Structural resistance and interlayer bonding of bridge-deck systems

Christian Dr. Angst[1, a], Dr Raab Christiane[2]

[1] *IMP Bautest AG, Oberbuchsiten, Switzerland*
[2] *EMPA-Swiss Federal Laboratories für Materials Science and Technology, Dübendorf, Switzerland*

[a] c.angst@impbautest.ch

Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.228

ABSTRACT

Bridge-deck systems on concrete bridges are complex systems which have to meet many requirements. Such systems must act as a protective layer against water and de-icing salt as well as withstand temperature fluctuations and traffic loads which are worsened by the channelling of traffic on bridges into narrower lanes.
The research packaged had the following research aims:
• to evaluate and rank testing methods for assessing structural resistance on several bridge-deck systems
• to identify deformation-prone layers or materials
• to develop a procedure to give information on the long-term behaviour of the bonding between sealing and concrete.
Several bridge deck systems with different sealing products (waterproofing material PU, and PMMA as well as polymer modified bituminous waterproofing membrane) on different concrete subbases (different void content and surface treatment) were tested by different test methods, such as rutting test with the Model Mobile Load Simulator MMLS3, cyclic compression test, dynamic shear test and dynamic tensile test.
The results will be presented and discussed.

Keywords: Bonding, Mastic Asphalt, Membranes, Testing, Waterproofing

1. INTRODUCTION

For the protection of concrete bridge decks from water and de-icing substances different systems are used in Switzerland combining soft bituminous layers and classical stiff layers [3]. Since traffic on bridge decks is extremely canalized and because of the special climatic condition on these structures (high temperature due to sun exposure in summer) their bituminous pavements are particularly subjected to rutting. This causes safety risks in form of ice and aquaplaning. Failing surface and binder courses may crack, allowing the infiltration of water between the layers (problems of interlayer bonding) and the propagation through the layers onto the concrete structure.
The bond between sealant and underlying concrete structure is also critical when subjected to traffic induced shear forces. A weakened bond due to slight installation shortcomings or material intolerances might further decrease with the "pumping action" of traffic and finally lead to corrosion of the supporting structure.

The need for structural resistant bridge deck systems is also very important. Their multifunctional requirements (noise reduction and insulation against water and de- icing substances) support the development of new structures and products whose applicability has to be proven. There are a lot of tests for the determination of stability and structural resistance for the individual layers (cyclic compression test, rutting test), but their significance for the durability and effectiveness of the whole bridge deck system has not been evaluated so far [1, 2]. Furthermore, there are no test methods for the adhesion between sealing ant concrete structure available with which it is possible to determine the long term performance under dynamic loading.

2. RESISTANCE TO DEFORMATION

2.1 Materials and test program

For the evaluation different bridge deck systems as shown in Table 1 were used. All systems were constructed on a standard concrete bridge deck plate with dimensions of 2600 mm by 1600 mm. The concrete surface was cleaned and in case of systems 1 to 6 sandblasted.

The polymer modifiers of the bituminous waterproofing membranes (PBD) were the elastomer SBS (systems 2, 3 and 4) and in one case (system 1) the plastomer APP. Alternatively in systems 5 and 6 a waterproofing of liquid polyurethane polymer (FLK PU) and liquid polymer acrylic glass (FLK PMMA) was used. The thickness for the water proofing layers was 3 to 5mm. For systems 7 and 8 the waterproofing consisted of mastic asphalt (MA8, thickness: 28mm). In both cases the waterproofing was applied without bonding to the concrete by putting an oiled paper on top of the concrete surface.
All protection layers with thicknesses between 37mm and 47mm were constructed using mastic MA 16 or MA 11. In case of systems 3 and 4 a binder layer of mastic asphalt MA 11 (thickness 37mm) was applied.
The surface layers were mastic asphalt MA 11 (thickness 38mm) or MA8 (thickness 30mm). For systems 3 and 8 a semi dense low noise asphalt (SDA 8) surface layer according to the Swiss pre-standard SNR 640436 [4] was used (thickness 30mm). The SDA mix has a gap graded aggregate curve, a binder content of 6% and an air void contents between 8 vol-% and 16 vol-%.
The waterproofing systems and the layers of mastic asphalt were laid by hand under optimal climatic conditions. For systems 3 and 8 the layer of SDA were compacted with a hand roller.

