The Influence of Hydrated Lime on IT-CY Stiffness Modulus of Foam-Based Asphalt Concrete Compacted at 95 °C

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Abstract. For a number of years worldwide, the road construction industry has been seeking new technologies for producing energy-saving asphalt mixtures in order to meet new environmental requirements and laws. Some of these techniques include new classes of mixtures characterized by reduced processing temperatures compared to the conventional Hot Mix Asphalt (HMA) production temperature of 165 °C and paving temperature of approximately 145 °C. These techniques include Half Warm Mix Asphalt (HWMA) mineral mixtures produced with the use of foamed bitumen as a binder at temperatures of about 100 °C and paved at 95 °C. Although generally HWMA mixes are comparable to HMA, depending on the mix, they may suffer from decreased mechanical parameters resulting in a reduced service life of the asphalt pavement. The implemented research program investigated asphalt concrete (AC 8) with foamed bitumen (HWMA) compacted at 95 °C and the control HMA sample produced and compacted at a regular temperature. A typical 50/70 road paving bitumen modified with 0.6% surface active agent SAA (fatty acid amide) was used as the foamed binder, dosed at 5.6% and 6.2% by weight to the mixture. Mineral filler replacement with hydrated lime at 15% and 30% by weight was evaluated. The content of voids in the asphalt mixture was examined. The indirect tensile stiffness modulus (IT-CY) characterizing the durability of the mixture was measured at -10 °C, 0 °C, 10 °C, 20 °C and 25 °C. The results of statistical analysis showed significant correlations between the mix production technology used and the content of foamed bitumen and hydrated lime in terms of the temperature of stiffness modulus testing. As confirmed by the stiffness modulus values, the application of hydrated lime provided the half-warm mix asphalt concrete AC8 produced with foamed bitumen with mechanical properties comparable to those of the HMA mix.

1. Introduction
Hot Mix Asphalt (HMA) is currently the most common technology employed in Poland for the production of asphalt mixtures designed for use in pavement structural layers. The technology is very energy-intensive, as it requires aggregates and bitumen to be heated to a temperature of 160 °C and higher depending on bitumen type used. A side effect of the production process is that noticeable amounts of harmful greenhouse gases are released to the atmosphere. The growth of environmental awareness, though, has facilitated technological change and the implementation of energy efficient and
eco-friendly asphalt mix technologies. For environmental reasons, interest in the use of Warm Mix Asphalt (WMA) has increased recently [1-4]. WMA mixes are produced at temperatures in the range 120 °C - 140 °C. The temperature reductions are achieved through the use of chemical additives or by lowering the viscosity of the binder with Fischer-Tropsch (FT) synthetic waxes [5, 6] or surface active agents (fatty acid amides). However, significant reductions in the mixing and paving temperatures are only possible with a technological process modification consisting of water based foaming [7, 8]. Jenkins, the forefather of this technology, and his research team [9] have developed the process of producing Half Warm Mix Asphalt (HWMA) with foamed bitumen. The use of this innovative binder allows the lowering of the mix production temperature to about 100 °C and its compaction temperature to 95 °C [10, 11]. To optimize bitumen foam parameters (ER - expansion ratio, HL - half-life time of bitumen foam decay), the bitumen is modified before foaming, by adding low-viscosity modifiers, for example, FT synthetic wax [12]. Different types of additives are capable of improving various mix properties, including the resistance to moisture damage and frost [13, 14] or the stiffness modulus [15, 16]. The stiffness modulus is one of the most important mechanical parameters of asphalt mix that determine the resistance of asphalt surface to the impact of loads from vehicles. The range of additives that are recommended for improving the modulus includes hydrated lime, used in producing HMA for some time now [17-22] and offering promising potential for successful use in HWMA mixtures.

The paper presents the stiffness modulus results determined in the IT-CY test for HWMA with foamed bitumen and hydrated lime in accordance with the guidelines set forth in [23, 24].

