EXPERIMENTAL INVESTIGATION OF MULTILAYER SURFACING SYSTEM ON ORTHOTROPIC STEEL BRIDGE WITH THE FIVE-POINT BENDING TEST

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ABSTRACT

Due to lightweight and flexibility, orthotropic steel deck bridges become popular the last decades but several problems were reported in relation to asphalt surfacing materials such as rutting, cracking, loss of bond between the surfacing system and steel deck. In the Netherlands a surfacing structure for orthotropic steel bridge decks mostly consists of five structural layers: top porous asphalt layer, guss asphalt layer, steel deck and two membrane layers.

The five-point bending fatigue test is the standard device in France for asphalt concrete used on steel orthotropic deck bridges to perform the best asphalt mixture having a strong resistance to cracking. For the needs of this paper the 5 PBT was employed in order to evaluate the performance of the whole multilayer structure on steel deck and also to evaluate the mechanical properties of both top and bottom membrane and the influence they have on the structure.

For the completion of the experimental investigation two types of specimen have been tested using the 5PBT set up. Displacement sensors have been used in order to detect the initiation of cracks where they are most likely to appear. Strain gauges have been used in order to monitor significant changes in strain on the Guss asphalt layer during the fatigue tests. Shear displacements between the asphalt layers are monitored and presented. It shows that the stiffness and the bonding characteristics of the intermediate membrane sheet as well as the wearing course behaviour seem to have great influence on the mechanical response of multilayer bridge surfacing system.

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Keywords: Five-point bending test; orthotropic steel deck bridge; multilayer surfacing system;

INTRODUCTION

Orthotropic steel bridges consist of a 10-14 mm steel deck plate supported in two perpendicular directions, by U-shaped stiffeners and crossbeams in the longitudinal and transverse direction respectively[1]. Due to lightweight and flexibility orthotropic steel decks have, become popular in the last decades but several problems were reported in relation to asphalt surfacing materials such as rutting, cracking, loss of bond between the surfacing system and steel deck [2].

The five point bending test (5PBT) is a laboratory scale test that allows studying the fatigue resistance of surfacing layers on orthotropic bridge decks [3]. Hameau et al. (1981) reported the most severe load case for surfacing layers of orthotropic bridge decks is when they are subjected to negative moments.. The 5PBT has become a French standard test method (NF-P98-286, 2006) [4].

For the purposes of this paper, the 5PBT was performed in order to understand if this type of test can be directly used to evaluate the performance of the multilayer system on steel deck and also to perform a laboratory scale test that would allow studying the fatigue resistance of surfacing layers on orthotropic bridge decks.

In the first part of this paper the experimental device of the 5PBT, test conditions and instrumentation are described. In the second part of this paper, results of 5PBT specimens with two different membrane products as bonding layers at two temperatures −5◦C and +10◦C are exposed. This paper shows that the in time deformation measurements are allowable to evaluate the fatigue response of the wearing course. The stiffness and the bonding characteristics of the intermediate membrane sheet as well as the wearing course behaviour seem to have great influence on the mechanical response of multilayer bridge surfacing system.

DESCRIPTION OF THE FIVE-POINT BENDING TEST

In order to assess the fatigue resistance of the steel bridge multi-layer surfacing system The French five-point bending test (5PBT) has been used. It was developed by the‘‘Laboratoire Central des Ponts et Chausse´es’’(LCPC) in the 70s, and its main advantage is the ability to safely represent the conditions on a real steel deck applying negative moments [4]. This occur at the alignment of the stiffener web when each of the wheel of a double tyre is positioned at each side of the web Figure 1

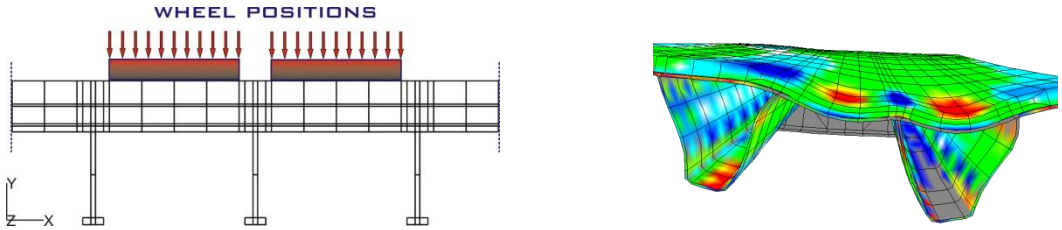


FIGURE 1 Scematic representation of the area of concern

In the Netherlands an asphaltic surfacing structure for orthotropic steel deck bridge mostly consists of two structural layers, Figure 2. The upper layer consists of Porous Asphalt (PA) because of reasons related to noise hindrance. For the lower layer a choice between Mastic Asphalt (MA) or Guss Asphalt (GA), can be made [5]. Therefore, in order to study the fatigue response of the typical Dutch steel deck bridge, 5PBT specimen with the two wearing course bonded by two membrane sheets are investigated.

