Investigating the use of moist aggregates in the production of low-temperature bituminous mixtures using foamed bitumen

Piotr Ramiaczek¹, Anna Chomicz-Kowalska¹, Krzysztof Maciejewski¹, Mateusz M. Iwanski², Justyna Stepień¹

¹Department of Transportation Engineering, Faculty of Civil Engineering and Architecture, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
²Department of Building Engineering Technologies and Organization, Faculty of Civil Engineering and Architecture, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

piotrr@tu.kielce.pl

Abstract. The use of moist/wet aggregate fractions in the asphalt mixtures with reduced production and compaction temperatures (HWMA - Half Warm Mix Asphalt) with foamed bitumen is aimed at obtaining an additional foaming effect of the binder. The paper presents results of investigations on the possibility of producing the asphalt concrete for the upper layers of the road pavement at reduced technological temperatures utilizing fine wet aggregates and foamed asphalt in opposition to specific patented solutions. This modification of the production process was evaluated in the scope of moisture content in the 0/4 mm aggregates in terms of mixture compactibility using the gyratory compactor and the assessment of related physical and mechanical properties of the asphalt mixtures. The analysed moisture contents resulted in a final 1% and 3% water contents in the whole mineral mix. In order to assess the effect of the addition of wet aggregates on the properties of the mixture produced at the reduced temperature with foamed bitumen, three identical asphalt concrete AC 16 mixtures in terms of composition were used, hot-mix HMAREF and warm-mix WMAREF, with differences only in technological temperatures of the mix constituents during their preparation and mix compaction, the form of the binder (liquid in HMAREF mixture, foamed with water in WMAREF mixtures) and half-warm mix HWMA with foamed bitumen additionally utilizing a portion of fine wet aggregates in the blends. The conducted studies have shown that the presence of the wet aggregates in the mixtures with foamed bitumen had a significant impact on the air void contents in the samples formed in the gyratory compactor. In a mixture with foamed bitumen, produced and compacted at a reduced temperature (HWMA), an improvement in the compaction in relation to the reference mixture WMAREF was found. Based on the results of indirect tensile strength tests and analysis of the ITSR indices, it was found that the use of wet aggregates had major, significant effects on the mechanical properties of the samples subjected to water and frost susceptibility testing. The mixture produced with wet aggregates obtained indices for resistance to the moisture and frost damage which were unsatisfying for the upper bituminous pavement courses as for Polish climatic conditions (ITSR<70%). This result was attributed to inadequate the aggregate coating and reduced adhesion of the binder. It was stated that the mixtures resembling HWMA, produced with moist or wet aggregates at reduced technological temperatures can be utilized in Polish and similarly harsh climatic conditions in the lower pavement structural layers, mainly due to their reduced moisture and frost resistance. The application of the tested mixtures to the upper structural layer would require using special
treatments, e.g. chemical additives, in order to improve the adhesion of asphalt to aggregate or raise the technological temperature (as for WMA blends) to increase the dynamics of water evaporation from the damp aggregates.

1. Introduction

Research focused on the technological development of asphalt mixtures with reduced production and compaction temperatures (using HWMA - Half Warm Mix Asphalt compacted at temperatures lower than 100°C) is in line with the general direction of European efforts aimed at environmental protection by reducing the amount of energy required to produce materials and limiting the industrial emissions of greenhouse gases. The quickest technological progress, at the moment, is observed in the group of warm mix asphalt (WMA) production techniques, which primarily use F-T synthetic waxes or Montan wax and chemical compounds produced from fatty acid amides – advanced adhesion agents. Research in this regard was started in Germany, France, Benelux countries, Scandinavia and in the USA and Canada [1]. Also in Poland, there are several research centres that conduct such research. This technology can be used to reduce the temperature during production and placement of asphalt concrete by approximately 20°C–30°C.

The first attempt at reducing the production temperature of a bituminous mixture with the use of foamed bitumen was made in 1956 by prof. Ladis Csanyi at the Iowa State University in the United States of America [2]. An innovative bituminous binder, i.e. foamed bitumen, was used during these efforts. Since then, the foaming technology has been used in various countries, including the USA, Australia and Europe, and also in Poland, primarily in deep cold recycling. Wax additives, in turn, have been used for the last twenty years primarily to improve the workability of asphalt mixtures. It was not until a dozen or so years ago that the reduction of the production and paving temperature of asphalt mixtures had become a priority. Low-viscosity modifiers were used in order to reduce this temperature, such as fatty acid amides, Fisher-Tropsch or Montan wax [3-5]. There were also experiments involving other advanced materials and foaming technologies [6-12].