Table 1: Overview on the investigated bridge deck systems

System No.	1	2	3	4	5	6	7	8
Surface layer	MA 11	MA 11	SDA 8	MA 8	MA 11	MA 11	MA 8	SDA 8
Binder layer	-	-	MA 11	MA 11	-	-	-	-
Protection layer	MA 16	MA 16	MA 16	MA 16	MA 16	MA 16	MA 11	MA 11
Water proofing	PBD APP	PBD SBS	PBD SBS	PBD SBS	FLK PU	FLK PMMA	MA 8	MA 8

Testing was performed using 4 different test methods as shown in Table 2. Apart from the interlayer bond test, all test methods were originally designed for testing single layers as opposed to whole systems. For interlayer bond testing and cyclic compression test all 8 systems were investigated, while according to financial restrictions the rutting test and the dynamic creep test was performed only on systems 1, 2, 5 and 6. These systems were chosen to evaluate the influence of the different waterproofing membranes.

Table 2: Testing program

Test method	Tested System
Cyclic compression test	Systems 1 - 8
Rutting test	Systems 1, 2, 5, 6
Dynamic indentation test	Systems 1, 2, 5, 6

2.2 Cyclic compression testing

The cyclic compression test is described in [5,6]. All test parameters are displayed in Table 3. The cyclic creep curve displays the cumulative axial strain, expressed in %, of the specimen as a function of the number of load applications (cycles). The test is finished when more than 3’000 load cycles are reached or when the deformation comes up to 5mm. The slope of the creep curve in the inflection point of the cyclic creep curve is a measure for the deformation of the specimen.

Table 3: Testing parameters for the cyclic compression test [6]

Parameter	Value
Test temperature	50 ± 0.3°C
Specimen diameter	148 ± 5 mm
Duration of load cycle	1.7 s
Duration of load	0.2 s
Duration of rest period	1.5 s
Upper stress	0.2 MPa
Lower Stress	0.025 MPa

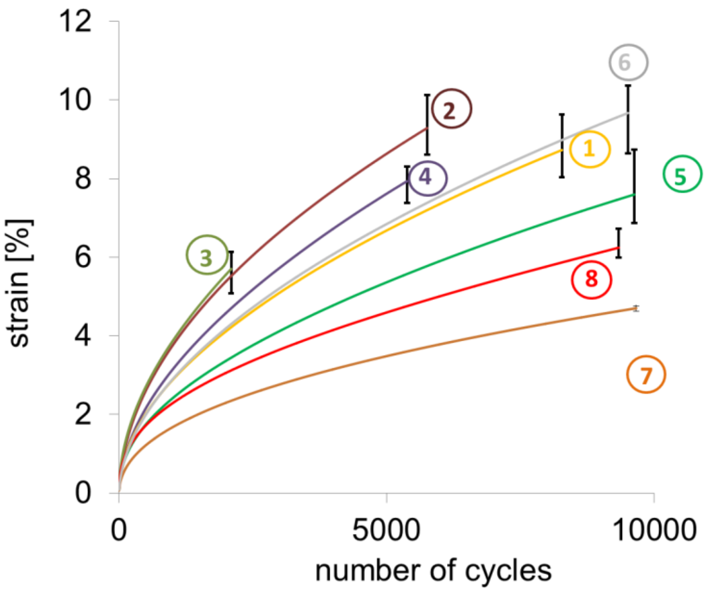

Figure 1: Cyclic compression test results for all systems with scatter in terms of minimum and maximum the 3 singles values

