



COMPARISON OF CALCULATED AND MEASURED THERMAL STRESSES IN ASPHALT CONCRETE

Marek Pszczoła¹✉, Józef Judycki²

Dept of Highway Engineering, Gdansk University of Technology, Narutowicza str. 11/12, 80–233 Gdańsk, Poland
E-mails: ¹marek.pszczola@wilis.pg.gda.pl; ²jozef.judycki@wilis.pg.gda.pl

Abstract. The paper presents the comparison of calculated and measured thermal stresses induced in restrained asphalt concrete specimens by cooling. Thermal stresses were measured in the Thermal Stress Restrained Specimen Test. The calculations of thermal stresses were performed with the use of a theoretical formula based on the temperature dependent stiffness modulus. The novel 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 Restrained 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 developed 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 Restrained 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.

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 Restrained Specimen Test (TSRST) according to the AASHTO Standard No. TP 10-93 Standard Test Method for Thermal Stress Restrained 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. 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 Technical University by Judycki (1990) and modified by Pszczoła and Judycki (2009).

The problem of low temperature cracking was a subject of extensive research for a few decades, mostly in the USA, Canada, Russia and in northern European countries. The first simple laboratory method of measurement of thermal stresses in restrained asphalt concrete specimens was developed by Monismith *et al.* (1965). After some years much more sophisticated technique of thermal stress measurement was developed by Arand (1990) and this method was the basis of the AASHTO Standard No. TP 10-93 and of the new European Standard EN 12697-46: 2012 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 46: Low Temperature Cracking and Properties by Uniaxial Tension Tests.

The first calculations of thermal stresses in asphalt layers based on the theory of viscoelasticity were presented by Monismith *et al.* (1965). Hills and Brien (1966) used simplified pseudoelastic model of asphalt concrete to calculate thermal stresses in asphalt layers subjected to cooling. Despite the shortcomings of this method it has been used in several research papers till now. The pseudoelastic approach with temperature dependent modulus of elasticity was recently used by Zhong and Geng (2009). Viscoelastic approach was applied to calculate thermal stresses in asphalt

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 Juknevičiūtė-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	Type of bitumen					
		50/70 plain		DE80B SBS polymer modified		50/70 multigrade	
		Before	After	Before	After	Before	After
TFOT							
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:

$$S(t, T) = \frac{\sigma(T)}{\varepsilon(t, T)}, \quad (1)$$

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 $V_T = 10 \text{ }^\circ\text{C/h}$ 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 (Pszczola 2006).

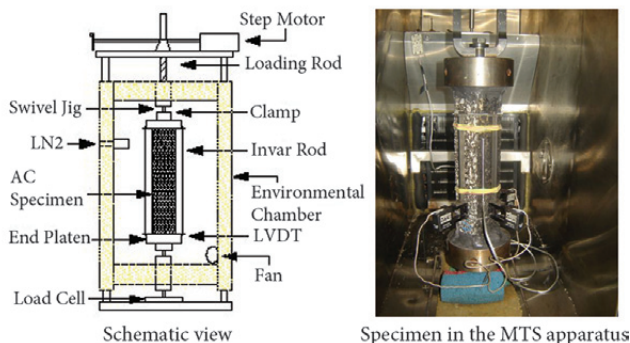


Fig. 1. Thermal Stress Restrained Specimen Test (TSRST) setup

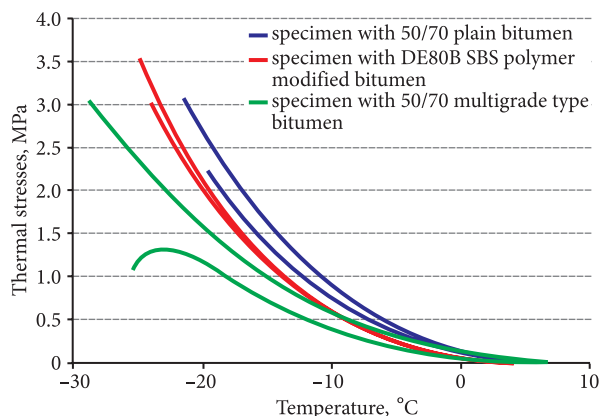


Fig. 2. Thermal stresses vs. temperature in TSRST testing of asphalt concrete specimens containing three bitumen types