The specimen is consisted of 10 mm-thick steel plate, 2 to 4mm-thick bottom membrane, 30mm Guss asphalt layer, 4.7-4.8mm-thick top membrane and 40mm thickness of porous asphalt layer, see Figure 2.

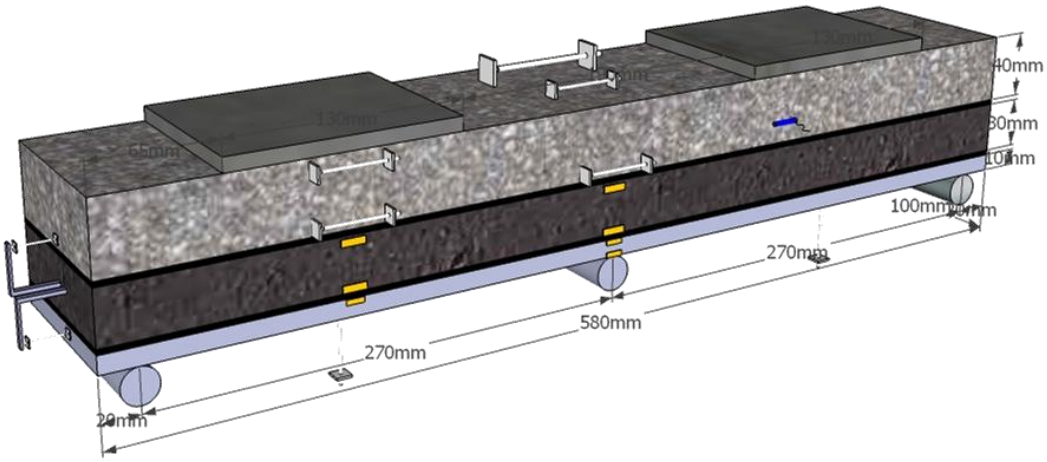


FIGURE 2 Specimen geometry and composition

For the specimen preparation a steel plate with 580 mm x 100mm x 10mm was used. Two different types of sample have been prepared by using membrane products A1 and A2 from company A and B1, B2 from Company B as bonding layer.

Tested materials

Membrane A1 and A2 from Company A

Product A1 (bottom membrane) is a single ply membrane with a total thickness of 2.4 mm, with non-woven polyester fleece. This product is made for the single-ply sealing under stone mastic asphalt, mastic asphalt or bituminous concrete.

Product A2 (top membrane) is a single ply membrane with a total thickness of 4.7 mm, which contains a 1.5 mm strong fleece. This membrane is provided with a modified bituminous mass of 1.6 mm thickness on both sides. It is easy to lay as waterproofing membrane for bridges, and high resistance to traffic loading. The details of specifications for product A1 and A2 are shown in Table 1.

Table 1 Specifications of product A1 and A2 from Company A[10]

Test and specification	Units	Standard	A1	A2
Thickness	mm	EN 1859-2	2.4	4.7
Dimensions	m	EN 1849-2	1.00-7.5	1.00-7.5
Water tightness	6bar /24h	EN 1928-B	o.k.	0.k.
Cold bend test	^{o}C	EN 495-5	-40	-40
Tensile strength at break (20^{o}C,100mm/min)	N/50 mm	EN 12311-1	1445	1115
Elongation at break (20^{o}C, 100mm/min)	%	EN 12311-1	50	35
Debonding Force at (-5C/10C) on steel/membrane interface	N		3410/3100	
Debonding Force at (-5C/10C) on membrane/Guss interface	N		2210/2230	
Debonding Force at (-5C/10C) on membrane/Guss interface	N			2400/2420
Debonding Force at (-5C/10C) on membrane/Porous interface	N			2140/2500

Product B1 and B2 from Company B

Product B1 and B2 are highly performed waterproofing membrane manufactured with SBS elastomeric bitumen and internally reinforced with a non-woven polyester textile. These two products are implemented on concrete deck, steel deck, sand asphalt or asphalt concrete.

Product B1 and B2 can be bonded to the prepared substrate by melting the film on the membrane surface and softening of the bitumen. Details of the product specifications can be seen in Table 2.

The mix composition of porous asphalt concrete and Guss asphalt is shown in Table 3.

Table 2 Specifications of product B1 and B2 from Company B[10]

Test and specification	Units	Standard	B1		B2	
			Nominal values	Critical values	Nominal values	Critical values
Main surface thickness	mm	EN 1849-1	4	3.8	4.8	4.6
Longitudinal overlap width	mm	EN 1848-3			110	100
Tensile strength at break (20°C,100mm/min)	N/5cm	EN 12311-1	950	820	950	820
Elongation at break (20°C, 100mm/min)	%	EN 12311-1	40	35	40	35
Pull-off resistance (20°C, 1.65 m/min)	MPa	NF P 98 282			>0.4	
Cold temperature flexibility	°C	EN 1109	-15	-10	-15	-10
Dimensional stability	%	EN 1107-1			≤0.5	
Heat flow	°C	EN 1110			100	95
Weight/sqm	kg		5.05	4.79	6.27	
Length × width	m×m		10×1	9.9×0.99	8(±10)	1(±0.1)
Weight/roll	kg		50.5	48	48.9	
Debonding Force at (-5C/10C) on steel/membrane interface	N		1040/1104			
Debonding Force at (-5C/10C) on membrane/Guss interface	N		1433/1280			
Debonding Force at (-5C/10C) on membrane/Guss interface	N				1770/1564	
Debonding Force at (-5C/10C) on membrane/Porous interface	N				1940/1520	