2. Tested materials and methodology

2.1. Experimental program

The tests aimed at determining the influence of hydrated lime on the durability of HWMA mixtures with foamed bitumen and that of HMA mixtures for comparative purposes. The AC 8 manufacturing technology effect was analysed based on the values of the parameters below obtained in the procedures set forth in the Technical Requirements WT-2 2014 [24], PN-EN 13108-1:2008:

- air void content \( (V_m, \%) \) to PN-EN 12697-8:2005:
- IT-CY stiffness modulus \( (S_m) \) at -10 °C, 0 °C, +10 °C, +20 °C and +30 °C to PN-EN 12397-26 (Appendix C).

Parameters \( V_m \) and \( S_m \) were determined by compacting the samples with a Marshall hammer using 75 blows on each side. A total of nine specimens satisfying all the assumptions in terms of physical and geometrical characteristics were used.

2.1.1. Air void content \( (V_m) \). The amount of air voids is the total volume of air voids throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture. This parameter was determined in accordance with PN-EN 12697-8:2005 using the formula:

\[
V_m = \frac{\rho_m - \rho_b}{\rho_m} \cdot 100 \% \text{ (1)}
\]

where: \( V_m \) – the air void content in the mix specimen (% (v/v)); \( \rho_m \) – the density of the mix (kg/m³); \( \rho_b \) – the bulk density of the mix (kg/m³).

2.1.2. Stiffness modulus of foamed bitumen asphalt concrete produced in HWMA technologies. The stiffness modulus of the asphalt concrete mixtures was determined based on the test conducted on cylindrical specimens (IT-CY). The test is non-destructive and provides early information about the stiffness of the asphalt concrete mixture under dynamic loading.

The tests for the indirect tensile stiffness modulus were carried out in the Universal Testing Machine (UTM-25) under the following conditions:
- test temperature: -10 °C, 0 °C, 10 °C, 20 °C, 30 °C;
- rise time: 124 ± 4 ms;
- deformation level: 5 μm;
- number of loadings: 5;
- Poisson ratio values (depending on the test temperature): \( \nu=0.25 \) for -10 °C and 0 °C, \( \nu=0.30 \) for 10 °C and \( \nu=0.30 \) for 20 °C and 30 °C.

### 2.2. Materials and mix design procedure

The asphalt concrete mix in terms of grain size, type of aggregates used and the type and amount of asphalt binder was designed based on the Polish requirements for AC 8 wearing course mixes for KR1 to KR4 traffic loads [23, 24] (20-year design pavement life of \( 0.03 \times 10^6 < \text{ESAL}_{100kN} \leq 7.30 \times 10^6 \) in accordance with the Polish standards [24]).

Table 1 compiles the components of the mineral and asphalt mixtures. The design grading of the AC8 mineral mixture is shown graphically in Figure 1.

#### Table 1. Composition of AC 8 mixture

| Materials                                | Mineral mixture (% m/m) | Asphalt mixture (% m/m) |
|-------------------------------------------|-------------------------|--------------------------|
| Filler (limestone aggregate)              | 7.0                     | 6.6                      |
| Crushed fine continuously graded aggregate 0/2 mm | 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                      |

![Figure 1. Grading curve of AC 8 mineral mix with limiting points as in Polish requirements WT-2 2014 [24]](image)

To ensure a high level of mechanical characteristics, the hydrated lime was added at 15% and 30% as a replacement of the equivalent amount of limestone filler.

For laboratory testing, 5.6% and 6.2% bitumen 50/70 were incorporated in the conventional HMA mixes for the wearing course in compliance with requirements [23, 24]. For the application in HWMA, the bitumen was modified with a 0.6% surface active agent (fatty acid amide) by mass of the binder, followed by foaming in the presence of water. The properties of the modified bitumen allow
the production of a low temperature asphalt concrete and the improvement of the resistance to moisture and permanent deformation in WMA mixtures [17].