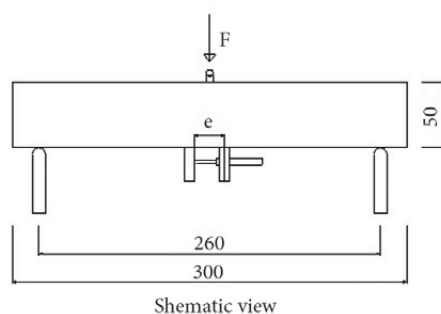


Fig. 3. Bending creep test – the test setup



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:

$$\sigma(T) = \alpha_T \sum_{i=1}^n S(t_i, T_i) \Delta T, \quad (2)$$

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

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 $+5^\circ\text{C}$ at the beginning of cooling the asphalt specimen is free from thermal stress;

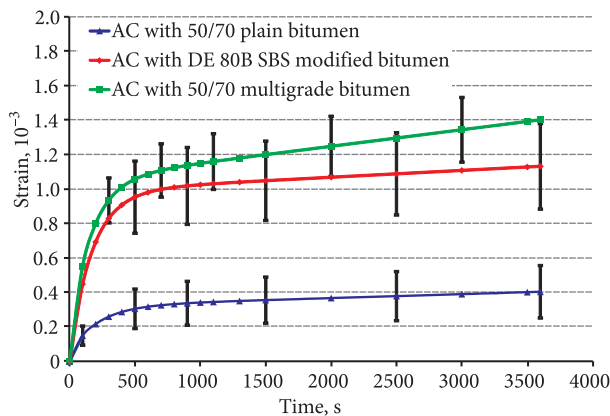


Fig. 4. The example of creep curves of asphalt concrete at temperature -15°C for three tested types of bitumen

Table 2. The values of stiffness modulus of asphalt concrete for different testing temperatures and constant loading time $t = 720$ s

Temperature during creep test, $^\circ\text{C}$	Stiffness modulus of asphalt concrete depending on type of bitumen at $t = 720$ s, MPa		
	50/70 plain	DE 80B SBS modified	50/70 multigrade
0	1509	825	484
-5	2101	1325	1015
-10	4161	2781	1524
-15	8263	2437	2126
-20	13 725	4474	3776

- the drop of temperature below $+5^\circ\text{C}$ is linear in time, as in the TSRST method;
- cooling rate is equal to $V_T = 10^\circ\text{C/h}$, as in the TSRST method;
- the thermal contraction coefficient of asphalt concrete is constant and independent of temperature $\alpha_T = 2.2 \cdot 10^{-5} (1/^\circ\text{C})$;
- temperature increment for calculation is $\Delta T = 2^\circ\text{C}$;
- 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°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°C to $+4^\circ\text{C}$ and from -15°C to -20°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:

$$t = \frac{\Delta T}{V_T}, \quad (3)$$

where t – loading time, s; ΔT – temperature increment, it was assumed in calculations that $\Delta T = 2^\circ\text{C}$; V_T – cooling rate, $^\circ\text{C/h}$.

For cooling rate of $V_T = 10^\circ\text{C/h}$ 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°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.

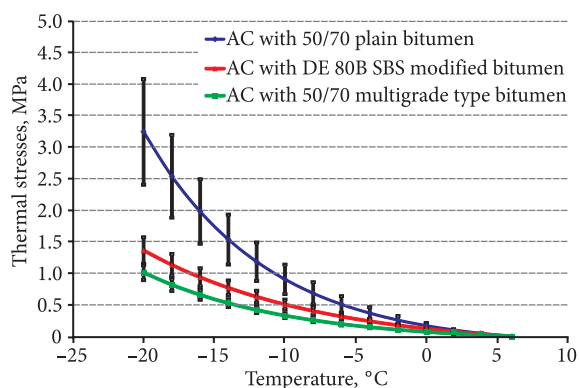


Fig. 5. Calculated thermal stresses induced in restrained asphalt concrete specimens by cooling with a rate of $V_T = 10 \text{ }^\circ\text{C/h}$