One of the methods of producing WMA mixtures using foamed bitumen was to add cold wet fine aggregates to initiate bitumen foaming. The increased bitumen volume results in the aggregate particles being coated with thicker bitumen film, improving the workability of the mixture [13].

However, the presented technologies do not guarantee that the produced asphalt mixture will have parameters conforming to the requirements for hot-mix asphalt. In particular, it is important that the asphalt mixture has suitable functional properties and required resistance to permanent deformation and as well as the resistance to water and frost.

2. Purpose and methodology of research

The subject of the investigation was the use of wet aggregates in asphalt mixtures produced and compacted at low temperatures using the “half-warm” methods with bitumen foamed with water.

The purpose of the laboratory tests was to assess the possibility of producing asphalt concrete at reduced technological temperatures using wet aggregates and foamed bitumen without using any specific proprietary solutions. This assessment also included the impact of this modification of the production process on the compactibility of the asphalt mixture and on related physical and mechanical properties of asphalt mixtures with a variable amount of water added to the 0/4 mm aggregate, resulting in a final 1% and 3% water content in the whole mineral mix. The presence of moisture in the aggregate should contribute to additional foaming of the binder, but it may also reduce adhesion and, consequently, adversely affect the water and frost resistance of the asphalt mixture.
The scope of the research activities included studies of the following physical and mechanical properties of the asphalt mixture:

- density $\rho_{mv}$ in acc. to PN-EN 12697-5:2010 [14],
- volumetric density $\rho_{bssd}$ in acc. to PN-EN 12697-6:2012 [15],
- air void content $V_m$ in acc. to PN-EN 12697-8:2005 [16],
- indirect tensile strength $ITS_i$ in the air-dry state in acc. to TG-2 2014 (Appendix no. 1) and in acc. to PN-EN 12697-12:2008 [17],
- indirect tensile strength $ITS_{freeze-thaw}$ after one freeze-thaw cycle in acc. to TG-2 2014 (Appendix no.1) and in acc. to PN-EN 12697-12:2008 [17],
- moisture and frost damage indices $ITSR$ in acc. to TG-2 2014 (Appendix no.1) and in acc. to PN-EN 12697-12:2008 [17].

Other analysed aspects included the compaction performance of asphalt mixtures in a gyratory compactor.

3. Materials, mix design procedure and production and compaction conditions

3.1. Materials

In order to assess the effect of wet aggregates addition on the properties of the mixture produced at reduced temperature with foamed bitumen, three AC 16 asphalt concrete mixtures were used, with composition identical to the reference mixture produced using the hot-mix method ($HMA_{REF}$) and warm-mix method ($WMAREF$), with differences only in technological temperatures of the ingredients and the asphalt mixture during their production and compaction, the form of the binder (liquid for the $HMA_{REF}$ mixture, foamed with water for $WMAREF$ mixtures) and the addition of wet aggregate to HWMA mixtures (as well as the method used to add it).

The same 35/50 paving-grade bitumen was used in all asphalt mixtures, and the content of the surfactant additive (Wetfix BE, WBE) in relation to the mass of the binder was 0.3% in the $HMA_{REF}$ reference mixture and 0.6% in the mixtures produced and compacted at reduced temperatures with foamed bitumen.

Wet material – 0/4 mm continuously graded natural aggregate whose content in the asphalt mixture was 15% – was added to the mixtures produced and compacted at reduced temperature using the foamed bitumen technology. The water content in relation to the entire mineral mixture was 1% and 3%.

Further in this paper, the asphalt mixtures are referred to as follows:

- $HMA_{REF}$ reference asphalt mixture produced using the hot-mix method with 35/50 bitumen, including an adhesion agent in the amount of 0.3% (m/m);
- $WMAREF$ reference asphalt mixture produced using the “warm” method with foamed bitumen produced from 35/50 binders, including an adhesion agent in the amount of 0.6% (m/m);
- $HWMA_{MA1}/HWMA_{MA3}$ asphalt mixture produced at reduced temperature with foamed bitumen made from 35/50 binders, including an adhesion agent in the amount of 0.6% (m/m), containing 0/4 mm wet aggregate corresponding to the water content of the mineral mixture of 1% in $HWMA_{MA1}$ and 3% in $HWMA_{MA3}$.