The results for selected characteristics of unmodified bitumen 50/70 and bitumen 50/70 modified with the 0.6% surface active agent (SAA) are summarized in Table 2.

| Property                  | Unit         | Testing method | Bitumen 50/70 | Bitumen 50/70 + 0.6 |
|---------------------------|--------------|----------------|---------------|---------------------|
| Penetration at 25°C       | 0.1mm        | PN-EN 1426     | 65.9          | 70.4                |
| Softening point           | °C           | PN-EN 1427     | 50.4          | 49.8                |
| Fraass breaking point     | °C           | PN-EN 12593    | -15.1         | -13.2               |
| Plasticity range          | °C           | -              | 65.5          | 63.0                |
| Penetration Index         | -            | EN 12591       | -0.6          | -0.4                |

Figure 2 illustrates the characteristics of bitumen 50/70 and bitumen 50/70 with a 0.60% surface active agent content subjected to foaming.

![Figure 2](image_url)

**Figure 2.** Characteristics of foamed bitumen produced with unmodified bitumen 50/70 (a) and bitumen 50/70 modified with 0.6% surface active agent (b)

The characteristics above allowed establishing the optimal foaming water content (FWC):
- For bitumen 50/70: \( FWC = 2.5\% \), \( ER = 10 \), \( HL = 10 \) s,
- For bitumen 50/70+0.6% SPC: \( FWC = 2.5\% \), \( ER = 20 \), \( HL = 20 \) s.

3. Test results and analysis

3.1. Air void content

The level of asphalt mix compaction is measured through its air void content determined in the test using 75 blows per face regardless of the mix production technology. An adequate amount of air in laboratory samples and in the produced asphalt layer is essential for providing sufficient resistance to different weather conditions and traffic loads. Low air voids in the mixtures are associated with a reduced resistance of the surface to permanent deformations, while too high of an air void content results in reduced resistance of the asphalt mixture to moisture and frost damage. In HWMA technology with foamed bitumen, the optimal compaction for preventing the asphalt layer against moisture damage is of critical importance.
Table 3 summarizes the obtained basic statistical quantities. Figure 3 compiles the average values of air void contents $V_m$ in the asphalt concrete.

**Table 3. Descriptive statistics for $V_m$**

| A (%) | Type of the AC | HL (%) | N | Mean  | Std. Dev. | Coef.  | Min | Max |
|-------|----------------|--------|---|-------|-----------|--------|-----|-----|
| 5.6   | AC-1           | 0      | 9 | 4.67  | 0.201     | 4.303  | 4.29| 4.91|
|       | AC-2           | 15     | 9 | 3.51  | 0.500     | 14.264 | 2.61| 4.08|
|       | AC-3           | 30     | 9 | 4.39  | 0.483     | 10.998 | 3.90| 5.19|
| 6.2   | AC-4           | 0      | 9 | 2.53  | 0.578     | 22.816 | 2.01| 3.88|
|       | AC-5           | 15     | 9 | 2.09  | 0.275     | 13.154 | 1.50| 2.44|
|       | AC-6           | 30     | 9 | 2.70  | 0.587     | 21.763 | 1.91| 3.90|

Figure 3. Mean air void content $V_m$ for AC mixtures

Analysis of the results indicates that the highest average air void content ($V_m$=4.67%) was recorded for the HWMA mixture with a 5.6% foamed bitumen content. Increasing the bitumen content up to 6.2% reduces the amount of air in the asphalt concrete ($V_m$=2.53%). The hydrated lime blended in as a 15% limestone filler replacement has a positive effect on the air void content reduction, regardless of the amount of bitumen used in the asphalt concrete AC8. The lime amount that increased to 30% causes air void content to increase within the bitumen content range under analysis. The percentage amount of air in AC2, AC4, AC5 and AC6 mixtures is from 2.0% do 4.0% as required for AC 8 mixtures designed for use in the wearing course of KR3-4 pavement ($0.50x10^6 < ESAL_{100kN} \leq 7.30x10^6$ in accordance with the Polish standards [23]).

Table 4 summarizes the results for the effect of bitumen and lime content on the amount of air voids $V_m$ in the asphalt concrete.

