1. Introduction
Low temperature cracking is one of the major distress of asphalt pavements in countries with cold winters. Despite great research effort and practical trials the problem of low temperature cracking of asphalt pavement has not been solved till now. On the contrary, in some countries the problem evidently increased during last few years. Growth of axle load of vehicles and increased volume of heavy traffic caused severe rutting of some asphalt pavements. As a countermeasure harder bitumen started to be used to prevent rutting. Asphalt layers with harder bitumen are more susceptible to low temperature cracking and number of cracks in some asphalt roads increased.

Thermal stresses were measured in laboratory with the use of the Thermal Stress Restrainted Specimen Test (TSRST) according to the AASHTO Standard No. TP 10-93 Standard Test Method for Thermal Stress Restrainted Specimen Tensile Strength. Thermal stresses in restrained asphalt specimen were calculated with temperature dependent stiffness modulus of asphalt concrete. The new approach applied in this paper was that the stiffness modulus of asphalt concrete which was used in calculations was measured in a creep test at low temperatures on the same material which was used in the Thermal Stress Restrainted Specimen Test. Realistic values of stiffness moduli resulted in a good compatibility between calculated and measured thermal stresses. The creep test at low temperatures was performed in bending according to the method worked out at the Gdansk University of Technology. Three types of bitumen were used to produce asphalt concrete. The lowest thermal stresses were induced in the Thermal Stress Restrainted Specimen Test in asphalt concrete with 50/70 multigrade bitumen, next with DE 80B SBS polymer modified bitumen and the highest with 50/70 plain bitumen.

Keywords: thermal stresses, low temperatures, creep test, stiffness modulus.
pavements by Hiltunen and Rogue (1994), AASHTO Standard PP 42-02 Standard Practice for Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders, Qian et al. (2007), Chiasson et al. (2008) and by Faarar et al. (2013).

Recent comprehensive studies on low temperature cracking of asphalt pavements were performed by Zeng (1995), Marasteanu et al. (2004, 2007, 2012), Pszczoła (2006), Vervaecke and Vanelstraete (2008), Zofka et al. (2008), Rajbongshi (2011) and by Prieto-Muñoz (2013). Low temperature behaviour of asphalt concrete with the use of different testing methods was studied by Jung and Vinson (1994), Hiltunen and Rogue (1994), Pszczoła (2006) Marasteanu et al. (2007, 2012), Ceylan et al. (2011), Tabatabaee et al. (2012) and Wang et al. (2013). The applicability of tests to characterize low-temperature properties of binders and mixes with use of TSRST were studied by Sebaaly et al. (2002), Das (2012), Yiqiu et al. (2012) and by Faarar et al. (2013). The factors influencing on behaviour of bitumen during production process were described by Bražiūnas et al. (2010, 2013). Climatic studies which are most important in low-temperature crack prediction were performed by Juknevičiutė-Žilinskienė (2010), Hall et al. (2012) and by Leonovich et al. (2013).

The main aim of this paper was to find out what is the compatibility between thermal stresses measured in laboratory test and calculated with theoretical formula. The second aim was to determine the influence of the type of bitumen (plain, polymer modified and multigrade) on the magnitude of induced thermal stresses.

2. Laboratory testing of thermal stresses and stiffness of asphalt concrete at low temperature

2.1. Tested material

The material used in the tests was 0/16 asphalt concrete designed for the wearing course of pavement. Three types of bitumen, which were commercially produced in a refinery, were used for preparation of mixtures: 50/70 plain bitumen, DE80B SBS polymer modified bitumen and 50/70 multigrade bitumen. The polymer modified bitumen differed from others in significant elastic recovery. The multigrade bitumen had the lowest Fraass breaking temperature. The properties of bitumen are presented in Table 1. Bitumen content in asphalt mix was 5.4% by mass, for each type of bitumen. Voids content in compacted specimens was from 2.9% to 3.2%. Crushed granite aggregate and limestone filler were used. Asphalt concrete was compacted in slabs to achieve required density with a small static roller. Rectangular prisms (50×50×300 mm or 50×50×250 mm) were cut from compacted slabs and conditioned for testing.

