent studies [19, 20, 21] regarding HWMA mixes, produced with hydrated lime and other additives, intended for wearing courses. Because wearing course mixes are usually fine mixes (with aggregate size up to 11 mm) and contain increased amounts of asphalt cement and filler, the utilization of hydrated lime requires an independent approach.

2. EXPERIMENTAL PROGRAM AND SCOPE OF RESEARCH

The objective of this research was to examine the effects of hydrated lime (HL) on the properties of asphalt mix produced and compacted at reduced temperatures, in the half-warm mix asphalt technology with water-foamed bitumen. Asphalt concrete mixtures with a maximum aggregate size of 16 mm (AC 16) intended for binding and basecourses of pavements with design traffic ranging in 0.5 - 7.3 million $ESALs_{100\,kN}$ (Equivalent Single Axle Loads) were used to assess the impact of using hydrated lime in HWMA asphalt mixtures. All of the evaluated mixes had uniform composition which was identical to the composition of the reference mixture produced in the hot mix asphalt technology - HMA_{Ref}. The differences between the mixtures included the temperature of production (HMA_{Ref}: ca. 165°C, *HWMA* mixes: ca. 120°C) and compaction (HMA_{Ref}: ca. 145°C, *HWMA* mixes: ca. 95°C – 100°C), used form of the binder (conventional bitumen in HMA_{Ref}, mechanically water-foamed bitumen in *HWMA*).

Due to the stiffening effect of hydrated lime, the effects of increasing the content of bituminous binder while introducing the hydrated lime in the asphalt concrete mix was also analyzed. The experimental program therefore included an analysis of two factors on the properties of the asphalt concrete mix, i.e. hydrated lime content (HL) and bitumen content (B), according to the plan of the experiment shown in figure 1 and the information contained in table 1.

30%	•	•
10%	•	•
HL / B	**4.5%**	**4.8%**

Figure 1: The experimental plan showing the levels of the investigated variables, i.e. bitumen content (B) with low value of 4.5% and high value of 4.8% (4.5%+0.3%) and hydrated lime content in the limestone filler with low value of 10% and high value of 30%

The content of hydrated lime in relation to the weight of the limestone filler was 10% and 30%, which constituted 0.4% and 1.2% total weight of the mineral mix. These values are smaller than recommended in the literature (usually 1% -2% by mass of mineral mix) due to the nature of the tested mixtures (intended for the binding and basecourse) and the resulting low content of mineral filler in the composition of asphalt mix, relatively low binder content and the use of reduced technological temperatures. These factors and high dosing of hydrated lime could potentially strengthen the stiffening effect of HL leading to excessive drop the workability and compaction potential of the investigated asphalt concrete. Previous experience [19] showed that higher HL content can be used in HWMA technology in mixes intended for wearing course (also 30% in relation to filler aggregates but 2% in relation to total mineral mix with higher 5.9% bitumen content).

In mixtures in which lime was used, the composition of asphalt concrete was corrected by reducing the content of limestone dust in the composition of mineral mix so that total amount of mineral filler and hydrated lime was equal to the contents of mineral filler in the reference mixes.

The mix was designed in accordance to EN 13108-1 [22] and Polish technical requirements WT-2 [23]. The same 35/50 road asphalt was used in all asphalt mixtures. Due to the fact that quartzite aggregate was used in the mineral mix, it was necessary to use a surface-active adhesion promoter (further referred to as WBE), which content by weight of the binder was established at 0.3% in the reference mix HMA_{Ref}. In the case of HWMA mixtures produced with foamed bitumen, the amount of additive was 0.6% by weight of the bituminous binder and was determined on the basis of previous experiences and studies [19, 21, 24, 25].

Table 1. Framework composition of AC 16 asphalt concrete mixtures

AC constituents	Material type			Mixtures
Natural aggregates	Filler aggregate (limestone dust)			HMA_{Ref}
	Fine natural aggregate 0/2 mm (*limestone*)			$HWMA_{Ref}$
	Continuously graded natural aggregate 0/4 mm (*limestone*)			$HWMA_{HL10\%,B4.5\%}$
	Coarse aggregate 2/5 mm (quartzite)			$HWMA_{HL30\%, B4.5\%}$
	Coarse aggregate 5/8 mm (quartzite)			$HWMA_{HL10\%,B4.8\%}$
	Coarse aggregate 8/16 mm (limestone)			$HWMA_{HL30\%,B4.8\%}$
Bituminous binder	Paving bitumen 35/50	Liquid (unfoamed)	4.5%	HMA_{Ref}
		Foamed (water injection)	4.5%	All *HWMA*
			4.8% (4.5%+0.3%)	All *HWMA*
Additives	Adhesion promoter	0.3%		HMA_{Ref}
		0.6%		All *HWMA*
	Hydrated lime (HL)	10% (by wt. of filler aggregates) 0.4% (by wt. of mineral mix)		$HWMA_{HL10\%,B4.5\%}$ $HWMA_{HL10\%,B4.8\%}$
		30% (by wt. of filler aggregates) 1.2% (by wt. of mineral mix)		$HWMA_{HL30\%,B4.5\%}$ $HWMA_{HL30\%,B4.8\%}$

The scope of laboratory work included testing of the following physical and mechanical properties of AC 16 asphalt concrete mixtures:

- density ρ_{mv} in acc. to EN 12697-5 [26] – 3 replicates,
- bulk density ρ_{bssd} in acc. to EN 12697-6 [27] – 10 replicates,
- air void content V_m in acc. to EN 12697-8 [28] – 10 replicates,
- indirect tensile strength ITS_{dry} of dry samples and after one freeze-thaw cycle $ITS_{freeze\text{-}thaw}$ - 8 replicates in each group,
- resistance to moisture and frost damage *ITSR* in acc. to EN 12697-12 [29] and WT-2 (Appendix no. 1) [23] – procedure was described in detail in [20] (procedure B, p. 2.3),
- resistance to permanent deformation in acc. to PN-EN 12697-22:2008 [30], based on proportional rut depth PRD_{AIR} and wheel tracking slope WTS_{AIR} after 10^3 cycles – 5 replicates.