The values of statistical parameters in Table 4 indicate that the bitumen and hydrated lime have a significant effect on the amount of air in the asphalt concrete AC8. No synergy effect has been observed of the lime and bitumen content on $V_m$. 
Table 4. Results of the analysis of variance (two-way ANOVA) for $V_m$

| Effect | Univariate Tests of Significance for $V_m$ (%) (MPa) | Sigma-restricted parameterization, Effective hypothesis decomposition |
|--------|------------------------------------------------------|------------------------------------------------------------------|
|        | SS                                                  | D.F.    | MS            | F         | p            |
| Intercept | 527.9391                                           | 1       | 527.9391      | 2476.405  | 0.000000     |
| Bitumen content B (%) | 36.7546                                           | 1       | 36.7546       | 172.405   | 0.000000     |
| Hydrated lime HL content (%) | 6.4623                                            | 2       | 3.2312        | 15.156    | 0.000011     |
| B content (%)*HL content (%) | 1.0698                                            | 2       | 0.5349        | 2.509     | 0.093462     |
| Error   | 8.9539                                              | 42      | 0.2132        |           |              |

3.2. Stiffness modulus of foam-based asphalt concrete

The values of the stiffness modulus descriptive for AC 8 are summarized in Table 5. Figure 4 shows the average values for the relationship between the stiffness modulus and bitumen content (5.6% and 6.2%).

Table 5. Descriptive statistics for $S_m$

| Type of mix | A (%) | HL (%) | Valid N | Mean | Minimum | Maximum | Std. Dev. | Coef. Var. |
|-------------|-------|--------|---------|------|---------|---------|-----------|------------|
|             |       |        | $S_{m(10{\degree}C)}$ (MPa) |       |         |         |           |            |
| AC-1        | 0     | 9      | 2383.10 | 2245.19 | 2531.33 | 870.814 | 3.65411   |            |
| AC-2        | 5.6   | 9      | 26445.56 | 22165.50 | 28677.50 | 2045.080 | 7.73317   |            |
| AC-3        | 30    | 9      | 27409.31 | 24739.00 | 30552.00 | 1473.677 | 5.37656   |            |
| AC-4        | 0     | 9      | 26733.63 | 25667.50 | 28120.50 | 797.876  | 2.98454   |            |
| AC-5        | 6.2   | 9      | 27155.13 | 25356.00 | 29747.00 | 1375.513 | 5.06539   |            |
| AC-6        | 30    | 9      | 30055.13 | 25502.50 | 31887.50 | 2179.954 | 7.25319   |            |
|             |       |        | $S_{m(0{\degree}C)}$ (MPa) |       |         |         |           |            |
| AC-1        | 0     | 9      | 12758.80 | 11552.45 | 13749.85 | 748.895  | 5.86964   |            |
| AC-2        | 5.6   | 9      | 16364.00 | 13855.50 | 18081.50 | 1351.323 | 8.25790   |            |
| AC-3        | 30    | 9      | 17404.94 | 15920.50 | 18535.00 | 764.726  | 4.39373   |            |
| AC-4        | 0     | 9      | 18548.25 | 15908.00 | 23241.50 | 2271.289 | 12.24530  |            |
| AC-5        | 6.2   | 9      | 20658.75 | 17323.00 | 22804.00 | 1769.251 | 8.56417   |            |
| AC-6        | 30    | 9      | 6644.13  | 5668.00  | 7938.50  | 812.048  | 12.22205  |            |
|             |       |        | $S_{m(+10{\degree}C)}$ (MPa) |       |         |         |           |            |
| AC-1        | 0     | 9      | 6644.13  | 5668.00  | 7938.50  | 812.048  | 12.22205  |            |
| AC-2        | 5.6   | 9      | 16364.00 | 13855.50 | 18081.50 | 1351.323 | 8.25790   |            |
| AC-3        | 30    | 9      | 17404.94 | 15920.50 | 18535.00 | 764.726  | 4.39373   |            |
| AC-4        | 0     | 9      | 18548.25 | 15908.00 | 23241.50 | 2271.289 | 12.24530  |            |
| AC-5        | 6.2   | 9      | 20658.75 | 17323.00 | 22804.00 | 1769.251 | 8.56417   |            |
| AC-6        | 30    | 9      | 2345.69  | 2005.00  | 2634.50  | 188.529  | 8.03726   |            |
|             |       |        | $S_{m(+20{\degree}C)}$ (MPa) |       |         |         |           |            |
| AC-1        | 0     | 9      | 3482.13  | 2416.50  | 4283.50  | 536.396  | 15.40246  |            |
| AC-2        | 5.6   | 9      | 4697.69  | 3234.50  | 5059.50  | 284.319  | 6.05235   |            |
| AC-3        | 30    | 9      | 2383.10  | 1995.00  | 2531.33  | 1182.048 | 9.83877   |            |
| AC-4        | 0     | 9      | 2383.10  | 1995.00  | 2531.33  | 1182.048 | 9.83877   |            |
| AC-5        | 6.2   | 9      | 2383.10  | 1995.00  | 2531.33  | 1182.048 | 9.83877   |            |
| AC-6        | 30    | 9      | 2383.10  | 1995.00  | 2531.33  | 1182.048 | 9.83877   |            |
Figure 5 illustrates the stiffness modulus as a function of AC 8 (bitumen and hydrated lime contents).

