Mechanical Performance Testing of Low-Noise Bituminous Plug Expansion Joints for Concrete Road-Bridges

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ABSTRACT

This paper contains a short state of the art overview on bituminous plug joints (BEJ) in Switzerland. Such BEJs are of particular interest because of their noise reduction properties. BEJs designed for joint movements up to 100mm were investigated in the lab and field as a basis for guidelines by the Swiss Federal Road Office. Special test procedures including gel permeation chromatography (GPC), testing of adhesion between joint filling material and adjacent pavement, rutting performance testing with model mobile load simulator MMLS3 as well as cold temperature movement capacity testing with a joint movement simulator are presented. It is also shown how the influence of moisture on the adjacent bridge deck pavement with the coaxial shear test CAST can be evaluated. In addition, long-term field performance of standard BEJs for small joint movements and special wide BEJs, some of them containing moving aids for large joint movements, are discussed. It was found that the tools and requirements elaborated in the Swiss guidelines are suited to reduce the risk of BEJ failure. It became also apparent that placing technology and climate play a significant role in achieving well performing BEJ for short and large joint movements.

Keywords: Bituminous plug joint, noise reduction, chromatography, adhesion, joint movement, concrete bridge, finite element method.

INTRODUCTION

Flexible bituminous (or "asphaltic") plug expansion joint systems (BEJ) are used for short concrete bridges with small maximal horizontal total movements in each joint of about 30 mm for more than 20 years and, recently, even for bridges with large joint movements in the order of 100 mm. As compared to other systems, these plug joints generally have a shorter life cycle of about 10 to 15 yrs but are easy to install, maintain and repair, provided that work is conducted carefully with sound technical know-how and under favorable weather conditions (dry and warm).

BEJ are mostly used in combination with asphalt bridge deck pavements allowing a smooth driving surface with a positive effect on traffic noise reduction and driving comfort for cars, motor cycles and bikes. In fact, the potential of noise reduction is one of the main advantages of this type of plug joint for bridges in heavily populated urban areas and in critical places such as exposed bridges in alpine nature reserves and recreational areas.

Low-noise BEJs are expected to provide good protection of the concrete bridge structure against corrosion from water and de-icing agents. They are required to be elastically deformable at very cold seasonal temperatures without suffering loss of stability during hot summer months or traffic induced damage (Figure 1). Such damage may result

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from vertical static or dynamic mechanical loads, vertical vibrations of the bridge and special situations such as replacement or adjustment of bridge bearings. It may also result from horizontal tire-road interaction in curves and slopes from breaking and acceleration maneuvers as well as exceptional loads during maintenance, such as winter maintenance with snow-ploughs. Hence, general requirements for BEJ read as follows:

- Durable (e.g. temperature & weather resistant)
- Waterproof (protection of concrete structure, de-icing salts)
- Resistance against quasi-static horizontal and vertical bridge movements and dynamic Traffic Loads without
  - Loss of adhesion in contact surfaces
  - Low temperature and fatigue cracks
  - Loss of stability in summer
  - Loss of friction (safe breaking)
  - Rutting and permanent deformation (aquaplaning, ice)
  - Raveling and loss of aggregates
- Driving comfort (incl. bikes & motor cycles)
- Noise reduction
- Easy application and maintenance
- Economically competitive

Due to the fact that BEJs are critical elements in asphalt bridge deck pavements that must meet high multifunctional requirements for avoiding failure, the Swiss Federal Road Office has issued guidelines (ASTRA 806.315.d, 2005) based on different research projects performed by EMPA which led to a considerable improvement of quality and performance of this type of plug joints [1,2,3]. This work together with activities and experience in other European countries such as Germany, Austria, The Netherlands and United Kingdom will soon lead to a European Technical Approval Guideline for Expansion Joints for Road Bridges (ETAG n° 032, Part 3: Flexible Expansion Joints).

In the following, a summary of EMPA research results regarding lab and in-situ performance testing is presented together with key elements of the framework developed for the assessment of BEJs in Switzerland.

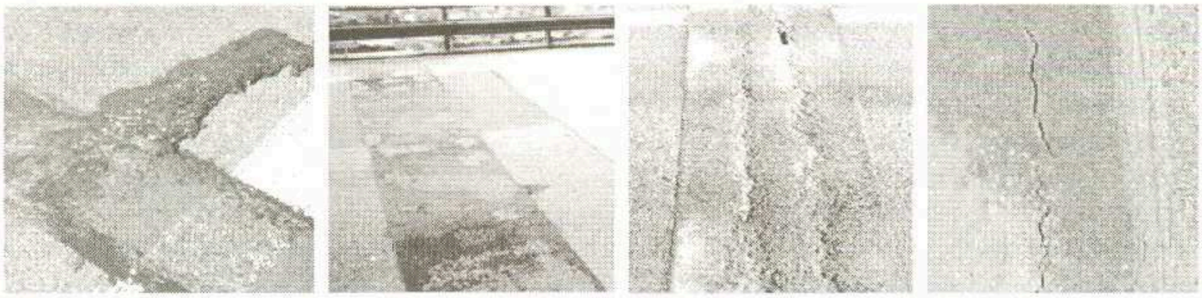


Figure 1. Damage of BEJ (from left to right): material transport. & displacement & run out in summer; aggregate loss & surplus of binder; cohesion cracks & adhesion cracks along BEJ site in winter; cracks from too large BEJ movement >30mm

FLEXIBLE BITUMINOUS PLUG EXPANSION JOINT SYSTEMS

Structural Elements and Materials

Bituminous plug joint systems (BEJ) for bridges are defined as in-situ poured flexible plug expansion joints comprising a band of specially formulated flexible joint filling material which is filled in a trench flush to the surface of the asphalt bridge deck pavement as schematically shown in

Figure 2. The trench of BEJs for small movements is typically 500 mm wide and 70...160 mm thick. BEJs for large movements may have a width of 1000 mm. The maximum acceptable slope in any direction is 6 % and the horizontal angle between bridge axis and the longitudinal axis of the BEJ should not be less than 65° (ASTRA 806.315.d, 2005).

Bituminous joint filling material may be a mixture composed of gap graded aggregates serving as mechanical skeleton for carrying the traffic loads and an elastomeric polymer-modified bituminous binder typically of a Styrene-Butadiene-Styrene (SBS) type. However, different other bituminous filling materials are possible and, in fact, under continuous development. The filling material forms the surfacing and is topped by a chip surface dressing for skid resistance purposes. It is supported across the bridge deck joint gap by thin metal plates or other suitable components with some sliding capability which prevents the filling material to be squeezed into the gap by traffic loads. The gap normally has a width of 10...60mm. In order to avoid stress concentrations and cracks, friction between the steel plate and the joint material should be reduced to a minimum. This may be achieved by a fabric layer serving as a separation between the filling material and the steel plate.