Table 3 specification for the asphalt mixtures

	Mass percentages (%)		
Guss asphalt	Targeted	Min	Max
C8 2mm 63µm Bitumen MA 8 SFB-5-20(JR)	2.1 52 78 9.0 (%)	1.1 45 76	3.1 59 80
Porous asphalt			
C11.2 C8 C 5.6 2mm 63µm Bitumen 50/50	4.9(%)	0 51.0 71.0 81.0 94.0	8.4 63.0 83.0 89.0 97

Calibration of the set up

The French standard NF P 98-286 recommends the testing procedures to begin with a calibration phase in order to determine the load corresponding to a strain of 625µm/m on the steel plate surface over the central support[6]. However due to immense differences on the test set up (specimen geometry, specimen composition, steel plate thickness, free central support) the calibration process changed taking into account direct the maximum dual wheel load which corresponds to load pressure of 0.707MPa, see Figure 3. This load pressure corresponds with 9.2 kN on each shoe (0.707MPa x 130mm x 100mm), which means a total of 18.4kN. If the same pressure load of 0.707MPa is applied on a wheel print type B (double tyre 220mm by 320mm), it corresponds with 100kN wheel load which is typical truck load utilized in the Netherland.

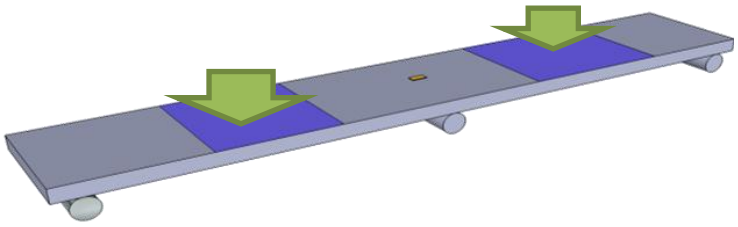


FIGURE 3 Schematic show of a dual wheel load on orthotropic steel bridge and 5PBT

Boundary effect

The fixed central support has replaced with roller support for this set up however higher stress concentration can be observed at the central support at the top face of the steel as it can been seen in finite element simulation in Figure 4. That proves the current set up at same loading condition becomes more flexible than the one with fixed central support condition.

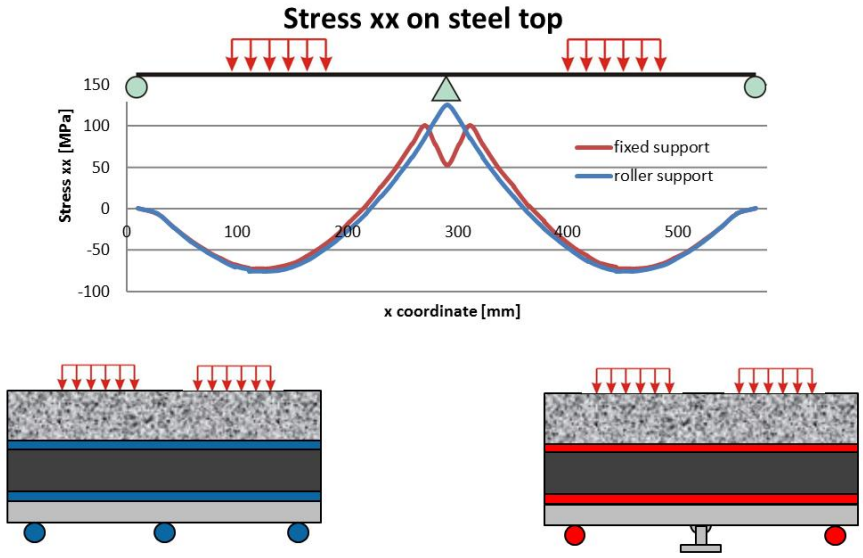


FIGURE 4 Stress concentration at central support

Instrumentation

Nine strain gauges has been glued on each sample. Two different displacement sensors of the LVDT (Linear Variable Differential Transformer) [7] type are positioned on the upper face of the sample at the center, see Figure 5 . Both accuracy and a large detection area are ensured: the first sensor (LVDT 1: ±2.5mm and l=60 mm) is certain to have a measurement zone where cracks are likely to appear, and the second (LVDT 2: ±1.0 mm) and l=30 mm) senses the displacements more precisely.