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

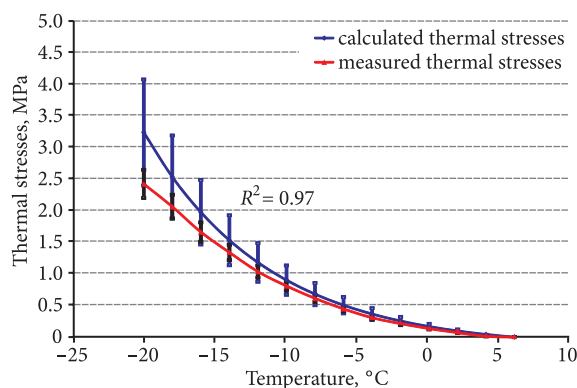


Fig. 6. Calculated and measured thermal stresses in asphalt concrete specimens containing 50/70 plain bitumen

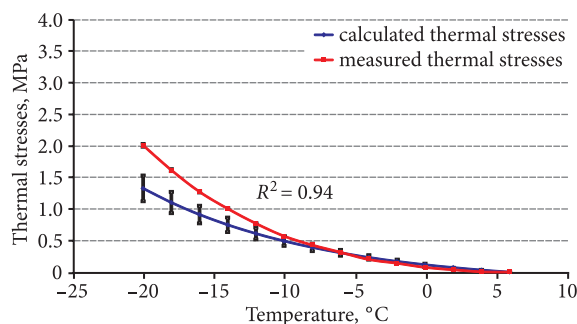


Fig. 7. Calculated and measured thermal stresses in asphalt concrete specimens containing DE 80B SBS modified bitumen

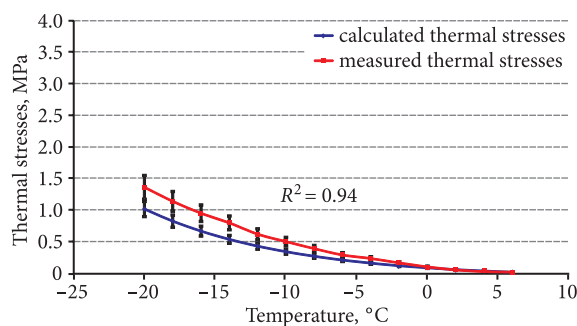


Fig. 8. Calculated and measured thermal stresses in asphalt concrete specimens containing 50/70 multigrade bitumen

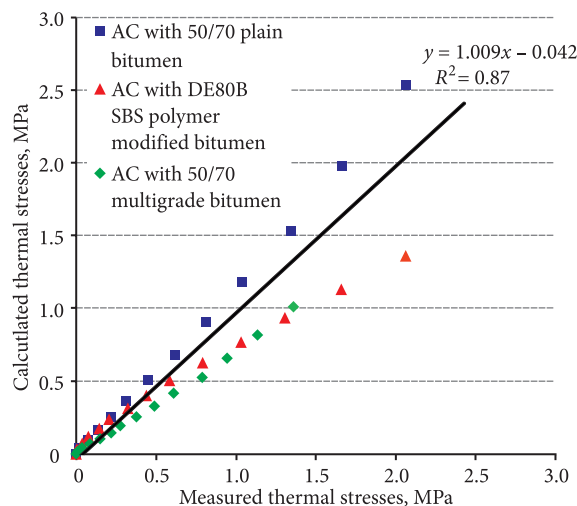


Fig. 9. Comparison of measured and calculated thermal stresses for three asphalt mixes with different bitumen

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.