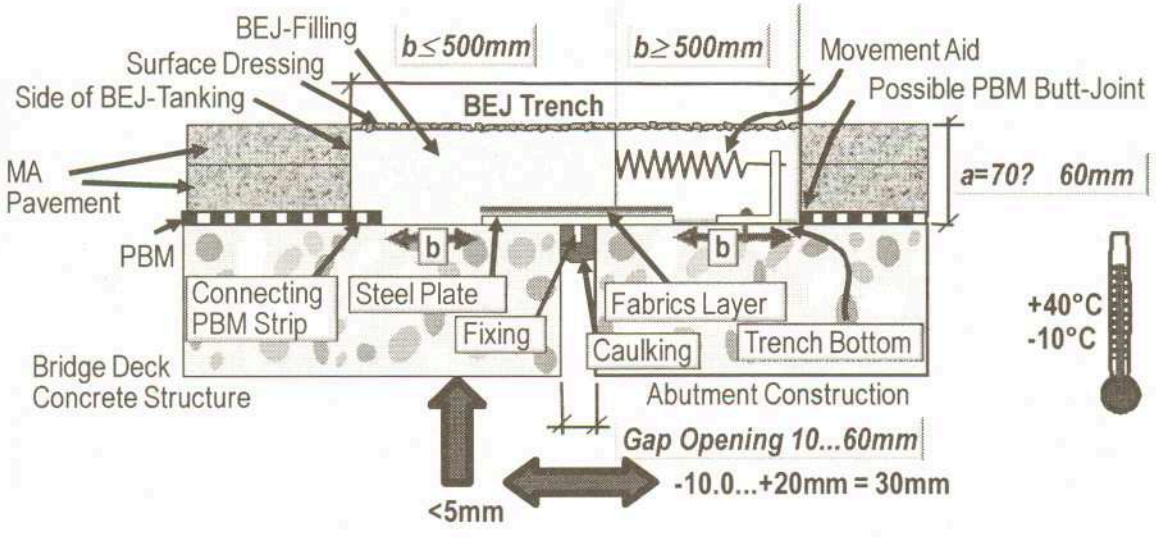


Figure 2. Elements of flexible bituminous plug expansion joint systems for small (b≤500mm) and large (≥500mm) joint movements (schematic); PBM = Polymer-bitumen sheet; MA= Mastic asphalt

BEJ for Small Joint Movements

According to the ASTRA guidelines (ASTRA 806.315.d, 2005), plug joint systems are required to work within a temperature range from -10°C to +40°C and, in case of BEJs for small joint movements, BEJs are expected to take repeated gap closing and opening between -10 mm and 20 mm (assuming zero-opening at 10°C). With respect to bridge bearing replacements, plug joints should also be able to endure vertical gap movements to a maximum of 5 mm.

Typical damage may occur in summer time when BEJs may be too soft and the filling material may be squeezed out by the tires, e.g. in case of horizontal breaking forces. In the winter, damage may show up as cracks, or, even worse, as de-bonding between BEJ and pavement (Figure 3).

In order to obtain a fully functional and waterproof system, the interface between the asphalt pavement and the bituminous plug joint materials deserves special attention [5]. This is particularly true during the construction phase which requires careful pre-treatment and activation of the BEJ-tanking sides and should only be carried out on dry material and in dry atmosphere (no rain). In addition, these pavements must have an air void content of less than 6 Vol-% otherwise a 1.0 m wide pavement patch of dense pavement, such as MA, should be placed on both sides of the BEJ in order avoid lateral water infiltration during construction and under service conditions because of the water barrier effect of the BEJ.

BEJ for large Joint Movements

In case of BEJs for large joint movements (b $\geq$ 500 mm), most of the basic principles and requirements (such as waterproof) remain, of course. However, the system may contain additional mechanical moving aids that are surrounded by the BEJ filling mixture and mechanically anchored to the concrete of the bridge deck on both sides of the joint. This makes the system more complex and deserves additional consideration. In Figure 2 half of such a system with a row of springs embedded in the filling mixture is depicted schematically.

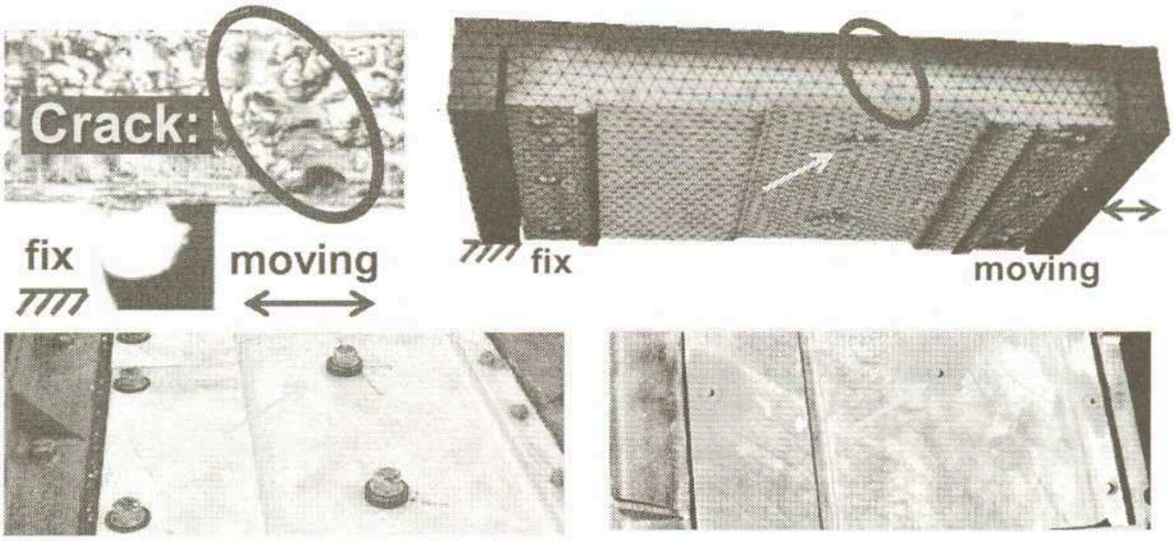


Figure 3. Top: Failure in tension at -20°C (left), normal stresses in gap opening direction right) - arrows mark the critical bolts; Bottom: Different fixations of the sliding plates, with protruding bolt heads (left) and countersunk bolt heads (right)

The steel plate may be replaced in these BEJs by a more sophisticated sliding plate kit with one-sided fixation. The construction of these sliding plate kits is special and may lead to premature failure. Figure 3 shows an example of a sliding plate kit where failure at -20°C was observed in a joint movement test with a joint opening velocity of 10mm/h (see below) after two tension compression cycles reaching only about 35% of the intended joint opening capacity [1] . Also shown is the linear elastic 3D Finite Element calculation of the normal stresses in gap opening direction with Abaqus which clearly reveals a stress concentration around the bolts for the case shown to the left of the figure. This stress could be reduced by countersunk bolt heads as shown to the right of the figure. With this improved configuration the BEJ survived 20 cycles at -20°C.

Depending on the type and construction of the mechanical movement aids, BEJs for large deformations may have some advantages with respect to the adhesion stress situation at the interface between the filling material and the adjacent pavement material. As shown in the finite element calculation in Figure 4, most of the stresses are taken over by the mechanical fixation of the movement aids. This does not prevent from a good pre-treatment of the BEJ-tanking side and a careful filling to assure waterproofing, of course. It also means that the distance between the fixation and the tanking side should be large enough to allow proper filling.

Figure 4. Von Mises stresses concentrating at the fixation of the moving aids of a BEJ for large joint movements

SPECIAL TEST PROCEDURES

General Tests for BEJ

Low-noise BEJs are special multifunctional bridge deck pavement elements that may have high impact on traffic safety (skid resistance, evenness, potholes from material loss) and durability of the bridge structure. Hence, they must be carefully evaluated and tested in type and quality testing as well as self-control testing during construction and placing. Testing of BEJs for small joint movements according to guidelines (ASTRA 806.315.d, 2005) is summarized in Table 1. Since most of the tests are well known and related to European Standards, only some special methods will be shortly described below.

However, BEJs for large joint movements cannot be assessed alone with the tests in Table 1, but need special performance related accelerated systems tests that provide information about possible risks of failure in practice. Empa has successfully developed and applied two different types of tests, one for the mechanical resistance to rutting from traffic using the MMLS (Model Mobile Load Simulator) and another one for the resistance to cracking at cold temperatures due to repeated slow quasi-static joint movements using the Empa-JMS (Joint Movement Simulator). These test are in line with the European Technical Approval Guideline for Expansion Joints under discussion (ETAG n° 032, Part 3: Flexible Expansion Joints) and will therefore also be described in the following.