3. MATERIALS

For the design of the reference AC 16 asphalt concrete mixture, aggregates, binder type and adhesion promoter were chosen in line with EN 13108-1 [22] and the domestic specifications [23, 31] for binder and basecourse with design traffic of 0.5 - 7.3 million $\text{ESALs}_{100\text{ kN}}$ regarded as a medium traffic load.

3.1. Aggregate mix grading

Table 2 presents the granular composition of the mineral mixused in producing AC 16 asphalt concrete. The mix comprised 4% of filler aggregate, 15% fine 0/2 aggregate, 15% continuously graded 0/4 aggregate, 12% coarse 2/5 aggregate, 12% coarse 5/8 aggregate and 42% coarse 8/16 aggregate in accordance to the materials listed in table 1.

Table 2. Grading of mineral aggregates used in 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**
Filler	0	0	0	0	0	0	0	0	0.8	2.3	4.8	92.1
0/2 mm	0	0	0	0	0.1	9.2	25.9	19.8	16.7	16.4	8.3	3.5
0/4 mm	0	0	0	2.4	13.3	29.0	20.6	11.1	6.7	3.8	2.7	10.4
2/5 mm	0	0	0	11.0	31.9	45.9	8.4	0.7	0.1	0.2	0.4	1.4
5/8 mm	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	6.8	42.3	40.8	7.0	0.5	0.2	0	0	0	0.1	0.2	2.0

3.2. Hydrated lime

The physical and chemical properties of hydrated lime used in the composition of the asphalt concrete are given in table 3, while figure 2 presents the results from the determination of fine particles content (hydrated lime grading) obtained by air jet sieving in accordance to EN 933-10 [32].

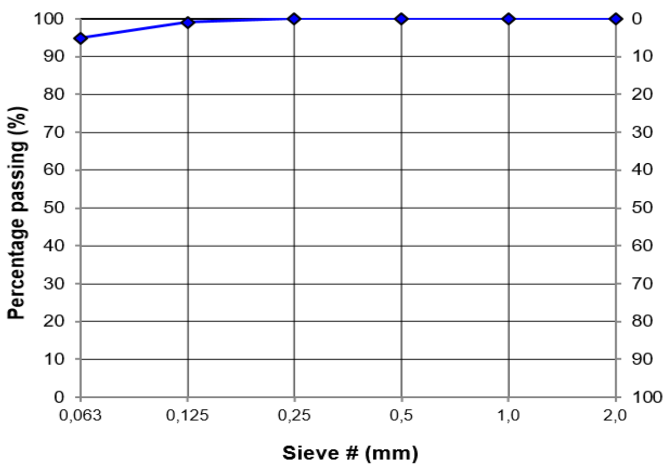

Figure 2: Grading of the hydrated lime

Table 3. Properties of the hydrated lime [33]

Property		Value
Chemical properties	CaO, (%)	94.8
	MgO, (%)	0.7
	$Ca(OH)_2$, (%)	92.2
	CO_2, (%)	1.2
	SO_3, (%)	0.1
	Al_2O_3, (%)	0.6
	Fe2O3, (%)	0.3
	Zawartość wolnej wody, (%)	0.7
Physical parameters	Loose bulk density (Mg/dm^3)	0.40 – 0.50
	Density, (Mg/m^3)	2.240
	% passing (sieve analysis):	
	0.09 mm, (%)	4.7
	0.2 mm, (%)	0.3

3.3. Bitumen binder

The 35/50 penetration paving grade bitumen was used in asphalt mixes, which is widely used in Central and Eastern European countries for asphalt mixes. In Poland, it is used in asphalt concrete intended for roads with medium traffic loads, usually up to 7.3 million $ESAL_{100\,kN}$. As already mentioned, the content of the surface active agent was 0.3% for the reference mix produced in the HMA technology, while for all mixtures produced in the HWMA technology with foamed bitumen, its content was 0.6% by bitumen mass. The quantitative range of use of the surfactant additive was not only due to the high silica content in the aggregates (SiO_2 > 60%), but also because of the decreased processing temperatures of the HWMA mixes with foamed bitumen. Increased dosing of this additive is also recommended due to the need to ensure water and frost resistance of the asphalt pavement, operational durability and thus ensuring the safety of traffic users. The properties of the bitumen before and after foaming, as well as the characteristics of the adhesion promoter were presented given in [24]. Figure 3 shows the foaming characteristics of the 35/50 + 0.6% WBE asphalt binder used in HWMA mixtures. The foaming water content for producing the asphalt concrete mixes was chosen at FWC = 3.0%, which produced bitumen foam with expansion ratio of ER = 14.1 and half-life of HL = 20.5 s.