Looking at the dynamic creep curves reveals no inflection points, showing a relatively big deformation for all systems (systems 1-8). Especially system 3 for which the strain does not even come up to 2500 cycles has a very low stability against deformation. The best stability of 8000 load cycles at 4% deformation is reached for system 7, followed by system 8 with approximately 4000 load cycles at 4% deformation. For both systems the difference between maximum and minimum values is also very small, especially system 7 has an extremely low scatter. System 5 reaches 3000 load cycles at 4% deformation, while all the other systems are below 2000 load cycles at 4% deformation.
The examination of the tested samples and the measurement of the layer thickness before and after cyclic compression testing shown in Table 4 reveal that in case of systems 1, 2, 5 and 6 the specimens deform along the whole specimen. For systems 3 and 4 the deformation takes mainly place in the binder and protection layer, while the surface layer of system 3 also displays some deformation. For both systems the water proofing layer is also pressed to the side. For systems 7 the deformation can be mainly found in the protection layer (MA11) and the water proofing layer (MA8). System 8, here the semi dense low noise surface layer also shows some deformation.

Table 4: Layer thickness before/after cyclic compression testing (mean value of 3 single values)

System No.	1	2	3	4	5	6	7	8
Surface layer	36/33	36/33	37/35	28/28	34/31	36/34	30/29	39/36
Binder layer	-		38/35	36/34				
Protection layer	33/30	36/32	35/32	31.5/29	33/30	36/30	35/34	32/31
Water proofing	5/5	4/3	5/4	5.5/4	4.5/5	3/2	29/26.5	30/27

2.3 Rutting testing

Rutting testing was done using the Model Mobile Load Simulator MMLS3[7] (see Figure 2, left). Testing was conducted at a temperature of 20°C and up to 500,000 load cycles.

For the evaluation of permanent deformation systems 1, 2, 5 and 6 were tested. These systems were selected to evaluate the influence of the different water proofing systems (PBD APP, PBD SBS, FLK PU and FKL PMMA). For each investigated system 2 profiles were determined on either side of the slabs, as shown in Figure 2, right. For each system the averages of two profiles were then combined for the rut depth measurements given in Table 5. From the rut depth measurements the regression curve was determined and the rutting for 7000,000 load cycles was calculated.

Figure 2: Left: Model Mobile Load Simulator MMLS3, right: 2 rutting profiles on system 5

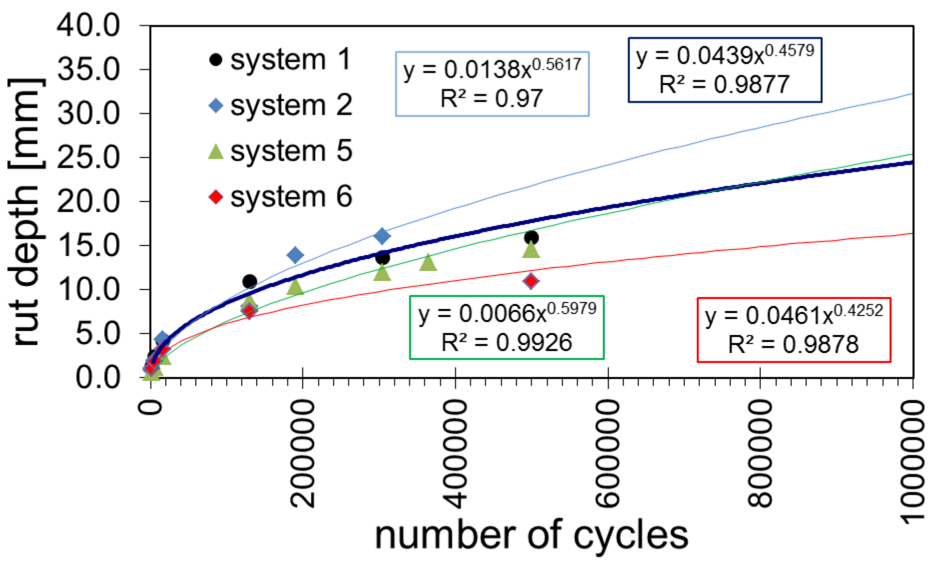

Figure 3: Rutting test results for systems 1, 2, 5 and 6 (Average of 2 profiles with each 3 measurements)