FIGURE 5 Instrumentation of Strain gauges and LVTDs on the specimen

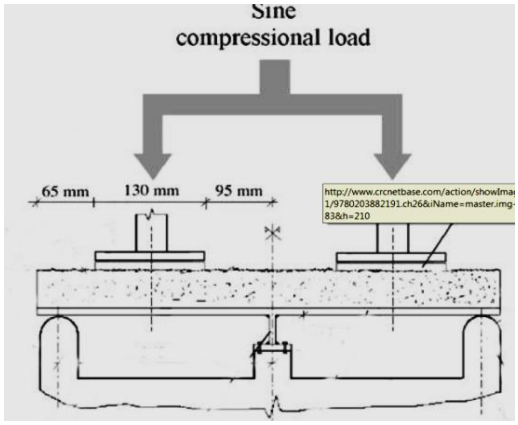
Experimental set up

In order to run the tests under temperature control the set up needed to properly insulated, Figure 6. A climate chamber was fitted to the 5PBT set up to enable testing under different temperatures.

For the purpose of this experiment the specimens were 100mm wide and therefore each shoe print was 130mm long and 100mm wide. The pressure load applied on each shoe was 0.707 MPa, which is slightly higher than the recommended by the standards. This load pressure corresponds with 9.2 kN on each shoe (0.707MPa x 130mm x 100mm), which means a total of 18.4kN. If the same pressure load of 0.707MPa is applied on a wheel print type B (double tyre 220mm by 320mm), it corresponds with 100kN wheel load which is typical truck load utilized in the Netherland. [8].

Tests were performed under two temperatures Ranges (-5^0C and $+10^0$C). The sinusoidal compression loading P ranking between F_{max} and $0.1x\,F_{max}$ at a frequency 4 Hz running for two million cycles.

The climate chamber and the specimen temperature were measured by two temperature sensors. One in the chamber to measure the chamber room temperature and one on the upper face of the porous asphalt to measure the specimen temperature.



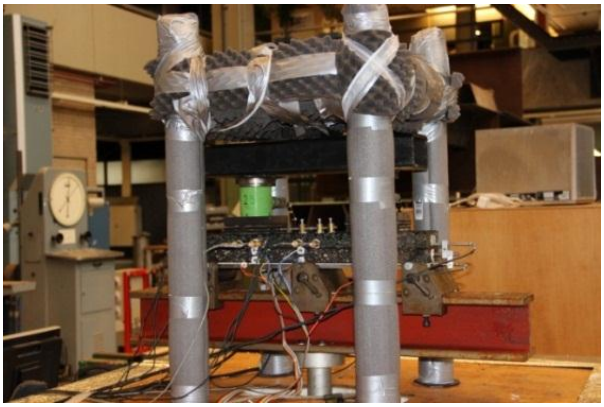


FIGURE 6 The 5 point bending set up,

PRELIMINARY FINITE ELEMENT STUDY

In order to understand the experimental observation, preliminary finite element simulation of 5PBT was investigated first. Based on static ramp loading tests and preliminary finite element analysis using the Zener Viscoelastic model the strain distribution on the specimen are shown in Figure 7 Steel is regarded as a linear elastic material with Young's modulus 210000 MPa and the Poisson's ratio 0.2. Asphaltic surfacings and membranes are assumed to be viscoelastic material.. The model parameters for the FE simulations are listed in Table 4.

Table 4 viscoelastic parameters of the materials used

Materials used	temperature($^\circ$C)	E_1(MPa)	E_∞ (MPa)	Poisson's ratio	η (MPa.s)
Porous asphalt	10	200	1	0.3	15750
Guss asphalt		450	3	0.3	15750
Upper/bottom membrane		9.18	5.9	0.3	267
Porous asphalt	5	2000	10	0.3	22500
Guss asphalt		4500	30	0.3	22500
Upper/bottom membrane		46	30	0.3	384

It can be observed that the stiffness of the two membrane layers plays quite important role in combining different surfacing material layers together as a whole. Assume that the stiffness of membranes is comparable with PA or GA layers, and those layers are properly bonded together, the multilayer surfacing structure could be regarded as a composite beam. By increasing the stiffness of the membrane the strain distribution change as well as it can be seen at section 2-2 in Figure 7. The effect of stiffness in less noticeable on top of PA, however at the interface between PA and GA and between GA and steel,the effect on the tensile stress is quite recognizable.