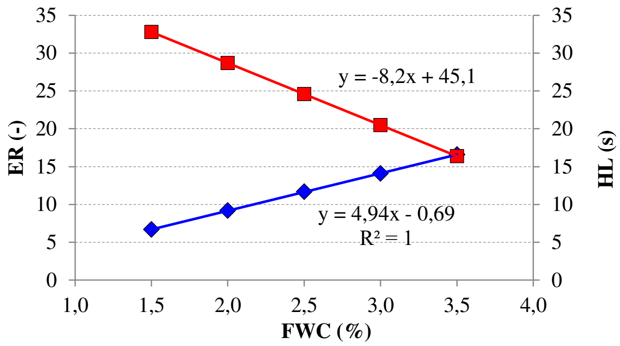

Figure 3: The foaming characteristics of the 35/50+0.6% WBE asphalt binders used for foaming in *HWMA* asphalt concrete

3.4. The AC 16 asphalt concrete mix

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 added. For all the asphalt concrete mixes the minimum bitumen content, added bitumen and soluble bitumen content was established in accordance with the domestic specification [23], which is presented in table 4. The framework composition of all mineral mixtures (mm) and asphalt concrete mixtures (acm) is given in table 5. Figure 4 represents the final grading of the mineral mix along with the boundary grading points. All of the utilized mineral materials fulfilled the requirements stated in appropriate technical documents [23, 31] regarding their use in binding and basecourses in pavements. The compositions of the investigated mixes were in line with the experimental program laid out in p. 2. In the design and manufacture of asphalt mixtures, the recommendations formulated in the relevant technical documents were used [23, 31, 34].

Before producing the asphalt mixtures, the aggregates were thermostated for 4 hours at 170°C (HMA mix) or 120°C (HWMA mixes). The adhesion promoter was added to the bitumen 15 min before production of the asphalt mix and was evenly mixed with the binder. Hydrated lime was dosed in appropriate proportions to the filler aggregate and mixed mechanically. The resulting composite filler was added to the mix without pre-heating.

Table 4. The characterization of investigated HMA and HWMA asphalt concrete mixes in the scope of the binder content

Parameter	Unit	Type of asphalt concrete mix				
		HMA_{Ref}, $HWMA_{Ref}$	$HWMA_{HL10\%,B4.5\%}$	$HWMA_{HL30\%,B4.5\%}$	$HWMA_{HL10\%,B4.8\%}$	$HWMA_{HL30\%,B4.8\%}$
Mineral mix density ρ_a	Mg/m^3	2.697	2.695	2.691	2.695	2.691
Minimum bitumen content B_{min}	%	4.6	4.6	4.6	4.6	4.6
Density correction factor α=2.650/ρ_a	-	0.983	0.983	0.985	0.983	0.985
Minimum bitumen content after correction (B_{min} x α)	%	**4.5**	**4.5**	**4.5**	**4.5**	**4.5**
Insoluble bitumen: B_A= 0.014·F+0.1, where F - mineral content <0.063 mm	%	0.2	0.2	0.2	0.2	0.2
Added bitumen	%	**4.5**	**4.5**	**4.5**	**4.8**	**4.8**
Soluble bitumen content	%	4.3	4.3	4.3	4.6	4.6

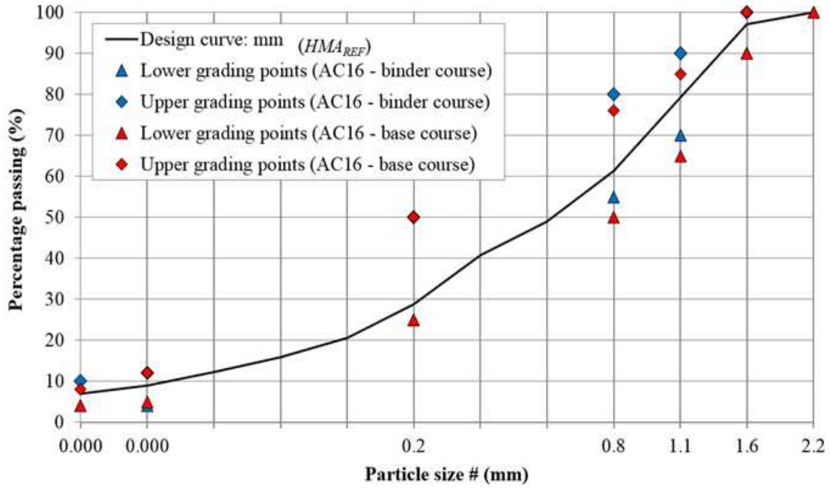

Figure 4: Grading curve of the AC 16 mineral mix with boundary points

Table 5. Framework composition of the investigated AC 16 asphalt mixes

Component	Percentage (% m/m)									
	Type of asphalt concrete mix									
	HMA_{Ref}, $HWMA_{Ref}$		$HWMA_{HL10\%,B4.5\%}$		$HWMA_{HL30\%,B4.5\%}$		$HWMA_{HL10\%,B4.8\%}$		$HWMA_{HL30\%,B4.8\%}$	
	mm	acm	mm	acm	mm	acm	mm	acm	mm	acm
Filler aggregate	4	3.82	3.6	3.44	2.8	2.67	3.6	3.43	2.8	2.67
0/2 mm	15	14.33	15	14.33	15	14.33	15	14.28	15	14.28
0/4 mm	15	14.33	15	14.33	15	14.33	15	14.28	15	14.28
2/5 mm	12	11.46	12	11.46	12	11.46	12	11.42	12	11.42
5/8 mm	12	11.46	12	11.46	12	11.46	12	11.42	12	11.42
8/16 mm	42	40.11	42	40.11	42	40.11	42	39.98	42	39.98
HL	**0**	-	**0.4**	0.38	**1.2**	1.15	**0.4**	0.38	**1.2**	1.14
Bitumen 35/50	-	4.5 [a) b)]	-	4.5 [b)]	-	4.5 [b)]	-	4.8 [b)]	-	4.8 [b)]
Total	100	100	100	100	100	100	100	100	100	100
Surface active agent added in the amount: [a)] 0.3% (m/m) to HMA_{Ref}, [b)] 0.6% (m/m) to all *HWMA*										