2.2. Laboratory testing of thermal stresses induced by cooling (TSRST)

TSRST was carried out according to the procedure of AASHTO Standard No. TP 10-93. The tests were performed in the MTS apparatus. The 50×50×250 mm rectangular prisms cut from compacted slabs were used for testing. Circular steel platens were glued to the specimens to enable gripping them in the frame of the tester. Extensometers were attached to three sides of specimens to measure the specimen displacements. A temperature sensor was attached to the fourth side. This assembly was secured in the strength tester frame and placed in the test chamber with controlled temperature. The specimen prepared for testing and the setup of the MTS apparatus are presented in Fig. 1.

The specimens were placed in the temperature chamber and conditioned for two hours at +5 °C. During the test the temperature was lowered at a rate of 10 °C/h. Lowering of temperature resulted in thermal shrinking, measured with three LVDT sensors. Each time when sample length decreased by more than 0.0025 mm the control system sent a signal to the actuator to maintain the length at a constant level by compensating the strain. Thus the thermal stresses generated in the specimen increased until the strength limit was exceeded and the specimen cracks. A test series consisted of two identical specimens 50×50×250 mm tested in the same conditions. The relationships between thermal tensile stress and temperature obtained in the TSRST for each of two asphalt concrete specimens produced with three types of bitumen are presented in Fig. 2. The test results from two specimens for plain bitumen 50/70 and DE80B SBS polymer modified bitumen were similar, but in case of 50/70 multigrade bitumen differed significantly. The greatest thermal stresses were induced in asphalt concrete with plain bitumen 50/70, next with DE80B SBS polymer modified bitumen and the lowest with 50/70 multigrade bitumen.

Table 1. Properties of plain, polymer modified and multigrade type bitumen

| Properties                                | Standard            | 50/70 plain Before | 50/70 plain After | DE80B SBS polymer modified Before | DE80B SBS polymer modified After | 50/70 multigrade Before | 50/70 multigrade After |
|-------------------------------------------|---------------------|--------------------|------------------|----------------------------------|---------------------------------|------------------------|------------------------|
| Penetration, 25 °C, 0.1 mm                | PN-EN-1426          | 58                 | 39               | 63                               | 45                              | 53                     | 42                     |
| R&B softening point, °C                  | PN-EN-1427          | 50                 | 55               | 51                               | 58                              | 59                     | 67                     |
| Fraass breaking temperature, °C           | PN-EN-12593         | –14                | –                | –15                              | –                               | –24                    | –                      |
| Elastic recovery, %                       | PN-EN-13398-2       | –                  | –                | 92                               | –                               | –                      | –                      |

| Type of bitumen | 50/70 plain Before | 50/70 plain After | DE80B SBS polymer modified Before | DE80B SBS polymer modified After | 50/70 multigrade Before | 50/70 multigrade After |
|-----------------|--------------------|------------------|----------------------------------|---------------------------------|------------------------|------------------------|
| TFOT            | Before             | After            | Before                           | After                           | Before                 | After                 |
| Penetration, 25 °C, 0.1 mm | PN-EN-1426 | 58 | 39 | 63 | 45 | 53 | 42 |
| R&B softening point, °C | PN-EN-1427 | 50 | 55 | 51 | 58 | 59 | 67 |
| Fraass breaking temperature, °C | PN-EN-12593 | –14 | – | –15 | – | –24 | – |
| Elastic recovery, % | PN-EN-13398-2 | – | – | 92 | – | – | – |
2.3. Testing of stiffness modulus of asphalt concrete in creep at low temperature

The schematic view of the test setup is presented in Fig. 3. In this test constant concentrated load was applied at the midspan of a simply supported beam. The specimens were rectangular beams 50×50×300 mm cut from compacted slabs. A test series consisted of two identical specimens tested in the same conditions. The specimens were conditioned in the temperature chamber for at least twelve hours before testing. Constant load was applied for 3600 s followed by 3600 s period of unloading. The strain at the bottom of the beam were recorded with a LVDT sensor both during loading and unloading, i.e. through 7200 s. Different load levels were used for different test temperatures. The level of loading force depended on the testing temperature according to the rule that the generated stresses did not exceed half of the bending strength of a particular asphalt mixture. The bending strength was measured at different temperatures in a separate test developed by Judycki (1990). Bending of specimens was carried out under constant load at the following temperatures: 0 °C, –5 °C, –10 °C, and –15 °C. The example of creep curves of asphalt concrete at temperature –15 °C for loading time of 3600 s and for three tested types of bitumen is presented in Fig. 4. It was observed that at temperature –15 °C all tested mixes exhibit some viscoelastic properties and creep under constant load. The asphalt concrete with plain bitumen was much stiffer than with SBS modified and multigrade bitumen.