Table 5: Rut depth measured and calculated (average of two profiles)

Rut depth [mm]	System 1	System 2	System 5	System 6
500,000 cycles (measured)	15.9	13.7 (profile 1) > 20 (profile 2)	14.6	10.9
700,000 cycles (calculated)	20.1	26.5	20.6	14.9

According to Figure 2 and the rut depth measurements shown in Table 5 system 6 shows the smallest rutting and therefore the biggest resistance against permanent deformation. All other systems behave quite similar. System 2 which has the biggest rutting shows very distinct differences between the two rut profiles.

2.4 Dynamic indentation

The test is conducted according [8], the test temperature is 50°C. The result of the test is given as the deformation under the center platen at 2’500 load cycles as the mean value of 2 specimens.

The dynamic indentation test was conducted to see if differences in the material (mastic asphalt) could be seen. Therefore, the samples from systems 1, 2, 5 and 6 were prepared by removing the waterproofing layer as well as the concrete layer. Figure 4 shows all test results (single values for systems 1, 2, 5 and 6, left) and the mean value calculated from systems 1 and 2 and systems 5 and 6, which have an identical layers , right.

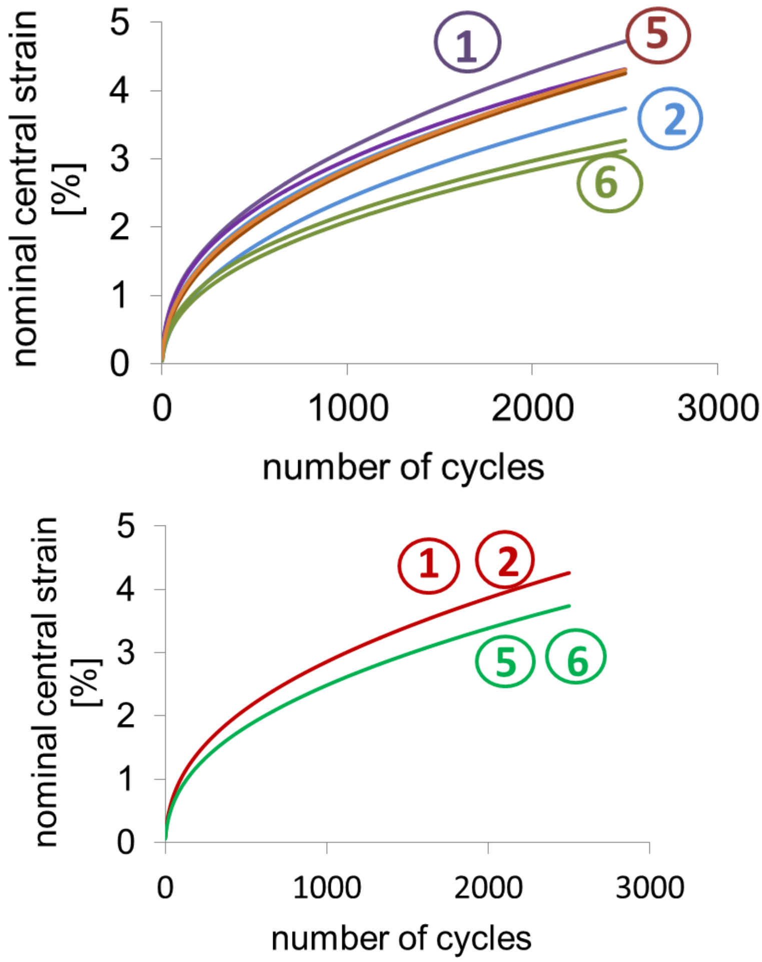

Figure 4: Dynamic indentation test results, above: all values for systems 1, 2, 5 and 6, below: mean values for systems 1 and 2 and systems 5 and 6

According to the results, systems 1, 2 are weaker than systems 5 and 6, with system 6 being the stiffest of all tested systems. This results corresponds on one hand side to the rutting test results were system 6 was also found to have the least rutting and on the other hand side it confirms the findings from the cyclic compression test giving lower deformation for systems 5 and 6 compared to systems 1 and 2.