References

- Arand, W. 1990. Behaviour of Asphalt Aggregate Mixes at Low Temperatures, in *Proc. of the 4th International RILEM Symposium Mechanical Tests for Bituminous Mixes, Characterization, Design, and Quality Control*. 23–25 October 1990, Budapest, Hungary. Chapman and Hall, 68–84.
- Bražiūnas, J.; Sivilevičius, H.; Virbickas, R. 2013. Dependences of SMA Mixture and Its Bituminous Binder Properties on Bitumen Batching System, Mixing Time and Temperature on Asphalt Mixing Plant, *Journal of Civil Engineering and Management* 19(6): 862–872.
<http://dx.doi.org/10.3846/13923730.2013.843587>
- Bražiūnas, J.; Sivilevičius, H. 2010. The Bitumen Batching System's Modernization and Its Effective Analysis at the Asphalt Mixing Plant, *Transport* 25(3): 325–335.
<http://dx.doi.org/10.3846/transport.2010.40>
- Ceylan, H.; Gopalakrishnan, K.; Lytton, R. L. 2011. Neural Networks Modelling of Stress Growth in Asphalt Overlays Due to Load and Thermal Effects during Reflection Cracking, *Journal of Materials in Civil Engineering* 23(3): 221–229.
[http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0000153](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000153)
- Chiasson, A.; Yavuzturk, C.; Ksaibati, K. 2008. Linearized Approach for Predicting Thermal Stresses in Asphalt Pavements Due to Environmental Conditions, *Journal of Materials in Civil Engineering* 20(2): 118–127.
[http://dx.doi.org/10.1061/\(ASCE\)0899-1561\(2008\)20:2\(118\)](http://dx.doi.org/10.1061/(ASCE)0899-1561(2008)20:2(118))
- Das, P. K. 2012. *Thermally Induced Fracture Performance of Asphalt Pavements*. Licentiate thesis, KTH, Royal Institute of Technology, Stockholm, Sweden. TRITA-TSC-LIC 12-006, ISBN 978-91-85539-91-8.
- Faarar, M. J.; Hajj, E. Y.; Planche, J. P.; Alavi, M. Z. 2013. A Method to Estimate the Thermal Stress Build-Up in an Asphalt Mixture from a Single-Cooling Event, *Road Materials and Pavement Design* 14 (Supplement 1): 201–211.
<http://dx.doi.org/10.1080/14680629.2013.774756>
- Hall, M. R.; Dehdezi, P.; Dawson, A.; Grenfell, J.; Isola, R. 2012. Influence of the Thermophysical Properties of Pavement Materials on the Evolution of Temperature Depth Profiles in Different Climatic Regions, *Journal of Materials in Civil Engineering* 24(1): 32–47.
[http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0000357](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000357)
- Heukelom, W.; Klomp, A. J. G. 1964. Road Design and Dynamic Loading, in *Proc. of the Association of Asphalt Paving Technologists* 33: 92–125.
- Hills, J. F.; Brien, D. 1966. The Fracture of Bitumens and Asphalt Mixes by Temperature Induced Stresses, in *Proc. of the Association of Asphalt Paving Technologists* 35: 292–309.
- Hiltunen, D. R.; Roque, R. 1994. A Mechanistic-Based Prediction Model for Thermal Cracking in Asphaltic Concrete Pavements, in *Proc. of Association of Asphalt Paving Technologists* 63: 81–117.
- Judycki, J. 1990. Bending Test of Asphaltic Concrete Mixtures under Static Loading, in *Proc. of the 4th International RILEM Symposium Mechanical Tests for Bituminous Mixes, Characterization, Design, and Quality Control*. 23–25 October 1990, Budapest, Hungary. Chapman and Hall, 207–233.
- Juknevičiūtė-Žilinskienė, L. 2010. Methodology for the Evaluation of the Effect of the Climate of Lithuania on Road Construction and Climatic Regioning, *The Baltic Journal of Road and Bridge Engineering* 5(1): 62–68.
<http://dx.doi.org/10.3846/bjrbe.2010.09>
- Jung, H. H.; Vinson, T. S. 1994. *Low-Temperature Cracking – Test Selection*. Strategic Highway Research Program Report, SHRP-A-10. 106 p.
- Leonovich, I.; Melnikova, I.; Puodžiukas, V. 2013. Estimation of the Cracking Probability in Road Structures by Modelling of External Influences, *The Baltic Journal of Road and Bridge Engineering* 8(4): 240–249.
<http://dx.doi.org/10.3846/bjrbe.2013.31>
- Marasteanu, M.; Buttlar, W.; Bahia, H.; Williams, Ch. 2012. *Investigation of Low Temperature Cracking in Asphalt Pavements*. National Pooled Fund Study – Phase II Mn/RC 2012-23.
- Marasteanu, M.; Li, X.; Clyne, T. R.; Voller, V. R.; Timm, H. D.; Newcomb, D. E. 2004. *Low Temperature Cracking of Asphalt Concrete Pavements*. Report No. Mn/DOT 2004-23. University of Minnesota, Minneapolis.
- Marasteanu, M.; Zofka, A.; Turos, M.; Li, Xinju; Velasquez, R.; Li, X.; Buttlar, W.; Paulino, G.; Braham, A.; Dave, E.; Ojo, J.; Bahia, H.; Williams, Ch.; Bausano, J.; Gallistel, A.; McGraw, J. 2007. *Investigation of Low Temperature Cracking in Asphalt Pavements*. National Pooled Fund Study Report No. 776 Mn/RC 2007-43.
- Monismith, C.; Secor, G.; Secor, K. 1965. Temperature Induced Stresses and Deformations in Asphalt Concrete, in *Proc. of the Association of Asphalt Paving Technologists* 34: 248–285.
- Prieto-Muñoz, P.; Yin, H.; Buttlar, W. 2013. Two-Dimensional Stress Analysis of Low-Temperature Cracking in Asphalt Overlay/Substrate Systems, *Journal of Materials in Civil Engineering* 25(9): 1228–1238.
[http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0000716](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000716)
- Pszczoła, M.; Judycki, J. 2009. Testing of Low Temperature Behaviour of Asphalt Mixtures in Bending Creep Test, in *Proc. of the 7th International RILEM Symposium ATCBM09 on Advanced Testing and Characterization of Bituminous Materials*. 2009. Rhodes, CRC Press Taylor & Francis Group, 303–312.
- Pszczoła, M. 2006. *Low Temperature Cracking of Asphalt Layers of Pavements*. PhD thesis. Gdansk University of Technology. 220 p.