The presence of hydrated lime in the composition of mineral mixtures did not cause significant changes in their grading relative to reference mixtures, and only the density of mineral mixtures (ρ_a) changed slightly. The value B_{min} = 4.6% given in table 5 refers to the binding layer, and the calculated amount of dosed bitumen also meets the requirements for the AC 16 mixture for the foundation layer, for which B_{min} = 4.2%.

4. RESULTS AND DISCUSSIONS

4.1. Test results and analysis of the impact of hydrated lime on the properties of AC 16 mixes (ITS_{dry}, $ITS_{freeze\text{-}thaw}$, *ITSR*, PRD_{air}, WTS_{air}

Figure 5 shows the average measured values of air void content in Marshall samples. Figure 6 shows the results of indirect tensile strength of dry and samples conditioned with one freezing cycle, produced from the investigated asphalt mixtures (HMA_{Ref}, $HWMA_{Ref}$, $HWMA_{HL10\%,B4.5\%}$, $HWMA_{HL30\%,B4.5\%}$, $HWMA_{HL10\%,B4.8\%}$, $HWMA_{HL30\%,B4.8\%}$). These results were used for determining the resistance to moisture and frost index (*ITSR*). The analyzed results of physical and mechanical parameters are presented in the form of column charts, with 2 standard deviations presented in the form of error bars.

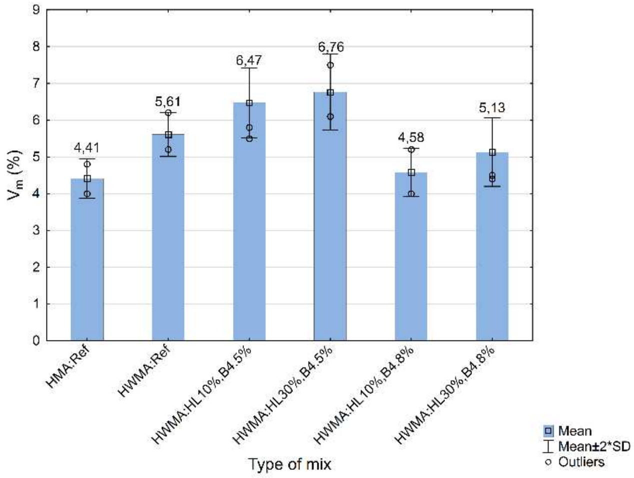

Figure 5: Air void content measurements (V_m) in the Marshall samples produced from the investigated asphalt concrete mixes

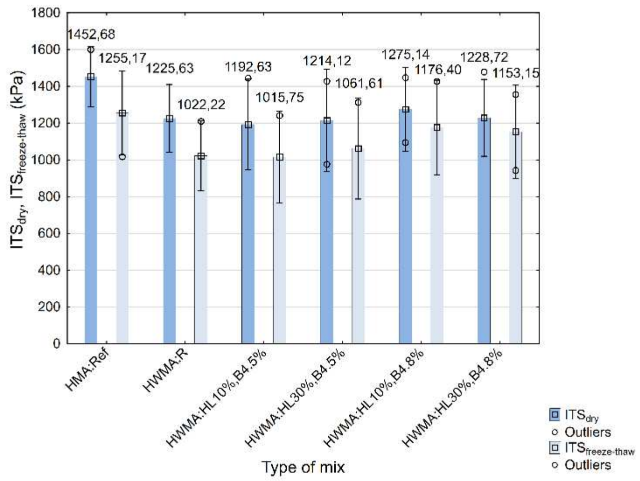

Figure 6: Indirect tensile strengths of dry (*ITS_d*) and freeze-thawed (1 cycle, *$ITS_{freeze\text{-}thaw}$*) Marshall samples produced from the investigated asphalt concrete mixes

Analysis of the results of the volumetric tests shows that the use of hydrated lime as a substitute for a part of the mineral filler (limestone dust) in the tested asphalt concrete mixes had a significant impact on the content of the air void content V_m in compacted Marshall samples. The addition of 10% hydrated lime in the filler of HWMA mix resulted in an increase in the V_m content from 5.61% in the reference mix to 6.47% in $HWMA_{HL10\%,B4.5\%}$. Further increase of hydrated lime content up to 30% resulted in the V_m increase to 6.76%. The combined use of hydrated lime and an increased amount of asphalt binder in the mix allowed for obtaining air void content 4.6%, which was similar to the reference mix HMA_{Ref}, where it was equal to V_m = 4.4%. The $HWMA_{HL30\%,B4.8\%}$ mix with the increased bitumen content was characterized by V_m = 5.1%.