3. LONG TERM PERFORMANCE OF BOND BETWEEN SEALING AND CONCRETE STRUCTURE

The evaluation of the long term performance of the bond was limited to the evaluation of the behavior under mechanical cyclic loading, while thermal cyclic loading was not considered.

3.1 Choice of test method

New methods had to be developed to be able to measure the bond between sealing and concrete structure in cycling loading. Two different methods were selected. The so called dynamic tensile test and dynamic shear test were developed. In both cases the testing parameters had to be chosen with the aim to reach a high number of load cycles to failure. In order to achieve the best possible repeatability swell tests were chosen.
For the dynamic shear test and dynamic tensile test the main parameters were evaluated and determined [9]. This included the lower and upper load, the temperature, and stress curves (haversine with rest periods). The ratio used between the upper and lower load was 1:10. Afterwards the precision of the newly developed procedures were determined. Repeated measurements were conducted with the same machine and the same operator performing the experiment. For the dynamic tensile test a reproducibility of 66% was reached. For the dynamic shear test the reproducibility was 16%. Therefore it is recommended to use the dynamic shear test for further testing.

For the shear bond testing a test set up developed by Bundesanstalt für Materialprüfung BAM was used. Here, the test set up was used for the first time under dynamic loading conditions. According to a detailed parameter study [9] the following test parameters were chosen:

Lower load:	0.015 N/mm^2
Upper load:	0.15 N/mm^2
Temperature:	23°C
Number of cycles:	2000
Loading:	Haversine-loading with rest periods Loading (Upper load: 0.2 sec) Rest period (Lower load:1.5 sec)

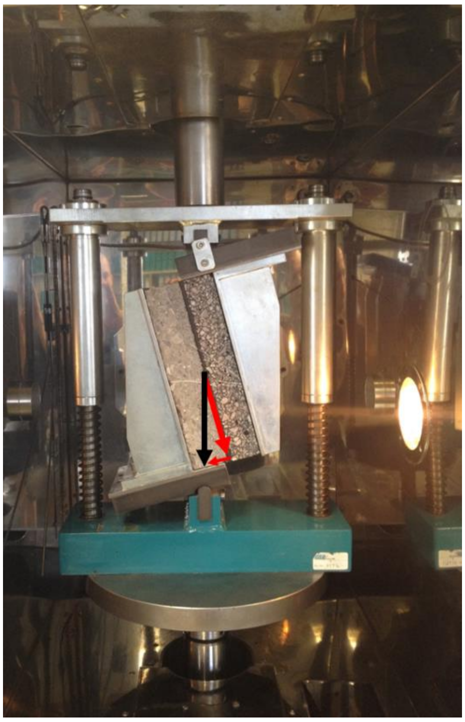

Figure 5: Test set up for the evaluation of the shear bond of bridge deck sealings developed by BAM

3.2 Test program

In a first step the different systems (see table 6) were evaluated. To evaluate the influence of the climatic situations the sealing was subjected to different conditionings being covered by the protective layer. Different conditioning was equal to optimum dry condition (L1), condition with rain on the previous day (L2) as well as humid foggy condition (L3).

Table 6: Evaluated systems and conditioning of the sealing before laying the protection layer.

System	Sealing	Water-proofing	Protection layer	Conditioning of the sealing before laying the protection layer
FLK PU	epoxy	PU	MA	L1 (dry)
				L2 (rain on previous day)
				L3 (foggy)
FLK PMMA	Epoxy	PMMA	MA	L1 (dry)
				L2 (rain on previous day)
PBD1	Bituminous	PBD-SBS	MA	L1 (dry)
				L2 (rain on previous day)
PBD2	Epoxy	PBD-SBS	MA	L1 (dry)
				L2 (rain on previous day)

In a second step the influence of the properties of the underlying concrete structure on the bond was determined.