The creep test allowed determination of the stiffness modulus of asphalt concrete at different testing temperatures, within loading time, from the following formula:

\[
S(t, T) = \frac{\sigma(T)}{\varepsilon(t, T)}
\]

where \( S(t, T) \) – stiffness modulus as a function of loading time \( t \) and temperature \( T \), MPa; \( \sigma(T) \) – tensile stress at the bottom of a beam in bending under constant load, MPa; \( \varepsilon(t, T) \) – strain at the bottom of a beam developed under constant stress at a given loading time \( t \) and test temperature \( T \).

For the purpose of calculating tensile stresses in restrained asphalt concrete specimens at cooling rate of \( V_T = 10 \text{ °C/h} \) the loading time was determined at \( t = 720 \text{ s} \) (see explanation in Chapter 4). Two identical specimens 50×50×300 mm of asphalt concrete for three types of bitumen, five testing temperatures were tested in a creep test at low temperatures. The results of stiffness moduli at loading time 720 s were averaged and presented in Table 2. The maximum scatter of measured stiffness \( S(t, T) \) from the average value for any given time of loading \( t \) and temperature \( T \) was in a range from 12% to 30%. The detailed results are presented elsewhere (Pszczoła 2006).
3. Calculation of thermal stresses induced by cooling in the restrained specimen

Uniaxial thermal stresses in the restrained asphalt concrete specimen, induced by cooling in the TSRST, were calculated from the following formula:

\[ \sigma(T) = \alpha_T \sum_{i=1}^{n} S(t_i, T_i) \Delta T, \]  

(2)

where \( \sigma(T) \) – accumulated thermal stress at temperature \( T \), MPa; \( \alpha_T \) – coefficient of thermal contraction, assumed to be independent of temperature, \( 1/\degree C \); \( S(t_i, T_i) \) – stiffness modulus depending on the loading time \( t \) and temperature \( T \), MPa; \( \Delta T \) – temperature increment, which was assumed in calculation as \( \Delta T = 2 \degree C \); \( i \) – time and temperature interval, \( i = 1, \ldots, n \).

The formula is similar to the elastic solution but to account for the viscoelastic properties of asphalt concrete the modulus of elasticity \( E \) was replaced by stiffness modulus \( S(t, T) \) as a function of temperature \( T \) and time of loading \( t \). The formula was developed earlier by Hills and Brien (1966) and was used earlier by others to calculate thermal stresses in asphalt layers of pavement structure.

The following assumptions were used in calculation:

– at \( +5 \degree C \) at the beginning of cooling the asphalt specimen is free from thermal stress;

– the drop of temperature below \( +5 \degree C \) is linear in time, as in the TSRST method;

– cooling rate is equal to \( V_T = 10 \degree C/h \), as in the TSRST method;

– the thermal contraction coefficient of asphalt concrete is constant and independent of temperature \( \alpha_T = 2.2 \times 10^{-5} (1/\degree C) \);

– temperature increment for calculation is \( \Delta T = 2 \degree C \);

– time of loading used in calculating is \( t = 720 \) s.

The main problem in calculating thermal stresses from the formula (2) is how to determine the reliable data on stiffness modulus of asphalt concrete \( S(t, T) \). In most of previous research stiffness modulus was determined from the empirical methods, such as Van der Poel (1954) or Heukelom and Klomp (1964) nomographs or from the computer program BANDS worked out by Shell. The novel approach used in this research is that the stiffness modulus \( S(t, T) \) was measured in the laboratory testing of the same material as used in the TSRST method. The laboratory testing method was creep under bending at low temperatures. Data presented in Table 2 were applied in calculations. The values of stiffness moduli at \( 2 \degree C \) increments for intermediate temperatures within testing range were taken directly from tests or were interpolated. The values of stiffness moduli outside the testing range (from \( 0 \degree C \) to \( +4 \degree C \) and from \( -15 \degree C \) to \( -20 \degree C \)) were extrapolated.