- Qian, G.; Zheng, J.; Wang, Q. 2007. Calculating Thermal Stresses of Asphalt Pavements in Environmental Conditions, *Pavements and Materials* 78–87. [http://dx.doi.org/10.1061/40986\(326\)8](http://dx.doi.org/10.1061/40986(326)8)
- Rajbongshi, P. 2011. Comparative Study on Temperature Stresses in Asphalt Material Using Nonlinear Viscoelastic Approach, *Journal of Transportation Engineering* 137(10): 717–722. [http://dx.doi.org/10.1061/\(ASCE\)TE.1943-5436.0000261](http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000261)
- Sebaaly, P. E.; Lake, A.; Epps, J. 2002. Evaluation of Low-Temperature Properties of HMA Mixtures, *Journal of Transportation Engineering* 128(6): 578–586. [http://dx.doi.org/10.1061/\(ASCE\)0733-947X\(2002\)128:6\(578\)](http://dx.doi.org/10.1061/(ASCE)0733-947X(2002)128:6(578))
- Tabatabaee, H. A.; Velasquez, R.; Bahia, H. U. 2012. Predicting Low Temperature Physical Hardening in Asphalt Binders, *Construction and Building Materials* 34(9): 162–169. <http://dx.doi.org/10.1016/j.conbuildmat.2012.02.039>
- Van der Poel, C. 1954. A General System Describing the Viscoelastic Properties of Bitumen and Its Relation to Routine Test Data, *Journal of Applied Chemistry* 4: 221–236. <http://dx.doi.org/10.1002/jctb.5010040501>
- Vervaecke, F.; Vanelstraete, A. 2008. Resistance to Low Temperature Cracking of High Modulus Bituminous Binders and Mixtures, *Road Materials and Pavement Design* (Supplement 1): 163–176. <http://dx.doi.org/10.1080/14680629.2008.9690164>
- Wang, D.; Linbing, W.; Christian, D.; Zhou, G. 2013. Fatigue Properties of Asphalt Materials at Low in-Service Temperatures, *Journal of Materials in Civil Engineering* 25(9): 1220–1227. [http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0000694](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000694)
- Yiqiu, T.; Lei, Z.; Lun, J. 2012. Analysis of the Evaluation Indices from TSRST, *Journal of Materials in Civil Engineering* 24(10): 1310–1316. [http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0000509](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000509)
- Zeng, H. 1995. *On the Low Temperature Cracking of Asphalt Pavements*. PhD thesis. Royal Institute of Technology, Stockholm, Sweden. TRITA-IP FR 95-7, ISSN 1104-683X, ISRN KTH/IP/FR-95/7-SE.
- Zhong, Y.; Geng, L. 2009. Thermal Stresses of Asphalt Pavement with Temperature Dependent Modulus of Elasticity, in *Proc. of the 8th International Conference (BCR2A), Bearing Capacity of Roads, Railways and Airfields*. 2009. University of Illinois at Urbana Champaign, Illinois, USA.
- Zofka, A.; Marasteanu, M.; Turos, M. 2008. Investigation of Mixture Creep Compliance at Low Temperatures, *Road Materials and Pavement Design* 9 (Supplement 1): 269–285. <http://dx.doi.org/10.1080/14680629.2008.9690169>

Received 5 October 2012; accepted 11 February 2014