3.3 Results

3.3.1 Influence of sealing conditioning

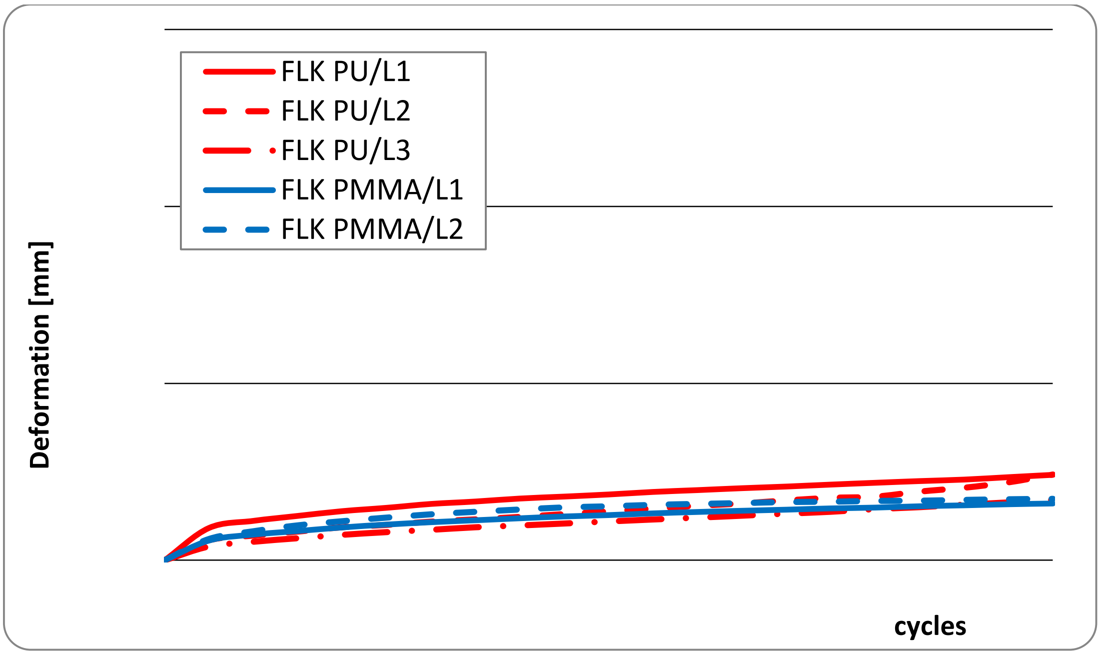

Figure 6: Dynamic shear test on systems with liquid polyurethane polymer (FLK PU), liquid polymer acrylic glass (FLK PMMA) and different conditioning (L1, L2, L3); test temperature 23°C; mean value of 3 single values