The results of the determination of strength in indirect tensile of samples from the tested mixtures presented in figure 6 indicate a small effect of the addition of hydrated lime on *ITS* parameters both after air-dry conditioning and after one freezing cycle. With the addition of 10% hydrated lime relative to the filler (0.4% in $HWMA_{HL10\%,B4.8\%}$ asphalt concrete mix*)*, a slight decrease was observed in values of ITS_{dry} i $ITS_{freeze\text{-}thaw}$ relatively to $HWMA_{Ref}$ reference mix, and an increase with further rising the hydrated lime content to 30% (1.2% in relation to the whole mix).

In the case of the mixtures with an increased amount of asphalt binder, the increase in hydrated lime resulted in a slight decrease in *ITS* parameters. For all *HWMA* mixtures with hydrated lime, the difference between the ITS_{dry} and $ITS_{freeze\text{-}thaw}$ values was noticeably decreased compared to the $HWMA_{Ref}$. reference mix. The highest values these parameters were obtained by the $HWMA_{HL10\%,B4.8\%}$ reaching ITS_{dry} = 1275.1 kPa and $ITS_{freeze\text{-}thaw}$ = 1176.4 kPa.
Based on the results of determinations of indirect tensile strength of Marshall samples, the resistance to moisture and frost damage indexes (*ITSR*) were calculated and are presented in figure 7.

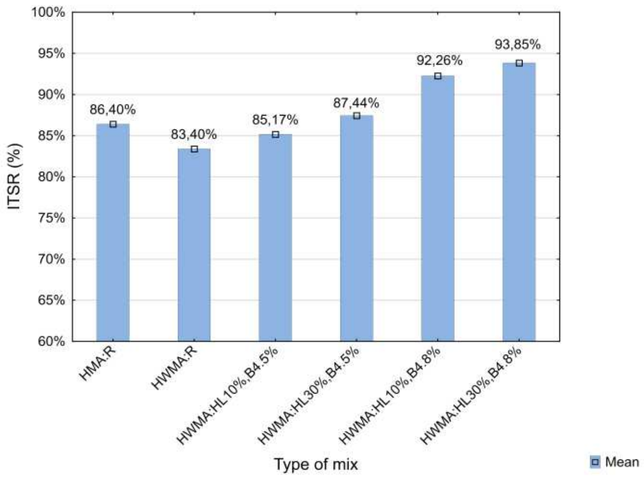

Figure 7: The results of determination of resistance to moisture and frost damage indexes (*ITSR*) of the tested asphalt concrete mixes

The analysis of the *ITSR* values, a significant impact was observed both due to the use of hydrated lime in asphalt mixtures and as a result of the increased amount of asphalt binder. The addition of hydrated lime to *HWMA* mixtures resulted in increased values of *ITSR* index from 83.4% up to 85.2% and 87.4% with 10% and 30% *HL* respectively. The highest values of the resistance to moisture and frost damage indexes characterized the *HWMA* mixtures with increased content of asphalt binder $HWMA_{HL10\%,B4.8\%}$ and $HWMA_{HL30\%,B4.8\%}$, with *ITSR*=92.3% and *ITSR*=93.9% respectively. These results were undoubtedly affected by the low air void content, increased amount of asphalt binder and the properties of hydrated lime. It was shown that hydrated lime is an efficient antistripping agent, which use, along with increased binder content, resulted in an up to 10% increase of moisture and frost resistance indexes in the investigated mixes.

The last of the analyzed parameters were proportional rut depth PRD_{air} and WTS_{air} wheel tracking slope, tested for all asphalt mixtures. The average values of the PRD_{air} and WTS_{air} parameters are presented in figures 8 and 9, respectively.

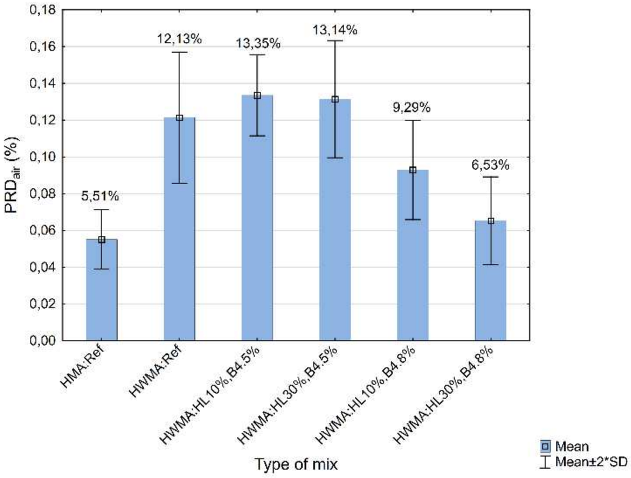

Figure 8: The results of proportional rut depth PRD_{air} of the investigated asphalt concrete mixes

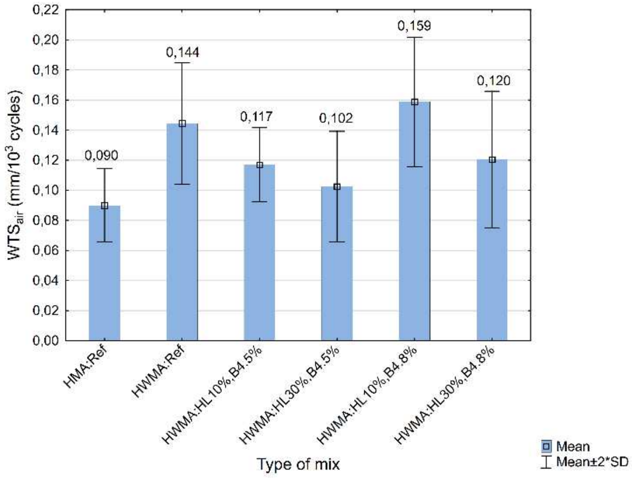

Figure 9: The results of wheel tracking slope WTS_{air} of the investigated asphalt concrete mixes