The properties of the surfactant used for the 35/50 bitumen (WBE), which was added in the liquid form, are specified in table 1. The results of tests of the bituminous binders used for asphalt mixtures are included in table 2, and the foaming performance of the 35/50 bitumen with 0.6% of the WBE
agent are shown in figure 1. The additive was used with the bitumen based on the author’s experience for ensuring workability and compactibility of mixtures with reduced technological temperatures. Also, the composition of the AC 16 mixture included acid aggregates (quartzites); consequently, in order to improve the wettability of the aggregate with the bituminous binder and, consequently, improve the conditions to achieve suitable adhesion, it was appropriate to use the additive.

Table 1. Properties of Wetfix BE surface active agent [18], [19]

| Property             | Unit     | Value          |
|----------------------|----------|----------------|
| Appearance           | -        | brown liquid   |
| Flowing point        | °C       | < 0            |
| Viscosity at 20°C    | mP       | 3000           |
| Viscosity at 50°C    | cP       | 400            |
| Amine number         | mg HCl/g | 159 - 185      |
| Acid number          | mg KOH/g | < 10           |
| Solidifying point    | °C       | < 0            |
| Flash point          | °C       | >218           |

Table 2. Basic properties of 35/50+0.3% WBE and 35/50+0.6% WBE asphalt binders used in the investigated HMA_ref, WMA_ref, HWMA_MA1 and HWMA_MA3 asphalt mixes

| Variable                        | WBE percentage (%) | Descriptive Statistics |
|---------------------------------|--------------------|------------------------|
| Penetration in 25°C (0,1 mm)    |                    | Valid N | Mean | Min. | Max. | Std. Dev. | Coef. Var. |
| 0.3                             | 10                 | 40.8     | 38.3 | 43.6 | 1.590 | 3.903     |
| 0.6                             | 10                 | 41.5     | 40.3 | 43.2 | 0.952 | 2.298     |
| Softening point (R&B) (°C)      |                    | Valid N | Mean | Min. | Max. | Std. Dev. | Coef. Var. |
| 0.3                             | 4                  | 53.9     | 53.8 | 54.1 | 0.126 | 0.233     |
| 0.6                             | 4                  | 53.7     | 53.6 | 53.8 | 0.082 | 0.152     |
| Fraass breaking point (°C)      |                    | Valid N | Mean | Min. | Max. | Std. Dev. | Coef. Var. |
| 0.3                             | 4                  | -13.3    | -15.0 | -12.0 | 1.528 | -11.456    |
| 0.6                             | 4                  | -12.7    | -13.0 | -12.0 | 0.577 | -4.558     |
Figure 1. The foaming characteristics of the 35/50+0.6% WBE asphalt binders used for foaming in WMAREF, HWMAMA1 and HWMAMA3 mixes (Optimum FWC=3.0%, ER=14.1, HL=20.5 s)

3.2. Mix design procedure

The framework composition of all mineral mixtures and asphalt mixtures (HMAREF, WMAREF, HWMAMA1 and HWMAMA3) and, consequently, the density of the mineral mixtures (ρa) were identical – the difference was in the addition of wet aggregate to HWMA mixtures (two moisture levels: 1.0% and 3.0%) and in the quantity of the surfactant added to the bitumen, i.e. 0.3% (m/m) for the HMA mixture and 0.6% (m/m) for WMA and HWMA mixtures. Bitumen content was equal in all mixtures and is specified in table 3.

The experiments utilized asphalt concrete designed with a maximum aggregate size of 16 mm, i.e. AC 16 mix for binding and base courses of pavements with 0.5 – 7.3 million equivalent single axle loads (100 kN) in accordance to PN-EN-13108-1:2008 [21] and technical requirements TG-2 2014 [20].

The test results of the reference AC 16 mix were used in this study to assess the utilization of the wet aggregates in the production of a half-warm mix with foamed bitumen.

Table 4 contains a reference to the mineral materials used in this study along with their grading obtained by the methods of air jet sieving (filler aggregates) in acc. to PN-EN 933-10 [22] and conventional sieving of fine and coarse aggregates in acc. to PN-EN 933-1 [23]. Figure 2 represents the final grading of the mineral mix along with the boundary grading points.