Table 1. Testing of BEJs for small joint movements (ASTRA 806.315.d, 2005)

	Suitability/Application			Identification/ Characterization
	Hot: Workability	Warm:Summer	Cold: Winter	
BEJ Binder	Heat-Resistance[1)] *Dynam. Viscosity* *Segregation* Polymer-Conditions (GPC) Placing Temp.[2)]	Flow Length 60°C	Elastic Recovery Ductility 0°C	Visual Aspect[3)] *Density* *Composition* Polymer Distribution (Homogeneity)
		Dynamical Properties in Service Range (Complex Modulus, Phase Angle)		
Aggre-gates	*Heap-Density* Heat-Resistance[1)] Dust-Content[3)] Placing Temperature[3)]	Shape, Round Aggr. Breaking[1)]		Visual Aspect[3)] Aggr. Type & Clean. *Density, Bulk Density, Porosity* Gradation
BEJ Filling		Penetration 5, 23, 40°C	Indirect Tension -20°C[1)]	Visual Aspect[3)] *Density, Bulk Density, Air Void Content Ratio Aggr./Binder*
BEJ System			*Cyclic Test -20°C (Traffic-Fatigue)* Adhesion-20°C[1)]	
		Elongation-Compression-Test, (Temperature-Fatigue) –20..50°C		

Italic: only type testing; Standard: also quality test; [1)] in case of doubt also quality test; [2)] self-control during construction and placing; [3)] self-control and quality test

Polymer Conditions (GPC)

Gel permeation chromatography (GPC) separates the binder components according to their molecular size. This is done with different detectors, such as UV detectors. The approximate molecular weight can be deduced from the analysis of a polystyrene standard under the same conditions. GPC is a valuable tool for identifying the binder and characterizing the polymers normally used in BEJs in the as-delivered condition by providing a molecular fingerprint. It allows determining the polymer decomposition due to the installation process, hence providing a means of verifying heat sensitivity of the most common polymers in the binder and determining thermal damage of the binder. Figure 5 shows how GPC allows detecting segregation of the polymer in the container of the filling material as well as differences in material and installation quality. In the diagram to the right, "System C: NW" shows the highest content of polymers with largest molecule size. As compared to this, the largest peak in case of "System C: TI" is much smaller and a little bit shifted to the right. This indicates that the composition of this presumably same binder was most probably not identical. In case of "System C: AG" the main peak is not shifted to the right, but much smaller and the second peak (which is also not shifted) becomes significantly higher. From this, one would conclude that the material was originally identical to the "System C: NW" but had suffered considerable overheating and molecular damage (smaller size of the molecules).

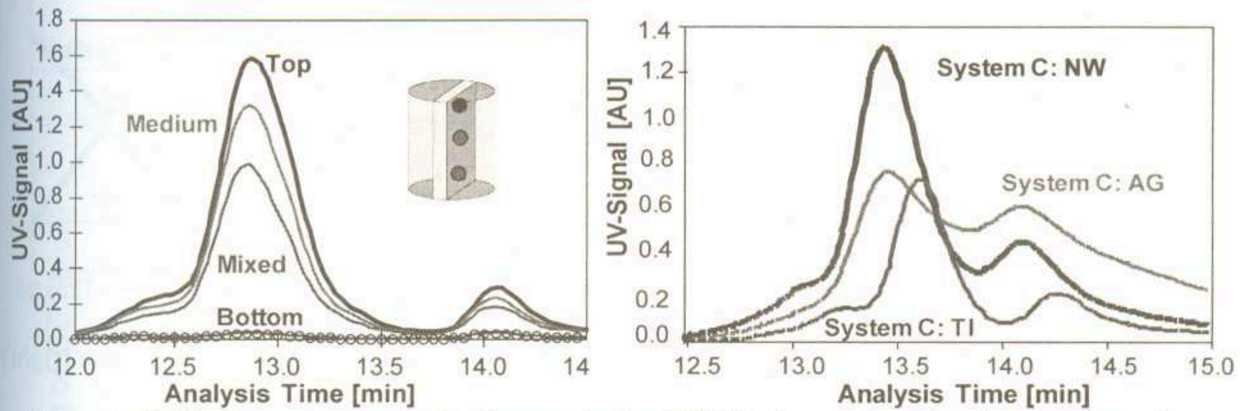


Figure 5. GPC-chromatograms of polymers in the BEJ binder; segregation in container of filling material (left); BEJ filling material C with different quality at different installation locations (right): NW good reference, AG overheated, TI smaller polymers

Adhesion Testing

Adhesion tests can be conducted either on laboratory specimens or on cores from a bridge. The test specimens have a diameter and height of 100 mm and are cored centrically from the adhesion plane between BEJ and the pavement (typically mastic asphalt MA) such that the cross section of the cylindrical specimen contains two semi-circles of each material. Tests are performed with a speed of 10 mm/min at –20°C. In [1] it was shown that the pull-off adhesion strength between BEJ and the adjacent pavement on bridges with good performance after a few years must clearly exceed 1.8 N/mm^2.

Traffic and Temperature Fatigue Tests

These two tests were developed by the German Institute BAM in Berlin, based on experience with their BEJs. They are conducted on small model systems (length x width x height = L x B x H= 500 mm x 235 mm x 70 mm).

The traffic fatigue test is conducted with a frequency of 1 Hz at -20°C in load groups of 6 different joint opening amplitudes, i.e. 0.37 mm, 0.43 mm, 0.49 mm, 0.55 mm, 0.61 mm and 0.67 mm, and 6 different numbers of cycles, i.e. 8'200, 1'220, 280, 180 and 60 cycles, for a maximum number of 1.3 mio cycles (i.e. 130 repetitions of the load groups).

The temperature fatigue test is conducted with a slow joint opening and closing at a speed of 0.2 mm/h. Starting at 15°C the specimen is cooled with 0.28 K/h down to a temperature of -20°C while the gap is continuously closed. Then the gap is continuously opened while the specimen is heated up to 15°C with 0.28 K/h and from there up to 50°C with double heating speed. From this point the gap movement and temperature regimes are reversed until -20°C is reached again and so forth. The loading regime for both tests is shown in Figure 6.

Rutting Performance Testing of BEJ for Large Joint Movements using MMLS3

This test is used in the laboratory and in the field for comparing the rutting behavior of a BEJ with a maximum width of 1000 mm at elevated summer-like temperature with the rutting behavior of the adjacent standard pavement (typically a mastic asphalt MA) that has been proven rutting resistant according to long term experience. Testing is done with the Model Mobile Load Simulator MMLS3 (Figure 7).

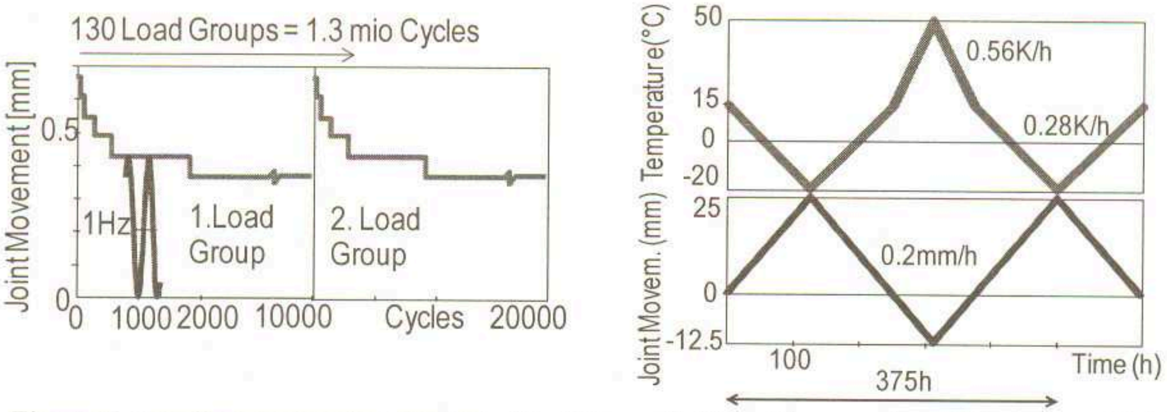


Figure 6. Loading regime for BAM traffic fatigue (left) and temperature fatigue test (right)

The MMLS3 consists of a rigid steel frame of 2'400 mm x 600 mm x 1'150 mm with four adjustable feet. The load is applied by four pneumatic tire wheels with a diameter of 300 mm and a width of 80 mm, which move like a chain saw in one direction along a rotary rail. The MMLS3 applies a load of up to 2.7 kN on each of its tires that are inflated up to 800 kPa. The distance between the tires is 1.05 m, and the MMLS3 operates at a maximum speed of 2.6m/s that corresponds approximately to a 4 Hz frequency of loading for a measured tread length of 110 mm. With regard to permanent deformation of BEJ, testing is often done at reduced speed by a factor of four in order to allow longer tire contact pressure interaction with the BEJ surface. Depending of the type of movement aids, it may be necessary to evaluate the performance not only in the main driving direction but also in a slight angle to this direction.