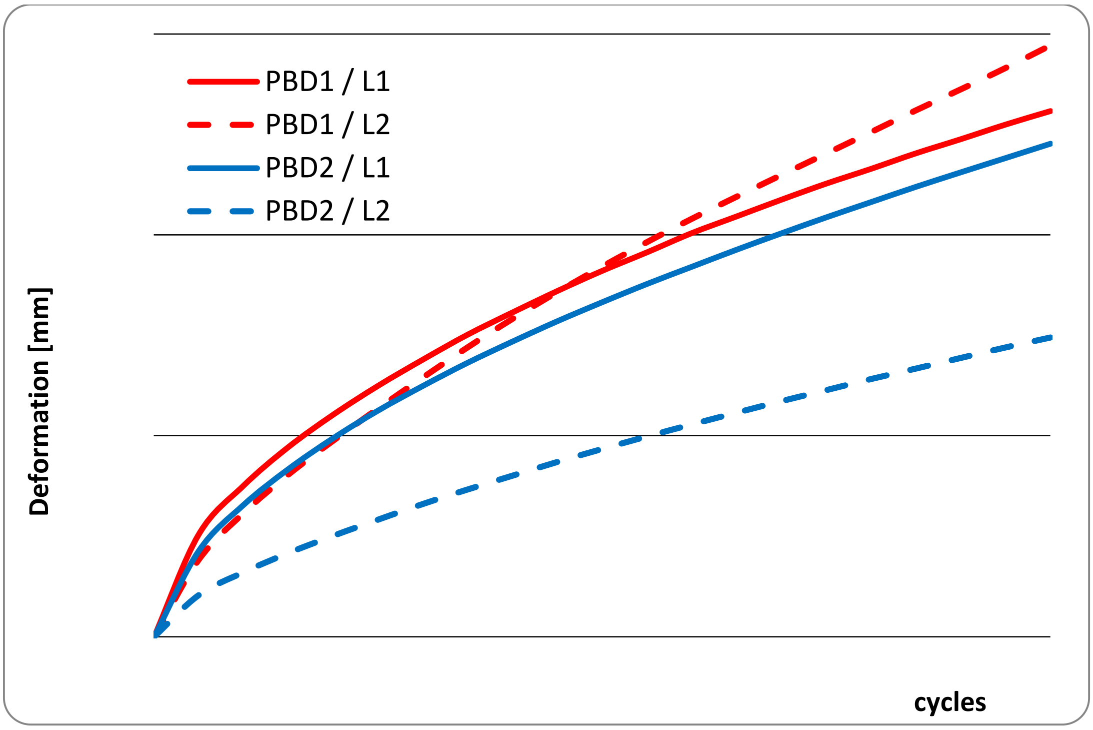

Figure 7: Dynamic shear test on systems whit waterproofing membranes (PBD) and different conditioning (L1, L2, L3); test temperature 23°C; mean value of 3 single values

The comparison of dynamic shear bond results from bituminous waterproofing membranes and liquid polymers clearly showed larger deformations for the bituminous waterproofing membranes. No influence of the climatic conditions before the construction of the protecting layer could be found. This seems to indicate that the climatic condition before the construction of the protecting layer does not have an influence on the bond. Obviously, the bond at the interface between sealing and protecting layer is much better than the bond at the interface between underlying concrete structure and sealing, meaning that the good bond at the interface between sealing and protecting layer is hardly influenced by climatic conditions. Nevertheless, it has to be kept in mind that all systems were constructed under controlled conditions and therefore a different result might be found for real situations with combinations of constructing faults and harsh weather.

3.3.2 Influence of the underlying concrete structure on the bond

For testing the newly developed method, test sections were constructed with different underlying concrete structures. Hereby, the following parameters were varied:

Air void content of fresh concrete:	1.1 / 5.4 Vol.-%
Treatment concrete surface:	wet screed/power trowel

The sealing systems (bituminous waterproofing membranes covered by a mastic asphalt layer) were applied using two different primers: bituminous primer and epoxy primer. Overall 8 test sections according to table 7 were constructed.

Table 7: Investigated test sections

Sealing	Waterproofing	Air void content of fresh concrete	Treatment of the concrete surface
		[vol.-%]	
Bituminous	PBD	1.1	power trowel
Bituminous	PBD	5.4	power trowel
Bituminous	PBD	1.1	wet screed
Bituminous	PBD	5.4	wet screed
Epoxy	PBD	1.1	power trowel
Epoxy	PBD	5.4	power trowel
Epoxy	PBD	1.1	wet screed
Epoxy	PBD	5.4	wet screed

Table 8: Dynamic tensile test on cores from the test fields (Table 7)

Section No.	Sealing	Air void content of fresh concrete [vol.-%]	Treatment of the concrete surface	Deformation at 2000 cycles (mean value; of 3 values) [mm]	Failure at n cycles (mean value; of 3 values) Cycles	Failure interface
1.1 A	bituminous	1.1%	power trowel	0.358	-	-
2.3 A	bituminous	5.4%	power trowel	-	80	concrete/ membrance
1.1 B	bituminous	1.1%	wet screed	0.628[1)]	350[2)]	concrete/ membrance
2.3 B	bituminous	5.4%	wet screed	-	69	concrete/ membrance
1.2 A	epoxy	1.1%	power trowel	0.747	-	-
2.2 A	epoxy	5.4%	power trowel	0.243	-	-
1.2 B	epoxy	1.1%	wet screed	1.477	-	-
2.2 B	epoxy	5.4%	wet screed	0.349	-	-