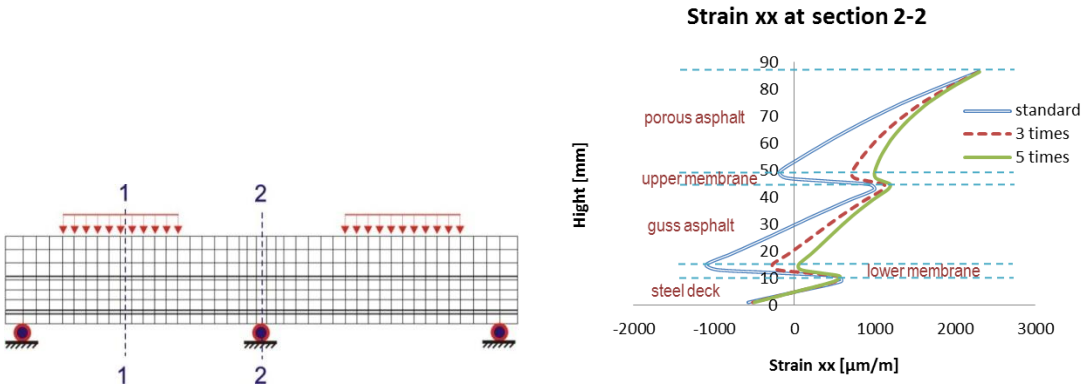


FIGURE 7 Profile of the strain distribution for all materials

DISCUSSION AND RESULTS

The results from two types of specimens denoted product A and B, the maximum strains and the displacements at two temperatures(-5^{0}C and 10^{0}C) are presented. The main concern is at the middle support where higher stress concentration occur and at the side of the specimen in order to monitor shear deformations on the asphaltic layers. Strains were monitored at two location on the front side of GA. The first one close to the top membrane referred as (TopG) and the second close to the bottom membrane referred (BotG). Strain measurements on steel plate are also monitored. Displacements were measured on the top face of PA via LVDT sensors (LVDT1 and LVDT2). Shear displacement measurements between PA and GA is denoted as (AvT). The shear displacement measurement between GA and steel is denotes as (AvBot). The schematic of specimen instrumentation is shown in Figure 8

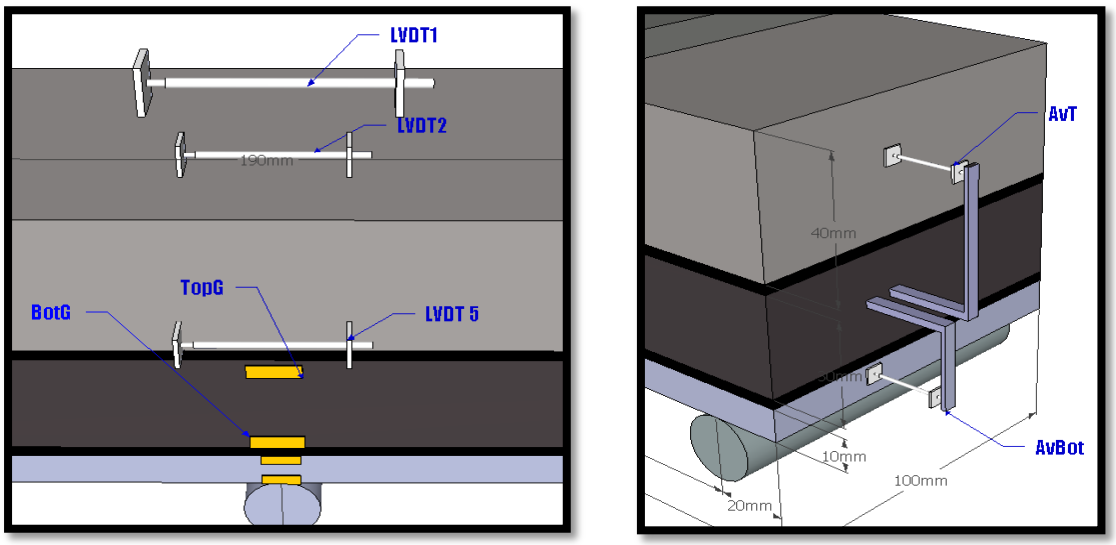


FIGURE 8 Location of Strain gauges and LVDTs

Strain measurements

In Figures 9 and 10 the results from the strain measurements over cycle counts for product A and B are presented. Strains are measured on the top and bottom side of the GA as it can be seen in Figure 9 for two temperatures, -5^{0}C and 10^{0}C.

From Figure 9 it can be observed that higher tensile strength occur at the top of GA at -5^{0}C .During the first 50.000 cycles the strain gradually increased so to reach a maximum value around 900μm/m and then a slight decrease until the end of the test. The same observation can be made for the (BotG) measurement thought the maximum strain is around 300μm/m and after the first 50,00 cycles the strain stabilized there. For both temperatures higher levels of strain concentration occur at the top face of the Guss asphalt (TopG).