In case of field testing, heat is applied to the pavement and BEJ surface with a heating system, which blows hot air across the surfacing of the BEJ underneath the machine from a nozzle attached to a plenum duct along one side of the machine. On the opposite side a similar nozzle and duct sucks up the air and returns it via an electric heater in a closed loop to the first nozzle. To ensure an even temperature over the pavement surface, the flow direction is reversed every 15 minutes.

For testing in the lab, model system slabs are produced with the maximum design width of the plug joint and tested in a temperature chamber to allow full depth equal temperature. Profile measurements are made with a profilometer at three different locations after 60, 2'000, 6'000, 9'300, 15'000 passes (1 Hz). The selection of the three locations should be such that the influence of the fixations of the movement aids can be determined (e.g. on top of the L-profile in Figure 2).

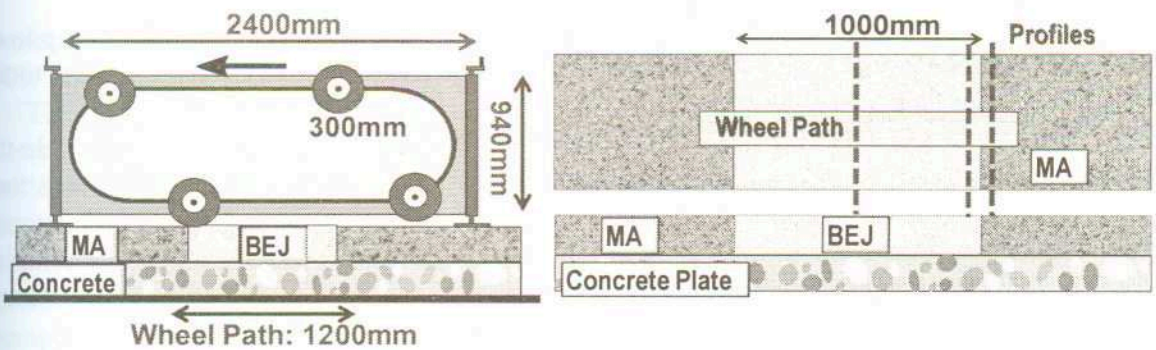


Figure 7. Model mobile load simulator MMLS3 and setup for rutting performance testing.

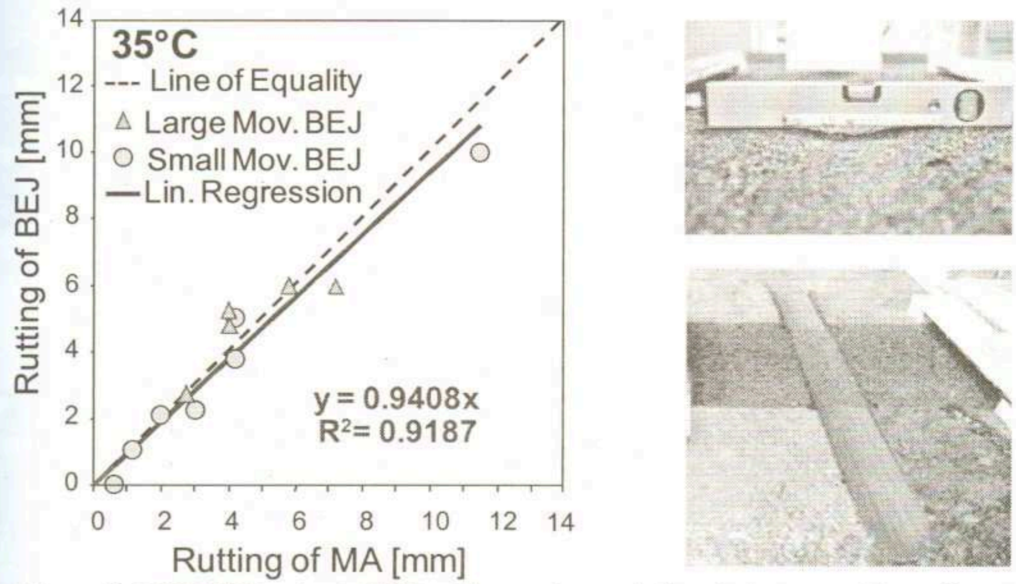


Figure 8. MMLS3 tests at 35°C with good correlation between rutting of mastic asphalt MA11 and two BEJs, one for small and one for large movements (15'000 passes, 1Hz)

Cold Temperature Movement Capacity of BEJ for large Joint Movements using JMS

The Joint Movement Simulator (JMS) is a horizontal stretching bench that consists of two parts: a stationary and a moving part that slides on rails. One side of the BEJ together with the concrete substrate is firmly fixed on the stationary part, whereas the other side of the BEJ is moved horizontally with a spindle motor in displacement-controlled mode (Figure 9).

The local expansion of the BEJ during loading is measured by determining the change in position of optical line markings that are drawn at spacing of 50 mm both on the surface and on the side of the bituminous joint filling material.

The force is continuously recorded while the BEJ is expanded from an original joint gap width of approximately $W_0 = 30$ mm to a maximum joint opening of $W_0 + \Delta W$ and then, at the same rate, pushed back to the original value W_0. This triangular movement cycle is repeated at least 20 times. The idea behind this approach is to determine fatigue behavior of the asphaltic plug joint system for 20 years; however, without being able to take into account long-term effects of traffic and weather in practice. Nevertheless, the test can be considered as quite severe, since it assumes that one full possible annual tension cycle takes place at the lowest declared design temperature of the BEJ with a fast gap opening rate of 10 mm/h. The test is performed at constant temperature, typically at –20°C, up to a joint opening movement of approximately 65% of the maximum admissible annual total movement for each system on a bridge.

Test results are evaluated as shown in Figure 10 by determining the load and cycle to failure and the strain distribution from evaluating the permanent deformation between the optical line markings in the horizontal direction. In addition, the vertical and lateral contraction is determined, which in case of large joint movement BEJs can be considerable and has to be taken into account in terms of driving safety and risk of lateral water infiltration.