Analysis of the results of rutting tests of the asphalt concrete mixtures showed the significant effects of using hydrated lime and the increased amount of foamed bitumen on the properties of *HWMA* mixtures. In the case of $HWMA_{HL10\%,B4.5\%}$ and $HWMA_{HL30\%,B4.5\%}$ mixtures, an increase in the proportional rut depth from 12.13% in the reference mixture $HWMA_{Ref}$ was observed to respectively 13.35% and 13.14%. In the case of mixtures with an increased amount of asphalt binder, it was observed that the addition of hydrated lime reduced the PRD_{air} to 9.29% and 6.53% for mixes with 10% and 30% hydrated lime in mineral filler respectively. Analyzing the values of the WTS_{air} index, it was found that in each case the increase of hydrated lime content caused a decrease in rutting rate, and WTS_{air} values were lower in the case of mixtures of $HWMA_{HL10\%,B4.5\%}$ i $HWMA_{HL30\%,B4.5\%}$ amounting respectively to 0.117 mm/10^3 cycles and 0.102 mm/10^3 cycles. It was shown that the addition of hydrated lime had a positive impact not only on the moisture resistance improving the bitumen-aggregate adhesion, but also improved the rutting resistance of the investigated half-warm mix asphalt concrete mixes, enhancing their hot-weather performance.

4.2. Statistical analysis of the test results

In order to assess the impact of the hydrated lime in the composition of asphalt mixtures with foamed bitumen produced with lowered processing temperatures, on their physical and mechanical properties, a statistical analysis of test results was performed. The analyses included inference about the significance of differences between the average values of the dependent variables (V_m, ITS_{dry}, $ITS_{freeze\text{-}thaw}$, PRD_{air}, WTS_{air}) in terms of composition and production method of asphalt concrete, using one-way ANOVA. Due to the compatibility of variable distributions with the normal distribution and meeting the assumption of homogeneity of variance, it was possible to use the parametric F test (Fisher-Snedecor), which allows a simultaneous comparison of several averages. The tested variable 'type of mix' had a statistically significant effect on all of the parameters tested. Because significant results were obtained for all considered parameters in the general F test (p-value <0.05), post-hoc comparisons (Tukey's multiple comparison test) were used to estimate the specific significance of the differences in the studied groups. Table 6 shows the results of the Tukey multiple comparison test.

Table 6. Results of Tukey multiple comparison test

Tukey HSD test, variable $\boldsymbol{V_m}$ (%). Approximate Probabilities for Post Hoc Tests. Error: Between MS = 0.13961, df = 54						
Type of mix	{1} 4.41	{2} 5.61	{3} 3.90	{4} 6.76	{5} 4.58	{6} 5.13
HMA_{Ref}		0.000138	0.039127	0.000138	0.910175	0.001058
$HWMA_{Ref}$	0.000138		0.000138	0.000138	0.000139	0.061295
$HWMA_{HL10\%,B4.5\%}$	0.039127	0.000138		0.000138	0.002157	0.000138
$HWMA_{HL30\%,B4.5\%}$	0.000138	0.000138	0.000138		0.000138	0.000138
$HWMA_{HL10\%,B4.8\%}$	0.910175	0.000139	0.002157	0.000138		0.020765
$HWMA_{HL30\%,B4.8\%}$	0.001058	0.061295	0.000138	0.000138	0.020765	
Tukey HSD test; variable $\boldsymbol{ITS_{dry}}$ (kPa). Approximate Probabilities for Post Hoc Tests. Error: Between MS = 12287, df = 42						
Type of mix	{1} 1452.7	{2} 1225.6	{3} 1192.6	{4} 1214.1	{5} 1275.1	{6} 1228.7
HMA_{Ref}		0.002534	0.000524	0.001408	0.029196	0.002965
$HWMA_{Ref}$	0.002534		0.990844	0.999947	0.946058	1.000000
$HWMA_{HL10\%,B4.5\%}$	0.000524	0.990844		0.998829	0.673164	0.986260
$HWMA_{HL30\%,B4.5\%}$	0.001408	0.999947	0.998829		0.878202	0.999829
$HWMA_{HL10\%,B4.8\%}$	0.029196	0.946058	0.673164	0.878202		0.958700
$HWMA_{HL30\%,B4.8\%}$	0.002965	1.000000	0.986260	0.999829	0.958700	
Tukey HSD test; variable $\boldsymbol{ITS_{freeze\text{-}thaw}}$ (kPa). Approximate Probabilities for Post Hoc Tests. Error: Between MS = 14834, df = 42						
Type of mix	{1} 1255.2	{2} 1022.2	{3} 1015.8	{4} 1061.6	{5} 1176.4	{6} 1153.1
HMA_{Ref}		0.005456	0.004043	0.031094	0.786894	0.555218
$HWMA_{Ref}$	0.005456		0.999998	0.986655	0.138146	0.282609
$HWMA_{HL10\%,B4.5\%}$	0.004043	0.999998		0.973784	0.110559	0.234962
$HWMA_{HL30\%,B4.5\%}$	0.031094	0.986655	0.973784		0.425404	0.664259
$HWMA_{HL10\%,B4.8\%}$	0.786894	0.138146	0.110559	0.425404		0.998912
$HWMA_{HL30\%,B4.8\%}$	0.555218	0.282609	0.234962	0.664259	0.998912	
Tukey HSD test; variable $\boldsymbol{PRD_{air}}$ (%). Approximate Probabilities for Post Hoc Tests. Error: Between MS = 0.00018, df = 24						
Type of mix	{1} 0.0551	{2} 0.1213	{3} 0.1335	{4} 0.1153	{5} 0.0928	{6} 0.0653
HMA_{Ref}		0.000138	0.000138	0.000139	0.002001	0.828536
$HWMA_{Ref}$	0.000138		0.698514	0.977359	0.026651	0.000143
$HWMA_{HL10\%,B4.5\%}$	0.000138	0.698514		0.287669	0.000932	0.000138
$HWMA_{HL30\%,B4.5\%}$	0.000139	0.977359	0.287669		0.122017	0.000180
$HWMA_{HL10\%,B4.8\%}$	0.002001	0.026651	0.000932	0.122017		0.033482
$HWMA_{HL30\%,B4.8\%}$	0.828536	0.000143	0.000138	0.000180	0.033482	
Tukey HSD test; variable $\boldsymbol{WTS_{air}}$ (mm/1000 cycles). Approximate Probabilities for Post Hoc Tests. Error: Between MS = 0.00034, df = 24						
Type of mix	{1}0.0900	{2} 0.1444	{3} 0.1173	{4} 0.1024	{5} 0.1588	{6} 0.1204
HMA_{Ref}		0.001292	0.224387	0.889862	0.000182	0.132394
$HWMA_{Ref}$	0.001292		0.211492	0.015647	0.813992	0.338454
$HWMA_{HL10\%,B4.5\%}$	0.224387	0.211492		0.805346	0.016280	0.999692
$HWMA_{HL30\%,B4.5\%}$	0.889862	0.015647	0.805346		0.000888	0.638478
$HWMA_{HL10\%,B4.8\%}$	0.000182	0.813992	0.016280	0.000888		0.031630
$HWMA_{HL30\%,B4.8\%}$	0.132394	0.338454	0.999692	0.638478	0.031630	