Figure 4. AC8 stiffness modulus versus bitumen content of a) 5.6% and b) 6.2%

From the data in Table 6, Figure 4 and Figure 5 it follows that the stiffness modulus increases considerably with decreasing temperature, regardless of the amount of bitumen and hydrated lime used. The modulus values are the highest at a 30% hydrated lime content with the temperature range under analysis. Compared to the control HWMA, higher stiffness modulus values within the range from -10 °C to 0 °C is undesirable as they may raise the potential for low temperature cracking. The addition of hydrated lime to the AC 8 mixture has a desirable effect on the stiffness modulus at temperatures above 0 °C regardless of the bitumen content. The hydrated lime acts as a stiffening agent at service temperatures above 0 °C, thus improving the resistance of the asphalt pavement to permanent deformations – rutting.

Figure 6 shows the average values of the stiffness modulus for AC 8 being analysed. Analysis of the stiffness modulus tests for AC 8 shows an interesting trend – the grouping of all the modulus values in the range of -10 °C to 0 °C, irrespective of the bitumen and hydrated lime contents. At temperatures above 0 °C, the modulus values are grouped according to the bitumen content (5.6% and 6.2%).
The impact of the significance of the factors being investigated – bitumen and hydrated lime contents – on the stiffness modulus of AC 8 is shown in Tables 6, 7, 8, 9 and 10.

**Table 6.** Results of the analysis of variance (two-way ANOVA) for Sm (-10 °C)

| Effect                        | Univariate Tests of Significance for Sm (-10 °C) (MPa) | Sigma-restricted parameterization. Effective hypothesis decomposition |
|-------------------------------|------------------------------------------------------|---------------------------------------------------------------------|
|                               | SS         | D.F. | MS            | F             | p               |
| Intercept                     | 3.483225E+10 | 1    | 3.483225E+10 | 14520.26      | 0.000000        |
| Bitumen content B (%)         | 5.221599E+07 | 1    | 5.221599E+07 | 21.77        | 0.000031        |
| Hydrated lime content HL (%)  | 9.567033E+07 | 2    | 4.783517E+07 | 19.94        | 0.000001        |
| B content (%)*HL content (%)  | 1.149909E+07 | 2    | 5.749545E+06 | 2.40         | 0.103355        |
| Error                         | 1.007527E+08 | 42   | 2.398873E+06 |              |                 |

**Table 7.** Results of the analysis of variance (two-way ANOVA) for Sm (0 °C)

| Effect                        | Univariate Tests of Significance for Sm (0 °C) [MPa] | Sigma-restricted parameterization. Effective hypothesis decomposition |
|-------------------------------|------------------------------------------------------|---------------------------------------------------------------------|
|                               | SS         | D.F. | MS            | F             | p               |
| Intercept                     | 1.369078E+10 | 1    | 1.369078E+10 | 6717.045      | 0.000000        |
| Bitumen content B (%)         | 9.132463E+07 | 1    | 9.132463E+07 | 44.806        | 0.000000        |
| Hydrated lime content HL (%)  | 1.962238E+08 | 2    | 9.811192E+07 | 48.136        | 0.000000        |
| B content (%)*HL content (%)  | 2.352681E+06 | 2    | 1.162840E+06 | 0.571         | 0.569551        |
| Error                         | 8.560500E+07 | 42   | 2.038214E+06 |              |                 |