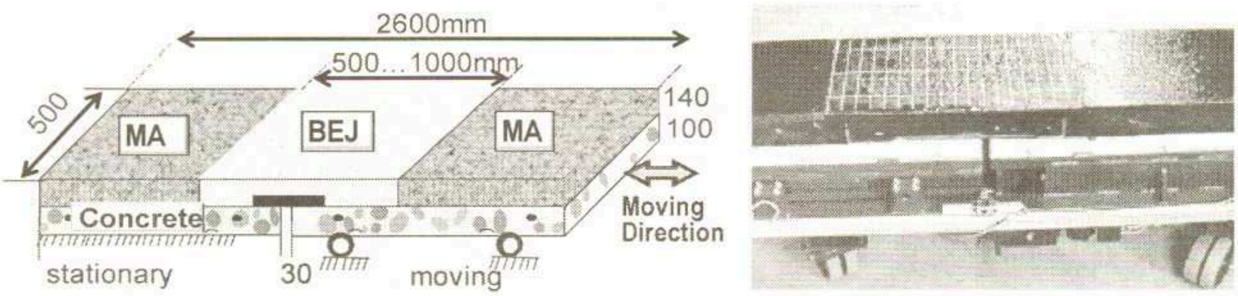


Figure 9. Joint movement simulator JMS and test setup

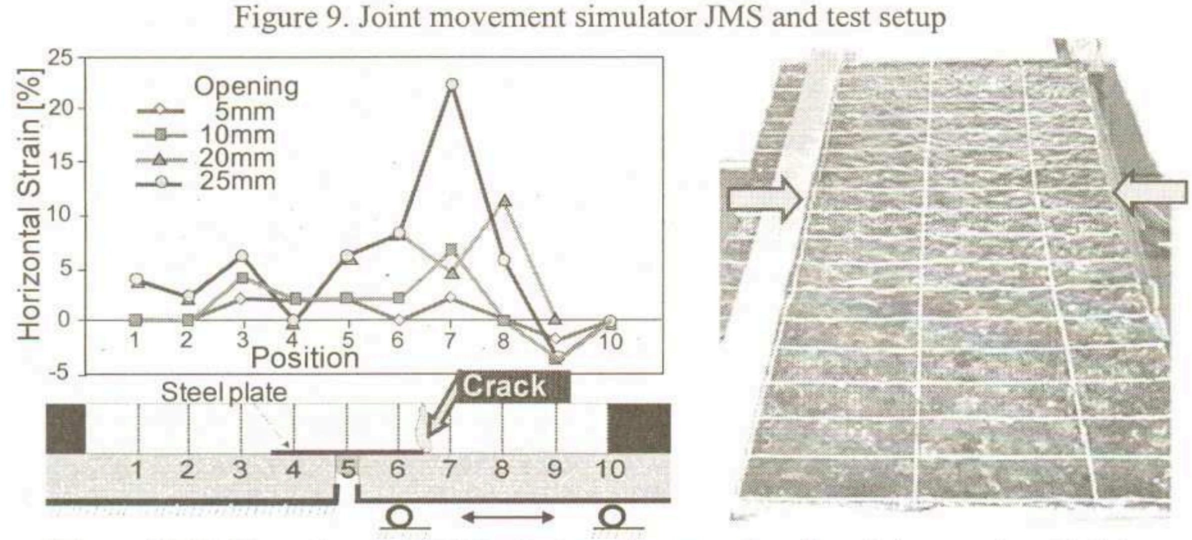


Figure 10. LMS results at -20°C (left); lateral contraction from joint opening (right)

Evaluation of the influence of moisture on the adjacent bridge deck pavement

Risk of moisture damage is of particular importance on bridges due the extreme weather exposure of most bridges and the risk of water accumulation at the BEJ. This is the reason why generally dense pavements with less than 6 Vol-% air voids should be used, or at least be placed in a 1.0 m wide stretch on both sides of the BEJ. However, due to the sensitivity of noise of the residents in urban regions and in order to take advantage of the noise reducing capabilities of BEJs the need for low-noise pavements such as porous asphalt PA on the whole bridge deck surface is drawing more and more attention (e.g. test site VD in Table 2).

Development of moisture damage assessment tools in terms of testing and modeling has made progress that last few years [8, 9, 10]. As an example, one promising test method developed in Switzerland and refined in collaboration with the University delle Marche in Ancona (Italy) will be shortly presented here. It takes into account the combined effect of water, temperature changes and cyclic mechanical loading. Details are published elsewhere [11, 12].

The method is based on the coaxial shear test CAST developed by Empa [13] for determining the modulus under triaxial strain constrained conditions. The test is performed under water as shown in Figure 11. The donut-shaped cored specimen is glued between an outer 150 mm steel ring and a central 50 mm steel rod. A sinusoidal axial displacement is applied at 10 Hz with 0.01 mm amplitude by means of the central steel rod in the same direction as on the road, i.e. vertically to the layers. During sinusoidal loading, repeated temperature ramps between 27°C and 32°C are applied with a rate of 1 K/h.

Figure 12 shows the Black diagrams for the decreasing temperature ramps of dry and wet tested laboratory compacted porous asphalt PA16 with 5.5 Mass-% of SBS polymer modified bitumen (pen=21 [0.1 mm]; R&B=83 [°C]) as reported in [11]. For the wet test, the ramps are clearly separated, the results for the first steepest ramp being at the highest and for the flatter last ramp at the lowest positions. Since the presence of water is the only difference between the tests, this evolution in terms of modulus reduction must be caused by moisture damage effect. By defining a water sensitivity index WSI, it was found in [11] that mixes with air void contents AV=13…25 Vol-% may have 4…20 times higher water sensitivity than a mix with AV=6 Vol-%. These results clearly show the importance of water drainage and the high durability risk with porous bridge deck pavements.

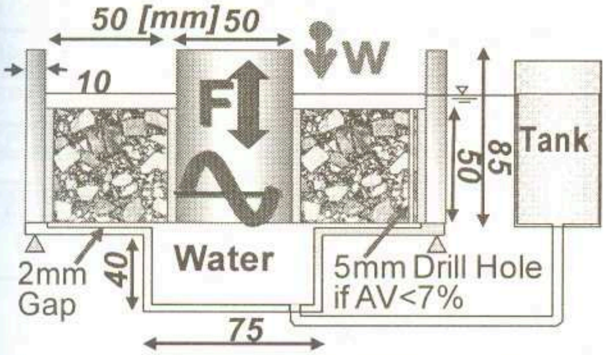


Figure 11. Setup of the wet test using coaxial shear test CAST (left); installed specimen in bright color for better visability (right)

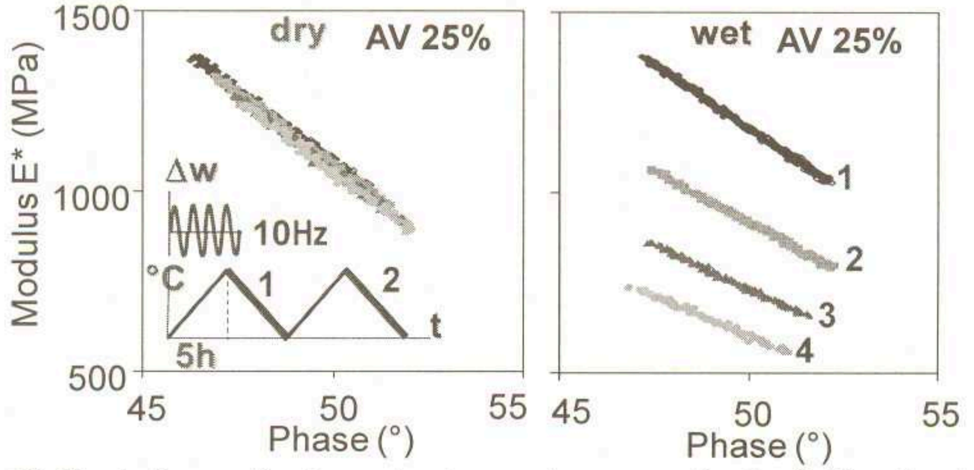


Figure 12. Black diagram for decreasing temperature ramps for dry (left) and wet (right) specimens, nominal air void content AV=25%

LONG-TERM FIELD PERFORMANCE OF BEJs FOR SMALL JOINT MOVEMENTS

Selection of Test Sites and Installation of BEJs

As a scientific basis for the Swiss guidelines (ASTRA 806.315.d, 2005), the impact of material properties, installation procedures, on site conditions and the field performance of plug expansion joints over a five-year period was extensively monitored and studied in a long term performance evaluation research program [2].