Table 3. Framework composition of the investigated AC 16 asphalt mixes

| Component                          | Percentage (% m/m) |
|------------------------------------|--------------------|
| Filler aggregate (limestone)       | 3.8                 |
| Fine natural aggregate 0/2 mm (limestone) | 14.3               |
| Continuously graded natural aggregate 0/4 mm (limestone) | 14.3               |
| Coarse aggregate 2/5 mm (quartzite) | 11.5               |
| Coarse aggregate 5/8 mm (quartzite) | 11.5               |
| Coarse aggregate 8/16 mm (limestone) | 40.1               |
| Paving bitumen 35/50               | 4.5 a), b)          |
| Total                              | 100                 |

Surface active agent (Wetfix BE) added in the amount: a) 0.3% (m/m) do HMAREF b) 0.6% (m/m) do WMAREF, HWMAMA1, HWMAMA2

Table 4. The grading of mineral aggregates used in the composition of the investigated AC 16 asphalt mixes

| Component | 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  | 0.1  | 9.2| 25.9|19.8|16.7|16.4|8.3  |3.5   |       |       |        |
| 0/4 mm    | 2.4| 13.3 | 29.0|20.6|11.1|6.7 |3.8 |2.7  |10.4  |       |       |        |
| 2/5 mm    | 11.0|31.9 |45.9|8.4 |0.7 |0.1 |0.2 |0.4  |1.4   |       |       |        |
| 5/8 mm    | 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  |0.1   |0.2   |2.0   |        |
All of the utilized mineral materials fulfilled the requirements stated in appropriate technical documents [20, 24] regarding their use in binding and basecourses in pavements.

3.3. Conditions of production and compaction of asphalt concrete
Recommendations specified in relevant technical documents [20, 24] were adhered to during the design and production of the asphalt mixtures. Before the asphalt mixtures were produced, the aggregates were kept for 4 hours at 170°C (HMA mixture) or 130°C (WMA mixture).

The dry and wet aggregate fractions in the HWMA mixtures were heated separately. The dry 4/16 mm aggregates were dried and kept for 4 hours at 120°C, while the wet 0/4 mm aggregates (without the filler), after initial drying, were mixed with a suitable amount of water, closed in sealed plastic bags and kept for 4 hours at 80°C.

The adhesion agent was added to the bitumen one hour before the production of the asphalt mixture, and it was thoroughly mixed with the binder.

The following technological temperatures were used during the production and compaction of asphalt mixtures:

- reference hot-mix $HMA_{REF}$ (road paving butimen 35/50+0.3%WBE):
  - bitumen temperature 35/50: 170°C,
  - temperature of produced mineral-bitumen mix: 160°C – 170°C,
  - specimen compaction temperature: 140°C – 145°C,
- reference warm-mix $WMA_{REF}$ (road paving butimen 35/50+0.6%WBE):
  - bitumen temperature prior to foaming: 155°C,
  - temperature of produced mineral-bitumen mix: 120°C – 125°C,
  - specimen compaction temperature: ca. 100°C.
– half-warm mixes with wet aggregates $HWMA_{MA1}$ and $HWMA_{MA3}$ (road paving butimen 35/50+0.6%WBE):
  - bitumen temperature prior to foaming: 155°C,
  - temperature of produced mineral-bitumen mix: ca. 95°C
  - specimen compaction temperature: ca. 85°C.

4. Results and discussions

4.1. Results of the analysis of the AC 16 asphalt concrete mixtures compactibility

Firstly, in order to assess the possibility of using wet aggregate and determine its impact on the properties of the AC 16 asphalt concrete mixtures produced at reduced temperatures with foamed bitumen, all mixtures ($HMA_{REF}$, $WMA_{REF}$, $HWMA_{MA1}$, $HWMA_{MA3}$) were subject to compactibility tests in a gyratory compactor in accordance with PN-EN 12697-31 [25].

Figure 3 and table 5 present the compactibility curves of the tested reference mixtures ($HMA_{REF}$ and $WMA_{REF}$) and the mixtures produced with an addition of water to 0/4 mm aggregates in the amount of 1% and 3% in relation to the mineral mixtures ($HWMA_{MA1}$ and $HWMA_{MA3}$, respectively).

![Figure 3. Results of the analysis of compactibility conducted in the gyratory compactor](image)

| Number of gyrations | Air void content $V_m$ (%) |
|---------------------|-----------------------------|
| 10                  | 16.23                       |
| 20                  | 13.69                       |
| 40                  | 11.02                       |
| 80                  | 8.44                        |
| 128                 | 6.76                        |
| 200                 | 5.33                        |
| 320                 | 4.09                        |
| 512                 | 3.12                        |

The analysis of the presented compactibility curves demonstrated that the curve for each of the tested mixtures was similar. The smallest levels of air void content ($V_m$) during the entire compaction process were achieved for the $HWMA_{MA3}$ mixture. After only 80 gyrations, the air void content in the $HWMA_{MA1}$ mixture was smaller (8.40%) than in the $HMA_{REF}$ reference mixture (8.44%). The results show that the presence of the wet aggregates in mixtures with foamed bitumen had a significant impact on the air void content in the samples formed in the gyratory compactor.