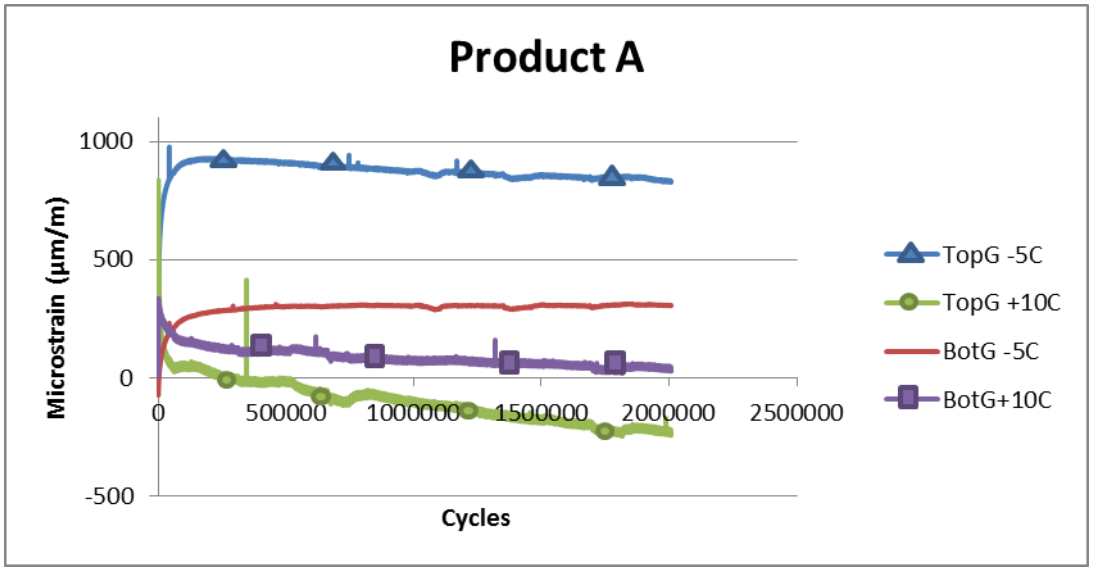


FIGURE 9 micro-strain measurements on Guss asphalt for product A

For product B in Figure 10, the strain concentration at the TopG location found to be higher as well for -5^{0}C, around 800μm/m. For the BotG location at -5C the magnitude of strain concentration is more or less the same as on the TopG location at +10C and the presence of the compression strain for both temperatures can be explained by using finite element analysis of composite beam in Figure 7. Strain measurements on BotG at 10^{0}C after 1.8 million cycles have not been recorded because of the existence of cracks. As it can be seen though from the trend of the line, immediately after loading the strain magnitude decrease to 800μm/m and then exponential decrease.

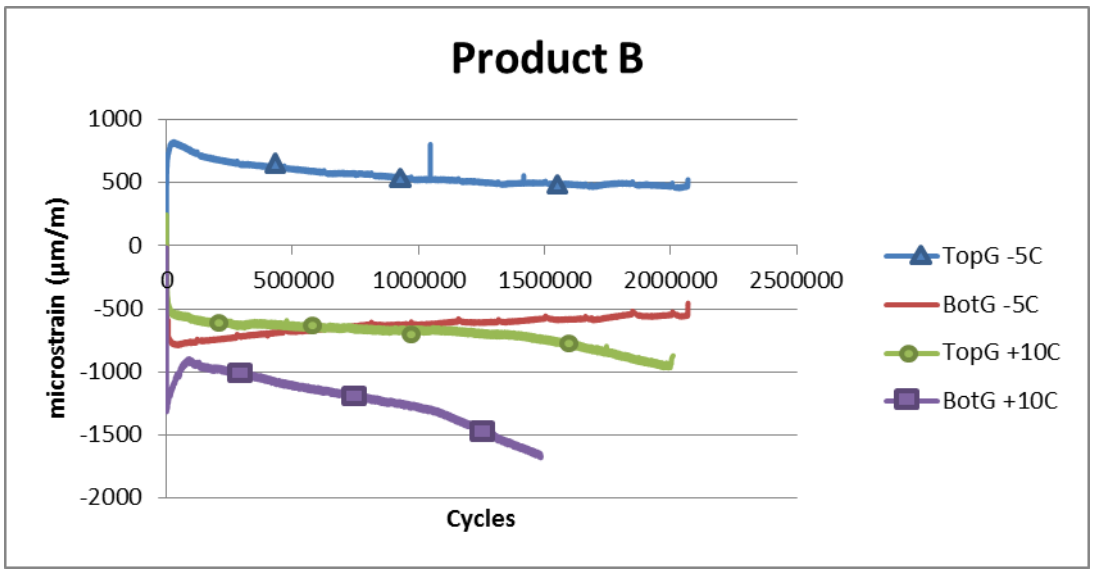


FIGURE 10 micro-strain measurements on Guss asphalt for product B

Displacement measurements

Four sets of LVDTs have been installed at both sides of the samples to measure the shear displacement between the asphalt layers but also the relative displacement between the GA and the steel deck. An average value from both side measurements for both interfaces has been used for the graphical representation.