With the assistance of various public works departments of six regional Swiss governments (cantons), 18 BEJs for monitoring were installed in 1996 and 1997 on seven motorway and regional road bridges in typical climatic regions (Figure 13). The bridges were designed for joint movements between 5…48 mm and located at height above sea level ranging from 225…1710 m (Table 2). The selected BEJ systems were the four most commonly used products in Switzerland at that time. All bridge deck pavement surface layers consisted of mastic asphalt MA or asphalt concrete AC, except for the bridge (VD) where the top layer consisted of porous asphalt PA.

Table 2. Bridges monitored in the survey

Bridge Object	Can-ton	BEJ Types	Road Type	Traffic	ASL [m]	Climate	Expected Horiz Movem. [mm]
Sisseln	AG	4	Motorway	heavy	340	Low Land	7…19
Fulach	SH	2	Canton. Rd.	medium	425	Low Land	5 (abutment) & 46
Inn, Isla Glischa	GR	2	Canton. Rd.	medium	1710	Alps	27 & 45
Fahrlibach	NW	3	Canton. Rd.	moderate	490	Pre-Alps	6 (abutment) & 24
Pont sur la enoge	VD	1	Motorway	heavy	418	Low Land	10…15 (& ca. 3 dyn., vertical)
Semiponte Roncaccio	TI,1	4	Canton. Rd.	heavy	225	South Alps	20
Viad. delle Cantine	TI,2	2	Motorway	heavy	330	South Alps	5 (abutment) & 32 … 48

All operations performed during installation were precisely observed and recorded. In order to assess the impact of the produced materials on the BEJ behaviour and for determining the changes in material properties under service conditions, the properties of the installed materials were examined in the original (as-delivered) state, after installation and during service, using chemical/physical analytical methods. Changes in the condition of the plug joint systems, e.g. debonding, cracking, blistering, material displacement etc., were periodically visually surveyed, recorded and rated by an expert group. In addition, long-term measurements of joint movements were conducted and the polymer-modified BEJ temperatures recorded for one of the structures.

In Situ Survey and Performance Evaluation

During the five-year monitoring period, three plug joints had to be partly or totally replaced due to severe damage. In these cases, excessive joint movement (up to 43 mm), leaks in the adjoining pavements and overheating of the binder during installation were the main causes of failure. Lateral debonding in non-trafficked areas, e.g. bridge parapet/footway zones, was recorded for nearly 70 % of the investigated polymer-modified BEJs. These non-trafficked locations clearly represent weak points in polymer-modified BEJ systems. The percentage of the total number of BEJs that suffered damage in the parapet zone, the border zone and emergency lane as well as the traffic lane are shown in Figure 13. In the bridge deck area, cracking and partial debonding were the major damage phenomena followed by blistering. In the parapet zone partial debonding was predominant.

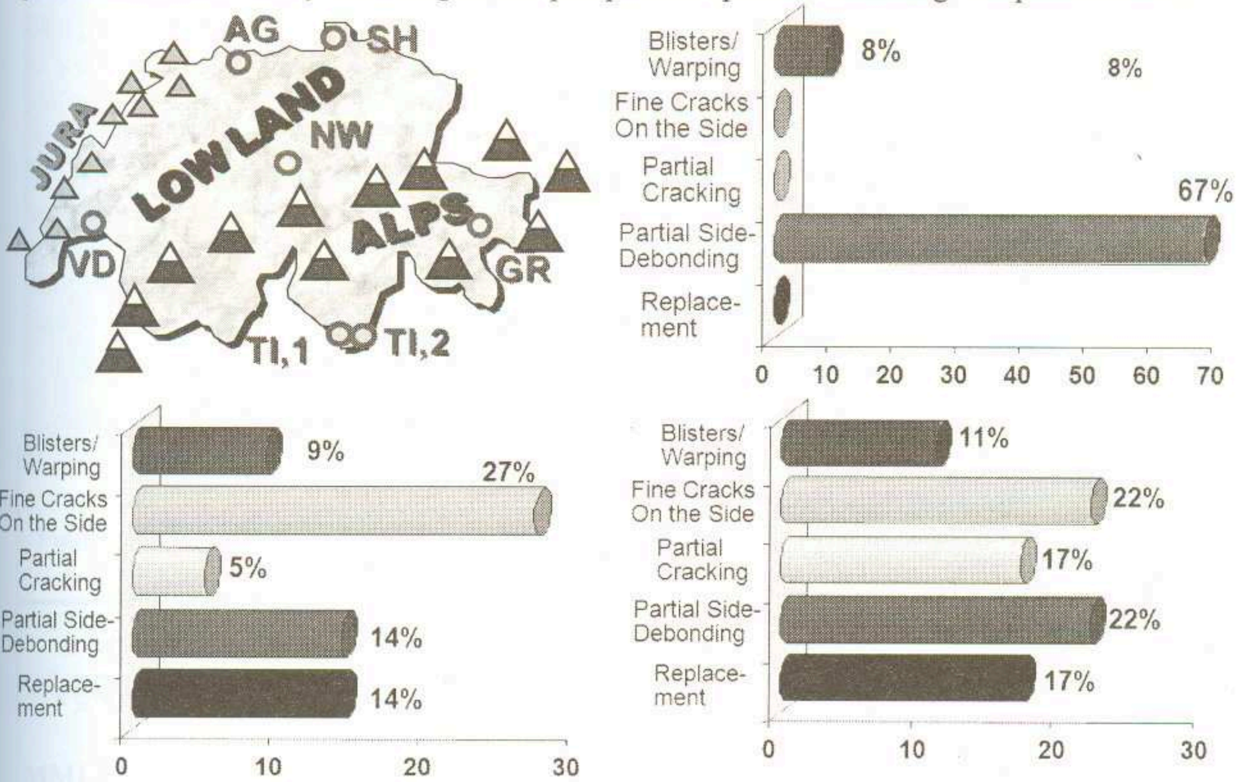


Figure 13. Locations of the BEJs (top left) and results of the damage assessment of the expert group at parapet (top right), in the border zone & emergency (bottom left) lane and in traffic lane (bottom right)

The high percentage of debonding underlines the importance of quality assurance during installation. In particular, installation should be avoided during rainy weather or in case of wet surfaces on the sides and bottom of the BEJ-tanking. For activating the BEJ-tanking side surfaces, it is recommended to use a hot-air fan because it blows also away the weak zones of the pavement. However, activation of the MA surface at the BEJ-tanking side surface has to be carried out carefully to avoid partial burning and overheating of the connecting PBM strip. Too little heating on the other hand may not activate the surfaces sufficiently. The use of bonding agents may be tricky and counterproductive. This is particularly true for agents with solvents which should also be avoided for environmental and health reasons. Adhesion test results in this investigation showed that the use of such bonding agents might also have negative mechanical effects, since the solvents may be partly absorbed by the mastic of the adjacent pavement and therefore not fully evaporate. Hence, solvents may remain trapped in the interface between the BEJ filling and the pavement, thus weakening the adhesion resistance and promoting debonding in wintertime when the maximum opening of the joint occurs.

The laboratory investigations described in the study revealed wide variations in the quality of the same binder product. This explains the sometimes divergent behaviour in different structures in spite of installing the same polymer-modified BEJ system by the same team (Figure 5). These findings further underline the importance of a quality certificate for the approval of polymer-modified BEJ systems and a control mechanism to verify material quality during manufacture and installation, in compliance with the guideline (ASTRA 806.315.d, 2005). However, it is interesting to note that some of the binder test results in the lab were in many cases clearly related to the performance in the field and the ranking of the expert group. Figure 14 shows the change of rating and properties over the years for the BEJs in dense pavements with respect to heat resistance in the lab tests and GPC measurements of polymer degradation in the field. Also shown are the dashed lines of requirement, dividing the zones with bad and good behavior. The agreement between lab and expert assessment is particularly satisfying in case of GPC polymer degradation. One specimen (TI,1) showed good expert rating of performance and moderate polymer degradation in the field, but bad rating in terms of heat resistance of the BEJ binder. This was probably due to the negligible loading from the little joint movements of this bridge which may have compensated for the unfavourable heat resistance properties in practice.