4.2. Results of the tests of physical and mechanical parameters of the AC 16 asphalt concrete mixtures

4.2.1. Air void content ($V_m$), indirect tensile strength ($ITS_d$, $ITS_{freeze-thaw}$ – after one freeze-thaw cycle), moisture and frost damage indices with one freeze-thaw cycle ($ITS_R$). Figure 4 shows the average air void contents in the Marshall samples. Figure 5, in turn, presents the results of indirect tensile strength tests for dry samples and conditioned samples with a single freeze-thaw cycle prepared from the tested asphalt mixtures ($HMA_{REF}$, $WMA_{REF}$, $HWMA_{MA1}$ and $HWMA_{MA3}$), which were used to determine the indices of susceptibility to water and frost ($ITS_R$). Results of the tests of physical and mechanical
parameters are presented in the form of bar charts, with standard deviations for the test presented in the form of error bars, and descriptive statistics of the test results have also been included under the figures.

![Figure 4. Results of air void content tests conducted on asphalt mixes](image)

![Figure 5. Results of ITS_d and ITS_freeze-thaw tests conducted on asphalt mixes](image)

The results of air void content ($V_a$) tests of the samples compacted in the Marshall compactor proved the impact of the use of 0/4 mm wet aggregate in the production of mixtures with foamed bitumen on their compaction. Samples made of the $HWMA_{MA1}$ mixture achieved the average air void content ($V_a$) of 4.66% – this was the closest to the result characterising the $HMA_{REF}$ reference mixture. Increasing the water content of the mineral mixture from 1% to 3% in the production of the mixture with foamed bitumen further increased the compaction level and led to the achievement of air void content ($V_a$) of 3.23%. In summary, it should be found that the presence of wet aggregate in the mixture with foamed bitumen, produced and compacted at reduced temperature, improved compaction in relation to the reference mixture $HMA_{REF}$. However, it should be expected that – despite the low value of the $V_a$ parameter in the $HWMA_{MA1}$ and $HWMA_{MA3}$ mixtures, the resistance to water and frost may not be ensured due to the poorer adhesion of the binder to the aggregate. This issue will be discussed later in this analysis.

Regarding the Polish requirements for asphalt mixtures, in turn, which are produced using the conventional hot-mix method in accordance with TG-2 2014 [20] or produced and compacted at reduced temperatures using the foamed bitumen method in accordance with TG-WMA [24], only the $HWMA_{MA1}$ mixture failed to meet the requirements for air void content defined for the binder course (criterion: $4\% \leq V_a \leq 7\%$); however, all mixtures conformed to the requirements for the road base, achieving air void content in the range of 4% to 8%.

The results of indirect tensile strength tests of the samples demonstrated a significant impact of the use of wet aggregates of the 0/4 mm fraction on the mechanical properties of the samples prepared from the tested mixtures. The strength test results for AC 16 mixtures with wet aggregate were much lower than the results for the reference mixtures. Both of the tested mixtures containing wet aggregate achieved similar results of indirect tensile strength tests. For air-dried samples and samples subject to a single freeze-thaw cycle, these differences were 95 kPa and 127 kPa, respectively. The addition of water in the amount of 1% to the $HWMA_{MA1}$ mixture significantly reduced both $ITS_d$ (from 1225.6 kPa to 740.18 kPa) and $ITS_{freeze-thaw}$ (from 1022.2 kPa and 497 kPa) in relation to the $WMA_{REF}$ reference mixture. The
HWMA_{M1} mixture, i.e. the mixture with 3% water content in the mineral mixture during production, received even smaller values of both parameters: $ITS_d$ of 645.03 kPa and $ITS_{freeze-thaw}$ of 370.32 kPa. There was a much greater difference in terms of the assessed parameters of the mixtures with wet aggregates in relation to the hot reference mixture.

The analysis of the values of descriptive statistics (figures 4 and 5) demonstrates that mixtures with reduced technological temperatures that contain wet aggregate added during their production were characterised by higher variability of the results (highest values of variability factors) for all tested parameters ($V_m, ITS_d, ITS_{freeze-thaw}$) in comparison with the reference mixtures.