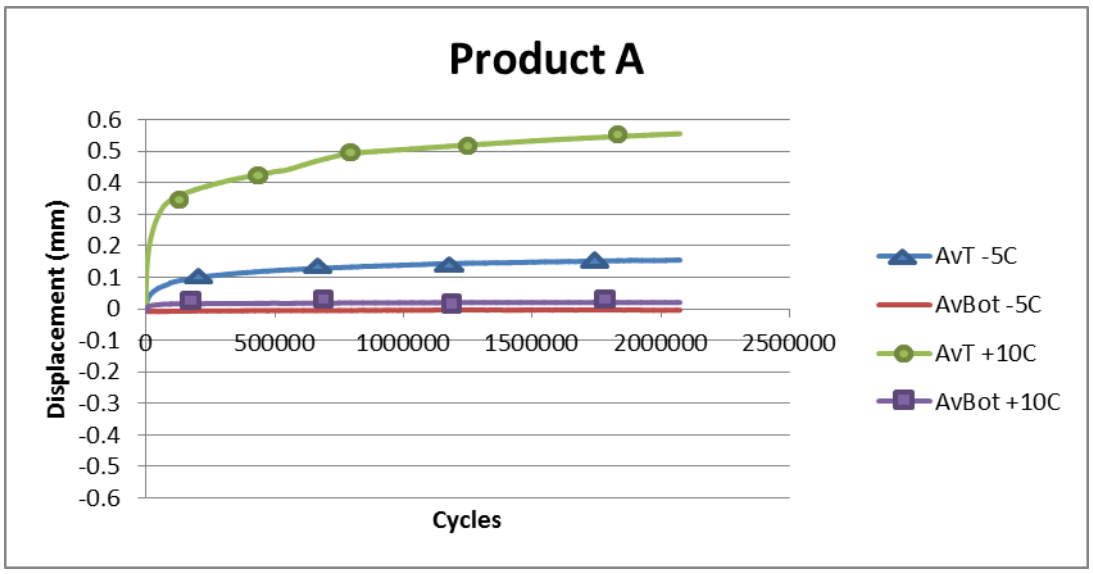


Figure 11 Shear displacement on PA/GA and GA/steel interface, product A

Figure 11 shows that the relative deformation between the (GA) and the steel is quite small for specimen with product A, especially at -5^{0}C is almost zero resulting no significant change during the entire fatigue test. However the temperature seems to have great influence on the GA/PA interface, especially at the temperature of 10^{0}C for the average top shear displacement. The influence of the top membrane on the structure is significant compared the shear displacement values at both temperature.

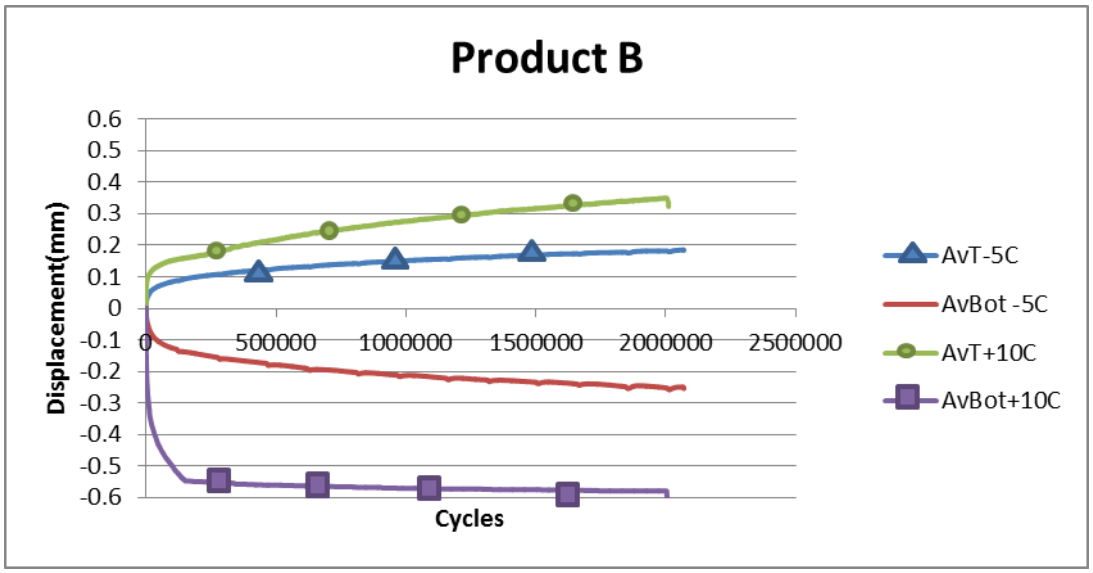


FIGURE 12 Shear displacement on PA/GA and GA/steel interface, product B

The shear displacements for product B are presented in Figure 12. In this case significant influence of the temperature is observed both for the PA/GA and GA/steel interface. By comparing the average bottom shear displacements between GA and steel and the average top shear displacement between PA and GA it can be observed that the bottom membrane gets higher influence from the

difference of temperature and it results the higher shear displacement increment. The top shear displacement is higher at 10^0C as it was expected.