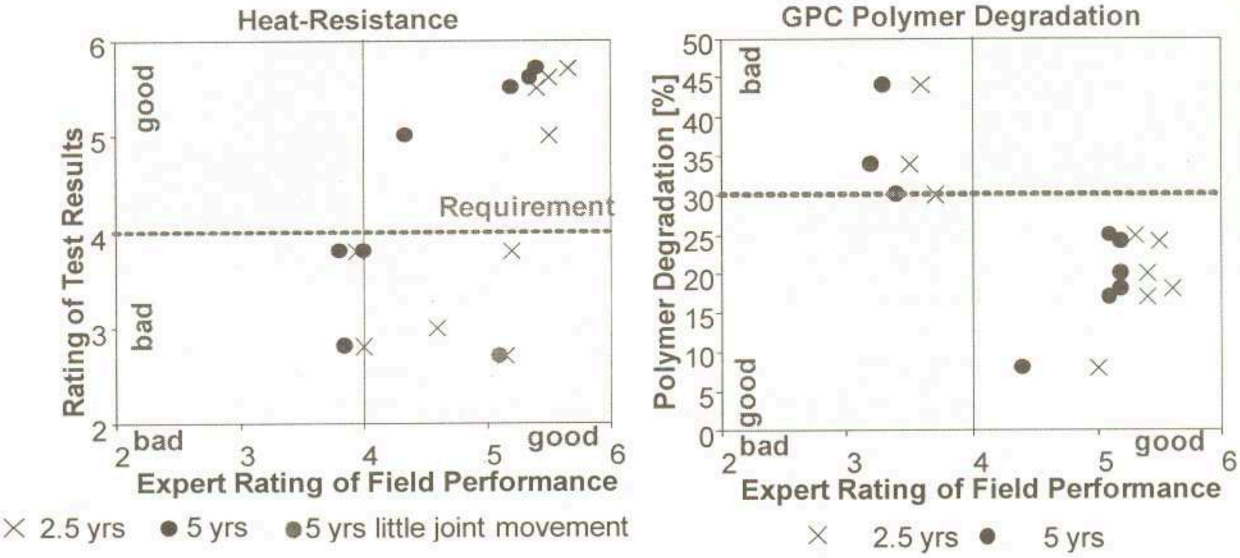
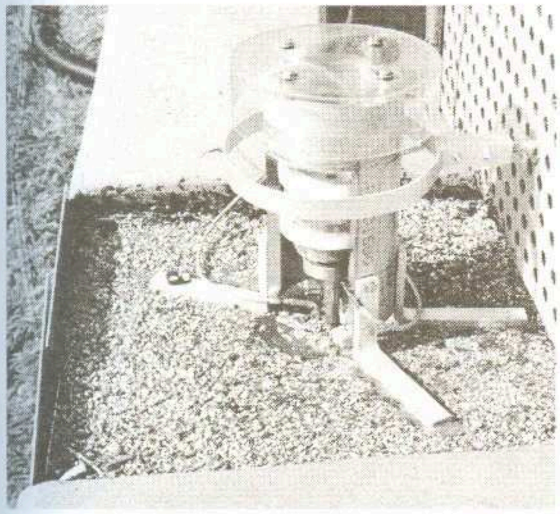


Figure 14. Lab results for heat resistance (left) and GPC polymer degradation (right) as compared to the expert assessment over a time period of five years

The potential change of polymer properties of the BEJ-filling in the field over the years could directly be demonstrated in one case (AG) with a new high frequency torsional rheometer HFTR which measures the material properties after removing the surface dressing right on top of the temperature and UV exposed surface of the BEJ filling. The method is based on resonance frequency measurements in the kHz range and is described in detail elsewhere [4, 6]. However, the development of the elasticity number cd (which is basically representing the elasticity of the material) in Figure 15 shows that there was a general shift over the years towards stiffer behavior in this specific BEJ.

The study brought much to light the influence of installation equipment and workmanship. Key requirements for the durability of BEJ systems were shown to include: a strong bond between the BEJ filling and BEJ-tanking side, strong cohesion between aggregate and binder, maximum expansibility and load bearing capacity of the BEJ- filling in both warm and cold conditions and a void-free BEJ mixture. Prerequisites for achieving these properties include comprehensive training of staff in handling materials, equipment and test apparatus, as well as strict compliance with good practice, backed by a quality control regime.



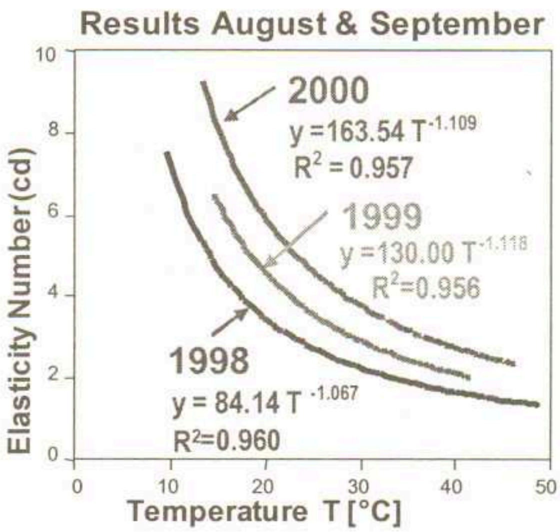


Figure 15 High frequency torsional rheometer installed on the BEJ (left) and comparison of regression curves for the elastic constants cd over temperatures in August and September of different years (HFTR measurements)

BEHAVIOR OF WIDE BITUMINOUS PLUG EXPANSION JOINTS AFTER HEAVY TRAFFIC

MMLS3 Field Testing of wide BEJs on a Multi-Span Bridge

In some special cases it may be necessary to install BEJs with a width exceeding 500mm. This may hold for multi-span bridges where the construction requires merging two plug joints (Figure 16) or in case of BEJ replacement, when the locally cracked or deteriorated pavement needs to be cut-off on the side of the trench. In order to account for such situations, condition and performance of ten quite special BEJs were investigated after heavy traffic loading and weathering, immediately prior to demolition of the relevant bridge structure. The plug joints were located on a series of 80 m span slope-side bridges of the A2 motorway in the Mediterranean southern part of Switzerland (TI,2 in Figure 13) with a traffic volume in each direction of 30'000 vehicles per day. The width of these plug joints ranged between 750 mm to 1'370 mm, thus considerably exceeding the standard width of 500 mm specified by Swiss guidelines (ASTRA 806.315.d, 2005). The horizontal design movement was between 8 to 48mm as indicated in Figure 16.

The goal of this study was to evaluate long term performance over and after a loading period of seven years, the assessment of specific refurbishing and repair actions undertaken immediately before the observed loading period as well as the investigation of the remaining rutting potential before demolition of the bridge.

Changes in the condition of the flexible plug expansion joints, such as debonding, cracking, blistering, material displacement etc., were recorded. Key mechanical laboratory tests as listed Table 1 were performed. Visual inspection after seven years showed that the BEJs were in good condition and that only fine cracks with unknown depth along the sides of the BEJ–tanking were visible. The course surface chipping (8/10 mm) of the surface dressing was still in place.

On-site investigations of the remaining rutting resistance of the plug joints within and between the wheel paths were conducted using the MMLS3 as indicated in

Figure 16. MMLS3 testing was performed in a tent at 30°C measured 20 mm below BEJ surface. This temperature condition was produced with a pair of heating fans. The experimental setup and the results are shown in Figure 17.

Except for the testing between wheel track at the testing site MMLS-3, with partly replacement of the BEJ top, all rut depths after 6'000 passings at 30°C remained clearly below 5 mm, i.e. in the order of 3 mm. From this result one can conclude that partial renewal of the BEJ surface material can only be considered as a temporary solution and should be evaluated very carefully.