The calculation method is simple but has certain disadvantages. The formula (2) is a modification of a formula used for elastic materials. The elastic modulus \( E \) is replaced by stiffness modulus \( S(t, T) \) related to time of loading and temperature what models to some degree viscoelastic behaviour of asphalt concrete, but relaxation of thermal stresses induced by cooling is not fully considered. The second disadvantage is that the loading time \( t \) was arbitrarily assumed. The loading time was calculated by the following formula:

\[ t = \frac{\Delta T}{V_T}, \]  

(3)

where \( t \) – loading time, s; \( \Delta T \) – temperature increment, it was assumed in calculations that \( \Delta T = 2 \degree C \); \( V_T \) – cooling rate, \( \degree C/h \).

For cooling rate of \( V_T = 10 \degree C/h \) the loading time calculated from formula (3) is \( t = 720 \) s. Fig. 5 presents calculated thermal stresses in a restrained asphalt concrete specimens subjected to cooling with a rate of \( 10 \degree C/h \). The results of calculations show that the type of bitumen affects greatly thermal stresses which develop in asphalt specimens. The greatest thermal stresses were calculated in asphalt concrete with plain bitumen 50/70, next with DE80B SBS polymer modified bitumen, and the lowest with 50/70 multigrade bitumen. In Fig. 5 the vertical bars indicate the scatter of calculated stresses resulted from dispersion of results from creep of two tested specimens.

| Temperature during creep test, °C | Stiffness modulus of asphalt concrete depending on type of bitumen at \( t = 720 \) s, MPa |
|----------------------------------|--------------------------------------------------|
| 0                                | 1509, 825, 484                                  |
| -5                               | 2101, 1325, 1015                                |
| -10                              | 4161, 2781, 1524                                |
| -15                              | 8263, 2437, 2126                                |
| -20                              | 13 725, 4474, 3776                              |

Fig. 4. The example of creep curves of asphalt concrete at temperature –15 °C for three tested types of bitumen

Table 2. The values of stiffness modulus of asphalt concrete for different testing temperatures and constant loading time \( t = 720 \) s
4. Comparison of calculated and measured stresses

Figs 6, 7 and 8 present calculated and measured thermal stresses in the TSRST method. Stresses measured in two identical specimens were averaged. Calculated stresses presented in Figs 6, 7 and 8 are based on the stiffness moduli $S(t, T)$ averaged from two measurements in creep test. The Figs 6, 7 and 8 present not only average values but also scatter of calculated and measured stresses indicated by vertical bars. In case of measured thermal stresses for asphalt concrete with modified bitumen DE 80B the scatter for two tested specimens was too small to be seen in Fig. 7.

The calculated thermal stresses for asphalt concrete with the 50/70 plain bitumen were slightly larger than measured stresses. On the contrary, the calculated thermal stresses for the modified bitumen DE 80B and for the multigrade bitumen 50/70 were slightly lower than measured values.

However, the comparison showed satisfactory level of consistency of measured and calculated stresses, which was explained by the fact that the values of stiffness moduli were obtained from laboratory testing of asphalt concrete at low temperature in creep.

The material tested in creep at low temperature was the same as tested in the TSRST method. Realistic values of stiffness moduli applied in calculation in formula (2) resulted in a good compatibility between calculated and measured thermal stresses.

Fig. 9 presents comparison of measured and calculated stresses for three tested asphalt mixes with different bitumen. The coefficient of determination $R^2 = 0.87$ what proves relatively good compatibility between measured and calculated thermal stresses.

5. Conclusions

1. The compatibility of thermal stresses calculated with use of the theoretical formula based on the temperature dependent stiffness modulus with stresses measured in the Thermal Stress Restrained Specimen Test is relatively good.

2. Satisfactory level of consistency between measured and calculated thermal stresses was explained by the
fact that the values of stiffness moduli used in calculations were obtained from laboratory testing of asphalt concrete at low temperature in creep on the same material as tested in the Thermal Stress Restrained Specimen Test method.

3. The creep test at low temperature is a simple and appropriate method to determine parameters of asphalt mixes for evaluation of thermal stresses induced by cooling. The viscoelastic material in creep under long term loading exhibits similar properties as in long term cooling.

4. The rating of bitumen in terms of sensitivity of asphalt concrete to low temperature cracking was the same according to data from measurement and from calculation. The greatest thermal stresses were induced in asphalt concrete with 50/70 plain bitumen, next with DE 80B SBS polymer modified bitumen and the lowest with 50/70 multigrade bitumen. Higher values of thermal stresses indicate greater risk of low temperature cracking in asphalt pavements.

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