The results of indirect tensile strength tests of the samples made from the tested asphalt mixtures, in turn, were used to determine the indices of susceptibility to water and frost ($ITSR$), which are depicted in figure 6.

![Figure 6](image)

**Figure 6.** The measured indices of susceptibility to water and frost damage $ITSR$ of the investigated asphalt mixes ($HMA_{REF}, WMA_{REF}, HWMA_{M1}, HWMA_{M3}$)

An analysis of the tests of susceptibility to water and frost demonstrated a significant impact of the water content of the input materials on the levels of $ITSR$ indices characterising the tested asphalt mixtures. HWMA_{M1} and HWMA_{M3} mixtures achieved much smaller values of $ITSR$ indices than the HMA_{REF} and WMA_{REF} reference mixtures, and these results were even worse with the higher water content of the input materials used to produce the mixtures. The HWMA mixture with foamed bitumen, with an addition of 1% of water in the mineral mixture, had $ITSR$ lower by 16.2 percentage points, and the mixture with 3% water content achieved $ITSR$ lower by 26 percentage points than the reference mixture produced and compacted with reduced temperatures ($WMA_{REF}$).

Regarding the requirements of TG-2 2014 [20] used in Poland for AC 16 asphalt concrete mixtures produced with the hot-mix method and the mixtures made in accordance with the TG-WMA [24] guidelines, it can be concluded that HWMA_{M1} and HWMA_{M3} asphalt mixtures, with $ITSR$ of 67.2% and 57.4%, respectively, did not meet the requirements for resistance to water with a single freeze-thaw cycle, both for the binder course ($ITSR \geq 80\%$) and for the base course ($ITSR \geq 70\%$) of a pavement subjected to $0.5 - 7.3$ million equivalent $100$ kN single axle load traffic. Lower values of the $ITSR$ parameter in the samples prepared from mixtures with wet aggregate could be attributed – despite the compaction of the samples being comparable to the compaction of the reference mixtures – to reduced adhesion. Although the wet aggregate contained only a small amount of water film in the pores, this water prevented full covering...
of the aggregate with the bitumen and, consequently, reduced the resistance to water and frost of the entire asphalt mixture.

4.2.2. Statistical analysis of the test results. In order to assess the impact of the use of the wet aggregate of the 0/4 mm fraction (1% and 3% in relation to the mineral mixture) in the asphalt mixtures with foamed bitumen and reduced technological temperatures on their physical and mechanical properties, the test results were subject to the statistical analysis. The analyses included inference on the significance of the differences between the mean values of the considered dependent variables ($V_m$, $ITS_d$, $ITS_{freeze-thaw}$) in the context of the composition and method of producing the asphalt mixture (mixtures: $HMA_{REF}$, $WMA_{REF}$, $HWMA_{MA1}$ and $HWMA_{MA2}$), using analysis of variance (one-way ANOVA). Due to the consistency of the distribution of variables with the normal distribution and fulfilment of the assumption of the uniformity of variance, it was possible to use the parametric $F$ (Fisher-Snedecor) test, which enabled simultaneous comparison of several means. Since significant results were achieved for all variables in the general $F$-test, the specific significance of the difference between the tested groups was estimated using a post-hoc comparison (Tukey’s multiple comparison test) to identify which specific means differed from each other. Table 6 summarises the results of the one-way analysis of variance performed to determine the impact of the type of asphalt mixture on the tested physical and mechanical properties.

**Table 6.** Results of the one-way ANOVA test assessing the significance of the Type of mix factor in regard to the physical and mechanical properties of the mixes ($V_m$, $ITS_d$, $ITS_{freeze-thaw}$)

| Independent variable | Effect       | df<sup>a</sup> | SS<sup>a</sup> | MS<sup>a</sup> | F            | p-value   |
|----------------------|--------------|----------------|---------------|---------------|--------------|-----------|
| $V_m$                | Intercept    | 1              | 801.9203      | 801.9203      | 8847.419     | < 0.0001  |
|                      | Type of mix  | 3              | 28.7668       | 9.5889        | 105.793      | < 0.0001  |
|                      | Error        | 36             | 3.2630        | 0.0906        |              |           |
| $ITS_d$              | Intercept    | 1              | 33024451      | 33024451      | 4765.880     | < 0.0001  |
|                      | Type of mix  | 3              | 3586610       | 1195537       | 172.532      | < 0.0001  |
|                      | Error        | 28             | 194022        | 6929          |              |           |
| $ITS_{freeze-thaw}$  | Intercept    | 1              | 19784300      | 19784300      | 2822.451     | < 0.0001  |
|                      | Type of mix  | 3              | 4255613       | 1418538       | 202.370      | < 0.0001  |
|                      | Error        | 28             | 196269        | 7010          |              |           |

<sup>a</sup> df – degree of freedom, SS – sum of squares, MS - Mean squares.