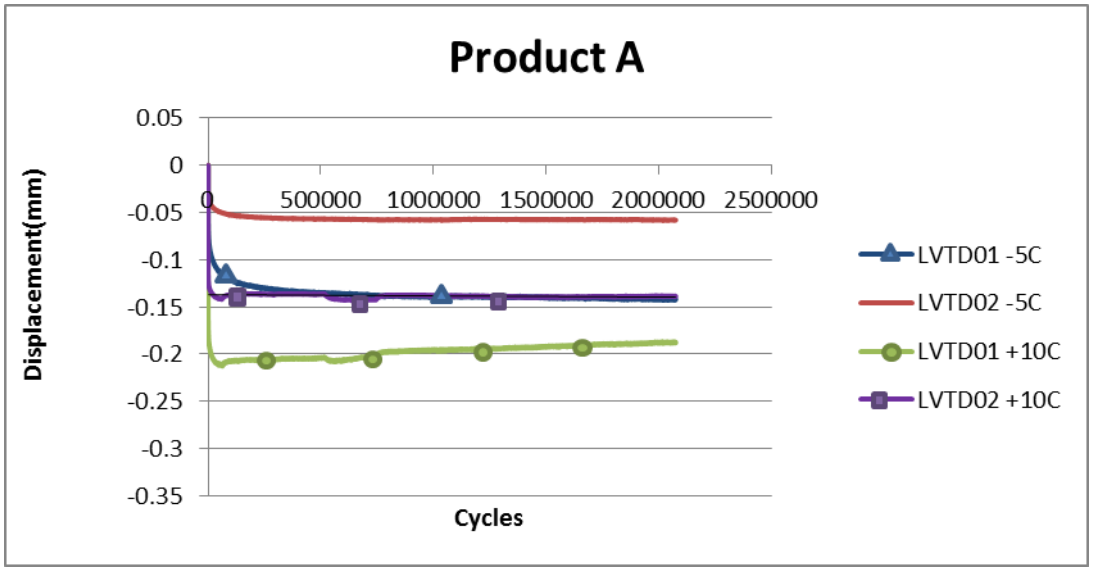


FIGURE 13 Displacement measurements on Porous asphalt, product A

In Figures 13 and 14 the results from the LVDT measurements over cycle counts for product A and B are presented. As it was explained earlier both LVDT1 and LVDT2 are placed at the top face of the specimen over the central support. LVDT 1 is exact at the middle of the specimen though LVDT 2 is placed half way from the LVDT1 and the front edge. From Figure 13 we can observe that Both LVDTs measurements show the appearance of compression deformation at the central location and this can be explained taking into account the nature of the porous asphalt material and the actual position of the LVDTs. Both of them are placed at the top face close to the loading area where the viscous deformation of the porous asphalt material may squeeze the porous asphalt material between the two loading platen hence produce compression deformation at the central location

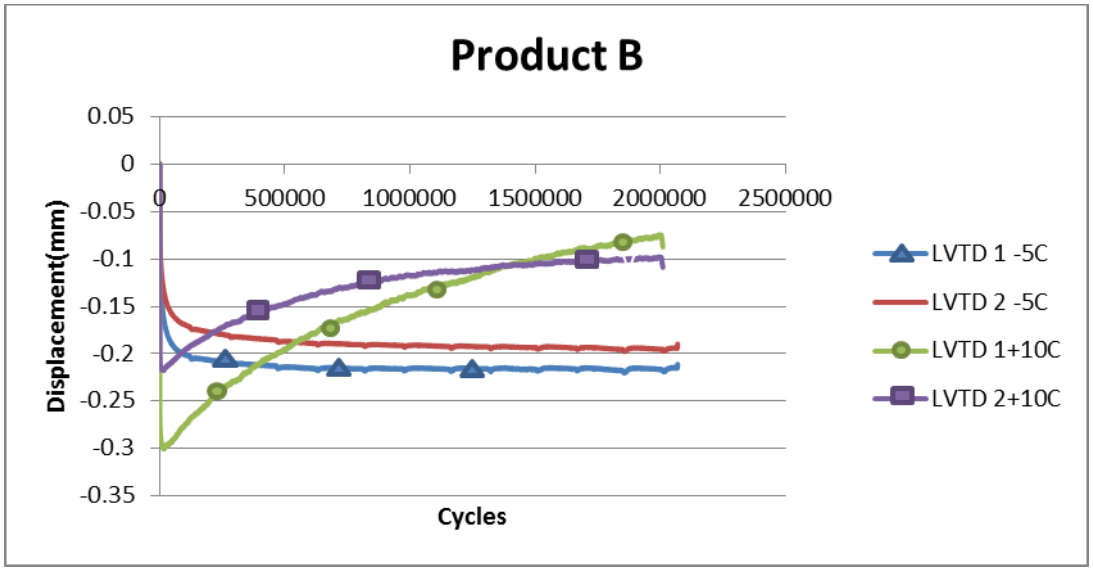


FIGURE 14 Displacement measurements on Porous asphalt, product B

From the LVDTs measurements in Figure 14 for specimen with product B, similar observations as specimen with product A in Figure 13 can be observed. The compression deformation instead of tension deformation are present on the top side of the PA at the location between the

loading area. At temperatures below zero both LVDT measurements show an exponentially increase during the first 70,000 cycles which finally stabilized during the test. At 10^0C both LVDTs monitor higher levels of displacements during the first 80,000 cycles which is followed by a gradual decrease until the end of the test. This decrease shows that elastic recovery occur at the mix after certain loading time.

CONCLUSIONS

The main findings that can be drawn from the results presented in this paper are summarized as follows.

- The five-point bending test offers a good tool in studying the composite behavior of the multilayer surfacing system on orthotropic steel deck bridges;
- The elastic model cannot be fully applicable in order to simulate accurately the response of the surface material. The Zener viscoelastic model is essential.
- Detection of top to bottom cracks for product B at 10^0C.
- Specimen with product B was found to have higher compressive strain concentration values at 10^0C.
- Due to the viscous effect of asphalt surfacings, the compression deformation instead of tension deformation occurs on the top side of the PA at the central location between the loading area. The criteria of judgment of specimen failure at the location where it is subjected to negative moments is not applicable.

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