[1)] one sample [2)] two samples

The evaluation of the results led to the following conclusions:

- In test sections with bituminous primers a premature failure could be found when the air void content was 5.4 vol.-%. For the sections with an air void content of 1.1 vol.-% the failure only happened after 2000 cycles.
- Test sections treated with a power trowel showed smaller deformations than sections treated with a wet screed.

4. CONCLUSIONS

From the results of this investigation it becomes clear that tests, such as cyclic compression and dynamic creep test and their requirements, which were developed for testing single layer cannot easily be transferred to bridge deck systems consisting of mastic asphalt or asphalt concrete and multiple layer systems.

Regarding rutting and dynamic indentation testing system tested system no. 6 seems to have the best properties of the 4 tested systems. Since it was found that the deformation after rutting was mainly concentrated in the upper layer, the test does not seem capable of evaluating the whole system (including the waterproofing membrane). For evaluation of rutting for a bridge deck system it seems necessary to do testing using dynamic indentation or situ traffic simulators such as Mobile Load Simulator MLS10 or Heavy Vehicle Load Simulator HVS.

When looking at the resistance against permanent deformation (cyclic compression test) systems 7 and 8 with a mastic asphalt waterproofing layer show the best performance. In contrast, systems with three bituminous layers on top of a polymer modified bituminous waterproofing membrane (systems 3 and 4) should be avoided.

For the dynamic shear test and dynamic tensile test the main parameters were evaluated and determined. For the dynamic tensile test a reproducibility of 66% was reached. For the dynamic shear test the reproducibility was 16%. Therefore, for further testing it is recommended to use the dynamic shear test.

Tests with polymer modified bituminous waterproofing membrane on different primers (bituminous and epoxy base) and different concrete surfaces showed, that the air void contents of the concrete has a big influence on the bonding for membranes laid on bituminous primers.

REFERENCES

[1] Witczak, M. Simple Performance Tests: Summary of Recommended Methods and Database. *NCHRP Report 547*, Washington, TRB, 2005, pp. 340-378.

[2] Eliott, R.C., Sida, M. Performance testing of mastic asphalt for bridge surfacing", Pr*oceedings of 2nd Eurasphalt and Eurobitume Congress*, Barcelona, Spain, September 20-22, 2000, pp.1022-8, ISBN: 90-8028884-3-8

[3] Swiss Standard SN 640450 Waterproofing Systems for Concrete Bridge Decks. Abdichtungssysteme und bitumenhaltige Schichten auf Betonbrücken, 2005

[4] Swiss Pre-Standard SNR 640436 Semi Dense Mixtures and Wearing Courses. Semidichtes Mischgut und Deckschichten SDA, Festlegungen, Anforderungen, Konzeption und Ausführung (in press)

[5] European standard EN 12697-25, Bituminous mixtures - Test methods for hot mix asphalt – Part 25: Cyclic compression test, 2005.

[6] German standard: Cyclic compression test. Technische Prüfvorschriften für Asphalt TP Asphalt-StB Teil 25 B 1 Einaxialer Druckschwellversuch - Bestimmung des Verformungsverhaltens von Walzasphalt bei Wärme, 2010.

[7] Hugo, F, Epps, A. Significant Findings From Accelerated Pavement Testing, *NCHRP Synthesis 325*, Washington, TRB 2004.

[8] German Guideline: Dynamic Creep Test. Technischen Prüfvorschriften für Asphalt im Straßenbau TP A-StB Teil 25 A1 Dynamischer Stempeleindringversuch (DSEV) – Bestimmung des Verformungswider-standes von Walzasphalten bei Wärme, 2009.

[9] Angst, Ch. Research package bridge-deck system: EP3 - Long term behaviour of the bond-layer, ASTRA-report 1514, Bern 2015