The analysis of the p-values for the $F$ statistic (table 6) with the assumed significance level ($\alpha = 0.05$) demonstrates that the analysed factor, i.e. asphalt mixture type, had a statistically significant impact on all tested parameters. Since for all considered parameters the $p$-value was smaller than 0.05, it was possible to use multiple comparison tests in order to determine which specific mixtures differed significantly. Table 7 includes the results of Tukey’s multiple-comparison test.

**Table 7.** Results of Tukey multiple comparison tests

| Type of mix | Tukey HSD test, variable $V_m$ (%) | Approximate Probabilities for Post Hoc Tests, Error: Between MS = 0.09064, df = 36 |
|-------------|------------------------------------|--------------------------------------------------------------------------------|
| $HMA_{REF}$ | {1} – 4.41                         | {2} – 5.61 |
| $WMA_{REF}$ | {2} – 0.000159                     | {3} – 0.264528 |
| $HWMA_{MA1}$| {3} – 0.264528                     | {4} – 0.000159 |
| $HWMA_{MA2}$| {4} – 0.000159                     | {5} – 0.000159 |

| Type of mix | Tukey HSD test, variable $ITS_d$ (kPa) | Approximate Probabilities for Post Hoc Tests, Error: Between MS = 6929.4, df = 28 |
|-------------|---------------------------------------|--------------------------------------------------------------------------------|
| $HMA_{REF}$ | {1} – {2} – {3} – {4} – {5}           | {6} – {7} |
| $WMA_{REF}$ | {2} – 0.000159                       | {3} – 0.000159 |
| $HWMA_{MA1}$| {3} – 0.264528                      | {4} – 0.000159 |
| $HWMA_{MA2}$| {4} – 0.000159                      | {5} – 0.000159 |
Multiple-comparison tests showed that, as regards the value of the $V_m$ parameter, there were no statistically significant differences ($p$-value = 0.264158) only between the $HMA_{REF}$ and $HWMA_{MA1}$ mixtures. For the remaining compared pairs of asphalt mixtures, in turn, the observed differences between the values for the analysed properties were statistically significant ($p < 0.0001$).

Also, upon analysis of the results of post-hoc tests for the remaining parameters, it can be found that for the $ITS_{freeze-thaw}$ parameter, all compared pairs differed significantly because the $p$-value was smaller than 0.0001, i.e. smaller than the assumed significance level of 0.05. The differences between the $HWMA_{MA1}$ and $HWMA_{MA3}$ mixtures, in turn, with respect to the $ITS_d$ means were not statistically significant ($p$-value = 0.125650).

5. Conclusions
The conducted studies have shown that the presence of wet aggregates in the mixtures with foamed bitumen had a significant impact on the air void contents in the samples formed in the gyratory compactor. In the mixture with foamed bitumen, produced and compacted at a reduced temperature, an improvement in the compaction in relation to the $WMAREF$ reference mixture was found. Based on the results of the indirect tensile strength tests and analysis of the $ITSR$ indices, it was found that the use of wet aggregates had major, significant effects on the mechanical properties of the samples subjected to the water and frost susceptibility testing. The mixtures produced with wet aggregates had $ITSR$ indices that were unsatisfactory for the upper pavement courses as for Polish climatic conditions. This result was attributed to reduce the adhesion of the bitumen to the aggregate due to the presence of a small amount of water film in the pores.

Due to the properties of the tested asphalt mixtures using wet aggregate and foamed bitumen at reduced technological temperatures, their application in the climate conditions similar to the ones in Poland can be further studied primarily for the lower pavement courses due to the possible reduction of water and frost resistance. The application of the tested mixtures to the upper pavement course would require using special treatments, e.g. chemical additives, in order to improve the adhesion of the bitumen to aggregate or raise the technological temperatures (as for WMA mixtures) to increase the dynamics of water evaporation from the wet aggregates.

Acknowledgements
The results of the study were processed under the project “The use of recycled materials” under the RID (The Development of Road Engineering Innovations number DZP/RID-I-06/1/NCBR/2016) project co-financed by the National Centre for Research and Development – Poland and the Polish General Directorate for National Roads and Motorways.