**Table 8.** Results of the analysis of variance (two-way ANOVA) for Sm (+10 °C)

| Effect                        | Univariate Tests of Significance for Sm (+10 °C) [MPa] | Sigma-restricted parameterization. Effective hypothesis decomposition |
|-------------------------------|------------------------------------------------------|---------------------------------------------------------------------|
|                               | SS         | D.F. | MS            | F             | p               |
| Intercept                     | 2.940005E+09 | 1    | 2.941005E+09 | 4932.949      | 0.000000        |
| Bitumen content B (%)         | 2.512778E+06 | 1    | 2.512778E+06 | 4.215         | 0.046339        |
| Hydrated lime content HL (%)  | 1.286770E+08 | 2    | 6.438489E+07 | 107.915       | 0.000000        |
| B content (%)*HL content (%)  | 5.431341E+06 | 2    | 2.715670E+06 | 4.555         | 0.016204        |
| Error                         | 2.504023E+07 | 42   | 5.961960E+05 |              |                 |
| Effect | Univariate Tests of Significance for Sm (+20°C) [MPa] | Sigma-restricted parameterization. Effective hypothesis decomposition |
|--------|-----------------------------------------------------|---------------------------------------------------------------|
|        | SS        | D.F. | MS    | F       | p        |
| Intercept | 506401289 | 1    | 506401289 | 3312.219 | 0.000000 |
| Bitumen content B(%) | 3255280 | 1    | 3255280 | 21.292  | 0.000037 |
| Hydrated lime content HL(%) | 38501510 | 2    | 19250755 | 125.913 | 0.000000 |
| B content (%)*HL content (%) | 869136 | 2    | 434568 | 2.842   | 0.069545 |
| Error | 6421332 | 42   | 152889 |

Table 10. Results of the analysis of variance (two-way ANOVA) for Sm (+30°C)

| Effect | Univariate Tests of Significance for Sm (+30°C) [MPa] | Sigma-restricted parameterization. Effective hypothesis decomposition |
|--------|-----------------------------------------------------|---------------------------------------------------------------|
|        | SS        | D.F. | MS    | F       | p        |
| Intercept | 116174401 | 1    | 116174401 | 7894.780 | 0.000000 |
| Bitumen content B(%) | 17553 | 1    | 17553 | 1.193  | 0.280987 |
| Hydrated lime content HL(%) | 6831393 | 2    | 3415697 | 232.118 | 0.000000 |
| B content (%)*HL content (%) | 2911 | 2    | 1455 | 0.099   | 0.906039 |
| Error | 618044 | 42   | 14715 |

Analysis of the parameters shown in Tables 6, 7, 8, 9, 10 indicates that the bitumen and hydrated lime have a significant effect on the stiffness modulus of AC8 at -10 °C to 0 °C. A noticeable lime and bitumen synergy effect on the AC8 stiffness modulus can be observed at +10 °C. Also at +30 °C the lime substantially influences the value of the modulus.

4. Conclusions
Analysis of the test results leads to the following conclusions:
- The use of hydrated lime has a substantial effect on the air void content in HMA concrete produced with foamed bitumen and surface active agents (fatty acid amides).
- The addition of 15% hydrated lime to AC 8 containing 5.6% bitumen and the addition of 30% hydrated lime to AC 8 containing 6.2% bitumen provide the optimal amount of air in the asphalt concrete.
- Between -10 °C and +30 °C, hydrated lime increases the stiffness modulus of asphalt concrete.
- Regardless of the amount of bitumen used (5.6% and 6.2%), the addition of 30% hydrated lime to AC 8 increases the stiffness modulus considerably at temperatures from -10 °C to 0 °C compared to the control HWMA, thus being a factor in low temperature cracking of asphalt pavements. At higher temperatures, this amount of hydrated lime will increase the pavement resistance to permanent deformation.
- The addition of hydrated lime to HWMA with foamed bitumen is an efficient tool for controlling the foam properties at temperatures below and above 0 °C.

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