Tukey multiple comparison tests showed that the observed differences between the mean values of air void content V_m were in most cases statistically significant. Statistical analysis showed no significant differences between the average V_m values obtained for the reference mixture HMA_{Ref} and $HWMA_{HL10\%,B4.8\%}$ and for the pair of mixtures $HWMA_{Ref}$ and $HWMA_{HL30\%,B4.8\%}$.

The performed tests failed to prove statistically significant differences in ITS_{dry} and $ITS_{freeze\text{-}thaw}$ results obtained by different evaluated *HWMA* mixtures. The HMA_{Ref} reference mix, however, differed significantly in terms of the ITS_{dry} values from all *HWMA* mixtures, and from the $HWMA_{HL10\%,B4.5\%}$ and $HWMA_{HL30\%,B4.5\%}$ mixtures in terms of $ITS_{freeze\text{-}thaw}$ results. Slight differences in the values of indirect tensile strength of samples with the addition of hydrated lime can probably be explained by the properties of hydrated lime, which requires higher amounts of bitumen than limestone dust and stiffens the asphalt binder. This causes a decrease in workability and compactability of the asphalt mix, but at the same time stiffened mastic is more resistant to the action of moisture and frost.

In the case of rutting results, it can be stated that the $HWMA_{HL30\%,B4.8\%}$ mixture obtained statistically similar results to the HMA_{Ref} reference mix, both in terms of PRD_{air} and WTS_{air} performance. The assessment of the rutting parameters also showed significant differences between the PRD_{air} and WTS_{air} assessment and which mixes were characterized by similar performance.

4.3. Multivariate optimization

To distinguish the best performing HWMA asphalt concrete mixture with the addition of hydrated lime, a multivariate optimization approach using desirability functions and desirability index in accordance to the methodology laid out in [35] was adopted. Desirability functions assessing the measured properties of the asphalt concrete mixes were constructed using specification limits given in table 7. The specific limits regarding air void contents, resistance to moisture and frost damage and wheel tracking performance were derived from the domestic requirements laid out in Polish specifications for binding courses (V_m, $ITSR$) and basecourses (V_m, WTS_{air}), so that all mixes could be evaluated with final desirability index in the range of $DI \in \langle 0, 1 \rangle$, where DI is defined as a geometric mean of partial desirabilities:

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

where:
DI – desirability index,
d_i – partial desirability assessing the mix performance using the chosen properties (V_m, ITS_{dry}, $ITSR$, PRD_{air}, WTS_{air}),
k – number of the evaluated properties

Figure 10 represents the results of the multivariate optimization, showing the best performing mixes in overall being the $HWMA_{HL10\%,B4.8\%}$ and $HWMA_{HL30\%,B4.8\%}$. Table 8 represents the results of the optimization along with the evaluation of the two reference mixes, HMA_{Ref} and $HWMA_{Ref}$.