References
[1] B. Prowell, G. Hurley and B. Frank, “Warm-Mix Asphalt: Best Practices 3rd edition,” National
Asphalt Pavement Association, 2012.

[2] L. H. Csanyi, “Foamed Asphalt in Bituminous Paving Mixtures”, Bulletin No. 160, Vol. 10, Highway Research Board, Washington D.C., USA, pp. 108-122, 1957.

[3] M. Zumanis M., “Warm Mix Asphalt Investigation”. Master of Science Thesis, Technical University of Denmark, 2010.

[4] M. Iwański, Cholewińska M., Mazurek G., “Impact of the Ageing on Viscoelastic Properties of Bitumen with the Liquid Surface Active Agent at Operating Temperatures”, World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium – Wmcaus, IOP Conference Series-Materials Science and Engineering, Vol. 245, 2017.

[5] M. Iwański, G. Mazurek, “Optimization of the Synthetic Wax Content on Example of Bitumen 35/50”, Modern Building Materials, Structures And Techniques, Procedia Engineering, vol. 57, pp. 414-423, 2013.

[6] F. Olard F., V. Gaudefroy, “Laboratory assessment of mechanical performance and fume emissions of lea® half-warm mix asphalt versus traditional hot mix asphalt”. Paper submitted for Presentation and Publication 2nd International Conference on Warm-Mix Asphalt, St Louis, September 7th, 2011.

[7] Wirtgen Group, “Wirtgen Cold Recycling Technology”. 2nd edition, Wirtgen GmbH, Windhagen, Germany, 2004.

[8] WAM Foam, “Asphalt pavements at lower temperatures”, BP, WMA TWG, 2007.

[9] E. Remisova, M. Holy, “Changes of Properties of Bitumen Binders by Additives Application” World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium – Wmcaus, IOP Conference Series-Materials Science and Engineering, vol. 245, DOI: 10.1088/1757-899X/245/3/032003, 2017.

[10] M. Holy, E. Remisova, M. Decky, M. Trojanova, “Fundamental and environmental properties of the asphalt pavement wearing course with rubber modified bitumen” (Conference Paper). International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, vo.: 18, issue 5.2, 2018, pp. 453-460. Bulgaria, 2018.

[11] F. Olard, A. Romier, “Low emission & low energy asphalts for sustainable road construction the european experience of LEA process”.

[12] PN-EN 12697-5:2010 Bituminous mixtures. Test methods. Determination of the maximum density, 2010.

[13] PN-EN 12697-6:2012 Bituminous mixtures. Test methods for hot mix asphalt. Determination of bulk density of bituminous specimens, 2012.

[14] PN-EN 12697-8:2005 Bituminous mixtures. Test methods. Determination of void characteristics of bituminous specimens, 2005.

[15] PN-EN 12697-12:2008 Bituminous mixtures. Test methods. Determination of the water sensitivity of bituminous specimens, 2008.

[16] Technical recommendation IBDiM No. RT/2009-03-0012/1. Adhesion promoters Wetfix BE and Wetfix AP17 for use in traffic engineering”. Warszawa 2014.

[17] WETFIX BE. “Thermally stable liquid adhesion promoter for asphalt binders”. Minova Ekohen S.A., Siemianowice Śląskie 2010.

[18] WT-2 2014 (TG-2 Technical Guideline) – part I. “Asphalt mixes. Technical Requirements”. Appendix to ordinance No. 47 of the General Director of National Roads and Highways 25.09.2014.
[20] PN-EN-13108-1:2008 “Bituminous mixtures. Material specifications. Asphalt Concrete”, 2008.
[21] PN-EN 933-10 “Tests for geometrical properties of aggregates. Assessment of fines. Grading of filler aggregates (air jet sieving”).
[22] PN-EN 933-1 “Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method.”
[23] M. Iwański, A. Chomicz-Kowalska, J. Stępień, K. Maciejewski, P. Ramiączek, M.M Iwański, “Zalecenia dotyczące projektowania, wytwarzania i wbudowywania mieszanek mineralno-asfaltowych z asfaltem spienionym o obniżonych temperaturach technologicznych” ("Recommendations regarding design, production and paving asphalt mixes with foamed bitumen at lowered temperatures"). Politechnika Świętokrzyska (Kielce University of Technology). RID-I/6. NCBiR, GDDKiA. Kielce 2018.
[24] PN-EN 12697-31 “Bituminous mixtures. Test methods. Specimen preparation by gyratory compactor.”