Table 7. Specification limits used in the multivariate optimization

Measured property	Unit	Lower specification limit (*Desirability* = 0)	Upper specification limit (*Desirability* = 1)
V_m	%	7	4
ITS_{dry}	kPa	90% · min(ITS_{dry})	max(ITS_{dry})
$ITSR$	%	80	100
PRD_{air}	%	110% · min(PRD_{air})	min(PRD_{air})
WTS_{air}	mm/1000 cycles	0.3	min(WTS_{air})

Table 8. The results of the multivariate optimization of the composition of the investigated asphalt concrete mixes containing hydrated lime substituting parts of the mineral filler in the scope of different bitumen contents

Type of mix	Measured mean values					Desirability values					
	V_m	ITS_{dry}	$ITSR$	PRD_{air}	WTS_{air}	V_m	ITS_{dry}	$ITSR$	PRD_{air}	WTS_{air}	DI
HMA_{Ref}	4.41	1452.68	0.86	0.06	0.09	0.86	1.00	0.46	1.00	1.00	0.40
$HWMA_{Ref}$	5.61	1225.63	0.83	0.12	0.14	0.46	0.40	0.25	0.28	0.74	0.03
$HWMA_{HL10\%,B4.5\%,}$	6.47	1192.63	0.85	0.13	0.12	0.18	0.31	0.37	0.15	0.87	0.01
$HWMA_{HL30\%,B4.5\%}$	6.76	1214.12	0.87	0.13	0.10	0.08	0.37	0.54	0.17	0.94	0.01
$HWMA_{HL10\%,B4.8\%}$	4.58	1275.14	0.92	0.09	0.16	0.81	0.53	0.88	0.59	0.67	0.23
$HWMA_{HL30\%,B4.8\%}$	5.13	1228.72	0.94	0.07	0.12	0.62	0.41	1.00	0.89	0.86	0.21

It can be seen, that the *HWMA* mixes with the addition of hydrated lime and increased bitumen content (+0.3%) performed significantly better than the reference *HWMA* mix. It can be also seen, that the poor performance of the $HWMA_{HL10\%(Bmin)}$ and $HWMA_{HL30\%(Bmin)}$ was mainly by the high air void content, which was also correlated with increased proportional rut depth. Both these factors could be improved by increasing the production and compaction temperatures by a small amount. The evaluated mediocre performance of the reference half-warm mix was mostly due to poor resistance to moisture and frost damage, which was significantly improved by the incorporation of hydrated lime.

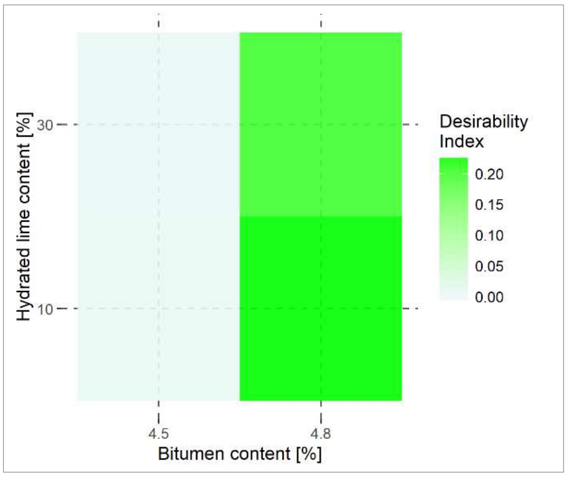

Figure 10: Results of the multivariate optimization of the HWMA AC 16 composition – values of the desirability index

5. CONCLUSIONS

The research carried out permitted assesing the impact of hydrated lime on the properties of the AC 16 asphalt concrete mixtures produced with the half-warm mix asphalt technique utilizing foamed bitumen and resulted in the following conclusions:

- the utilization of hydrated lime as a substitute for given fractions of limestone dust (10 and 30%) in HWMA AC 16 asphalt concrete with foamed bitumen produced at lowered temperatures resulted in significant positive changes in its mechanical parameters compared to the reference mixes;
- the use of hydrated lime resulted in an increase in air void content in mixtures produced at reduced temperatures above the values obtained in the reference $HWMA_{Ref}$ mix, however, increasing the amount of asphalt binder by 0.3% allowed to obtain density in Marshall samples comparable to those characterizing the HMA reference mix;
- the addition of hydrated lime as a multifunctional additive resulted in antistripping effects, providing significantly increased moisture and frost resistance of the evaluated HWMA asphalt concrete mixes which was further improved by the increase in bitumen content, outperforming the HMA_{Ref} mix;
- the stiffening effect caused by the addition of hydrated lime had positive impact on the rutting performance of the investigated HWMA mixes with increased bitumen content, reducing the resulting proportional rut depth and improving the wheel tracking slope of the $HWMA_{HL30\%,B4.8\%}$ mix.

The utilized simultaneous optimization of the volumetric and mechanical properties allowed for compound assessment of the addition of hydrated lime on the performance of the HWMA mixture. By the means of the desirability index it was objectively shown that the utilization increased bitumen content together with hydrated lime resulted in a significant overall improvement of half-warm mix asphalt mixes intended for binding and basecourses. This modification of the mix composition permitted major improvement in the moisture damage resistance, while at the same time preserving the rutting resistance and ease of compaction which are all crucial properties of HWMA mixtures.

Based on the above findings regarding design features of the HWMA mixtures with foamed bitumen and hydrated lime, it can be concluded that further research should be conducted on the use of hydrated lime as a multifunctional additive for asphalt mixtures produced at reduced temperatures for binder and basecouses including its impacts on the performance characteristics of these mixtures..

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