Experience with BEJ's for large Joint Movements

Polymer-modified BEJ systems with movement aids have been developed recently in Switzerland for total annual maximum joint movements of 100 mm and 70 mm [7]. These systems, here labeled S9 and S7, consist of a row of springs which are embedded in the bituminous joint filling material at spaces of approximately 150 mm and anchored to two opposite L-shaped profiles as shown in Figure 18. The springs are used to enforce a homogeneous longitudinal strain distribution in the plug joint during joint movements and to reduce the risk of local strain concentrations which could lead to cracks and failure. The joint filling material is supported over the joint gap by specially configured steel plates with sliding capabilities.

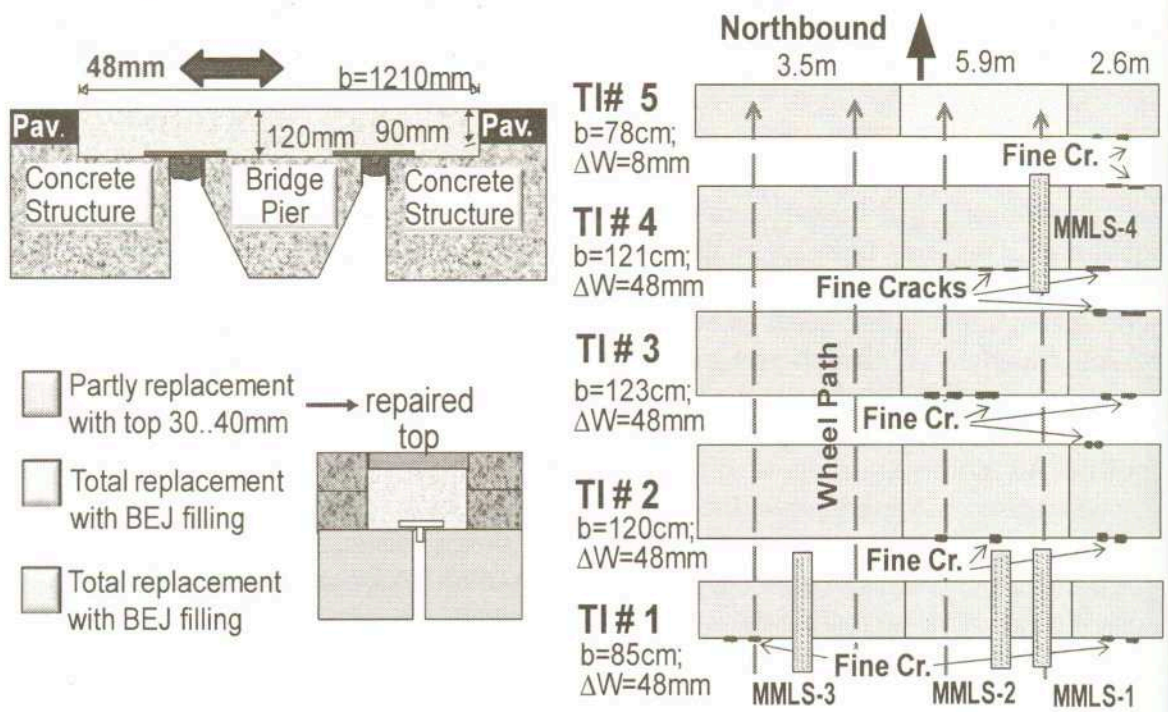
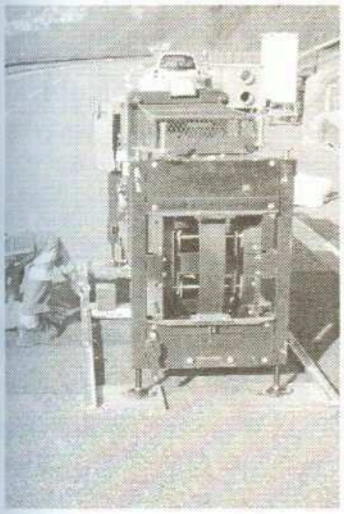


Figure 16. Wide BEJ systems, northbound MMLS3 testing sites and 7 year visual performance on Motorway A3 in southern Switzerland.

All test specimens were made by the manufacturer using gap graded 22 mm aggregates and 25 Mass-% binder with ca. 11 Mass-% SBS polymer-modified bitumen. The air void content was negligible.

JMS test were performed at -5, -10, -20°C with a max. joint opening Δw= 65 mm (S9) and at -20°C with Δw= 65 mm (S7).



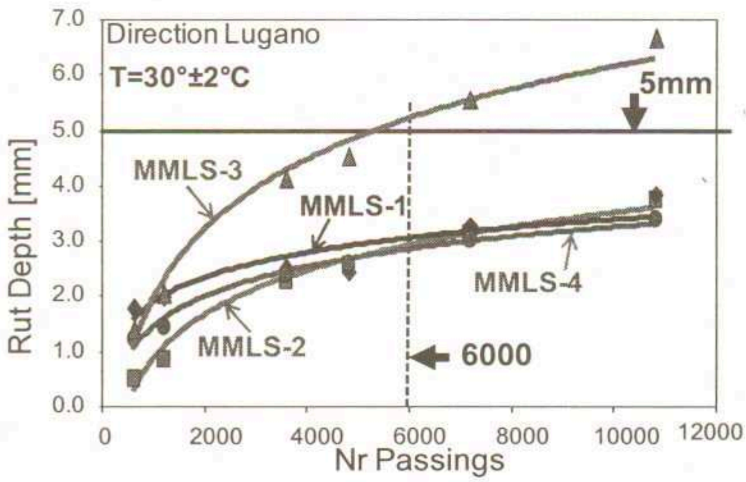


Figure 17. MMLS3 Setup before installing tent and heating fan (left) and rutting results on the northbound MMLS3 testing sites

The maximum force for S9 and S7 at –20°C was approx. 80 kN and 60 kN respectively. After the first cycle, the force decreased by about 20 % to 30 % (Figure 19) showing clearly that the maximum loading capacity during gap opening has been reached before the gap closing movement was activated. This gap closing movement started at the inflection point. During the gap opening of the next cycle, the load could not exceed the load value in this inflection point, of course. Reaching the maximum loading capacity during the first cycle is a clear indication that some significant damage in the BEJ occurred.

During joint opening of S9 up to 65 mm at –20°C, strains between the adjoining asphalt pavement and the L-shaped steel anchors of the springs remained minimal and most deformations are distributed in the zone between the two L-shaped steel anchors. The part of the asphaltic plug joint above the sliding steel plate suffered the most significant local expansion Figure 19. In JMS tests, S9 showed significant lateral contraction of about 16 mm (Figure 10, right) and a thickness reduction of 7mm.

Neither crack formation nor lateral debonding was observed in S9 after 20 test cycles. One of three S7 specimens suffered a crack after 18 cycles.

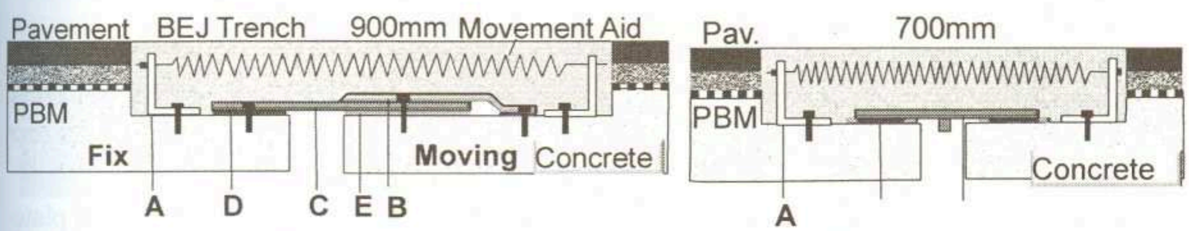


Figure 18. System S9 (left) and S7 (right); A = spring anchor, B = upper steel plate, C = bottom steel plate, D = sliding bearing, E = deformation layer, PBM =

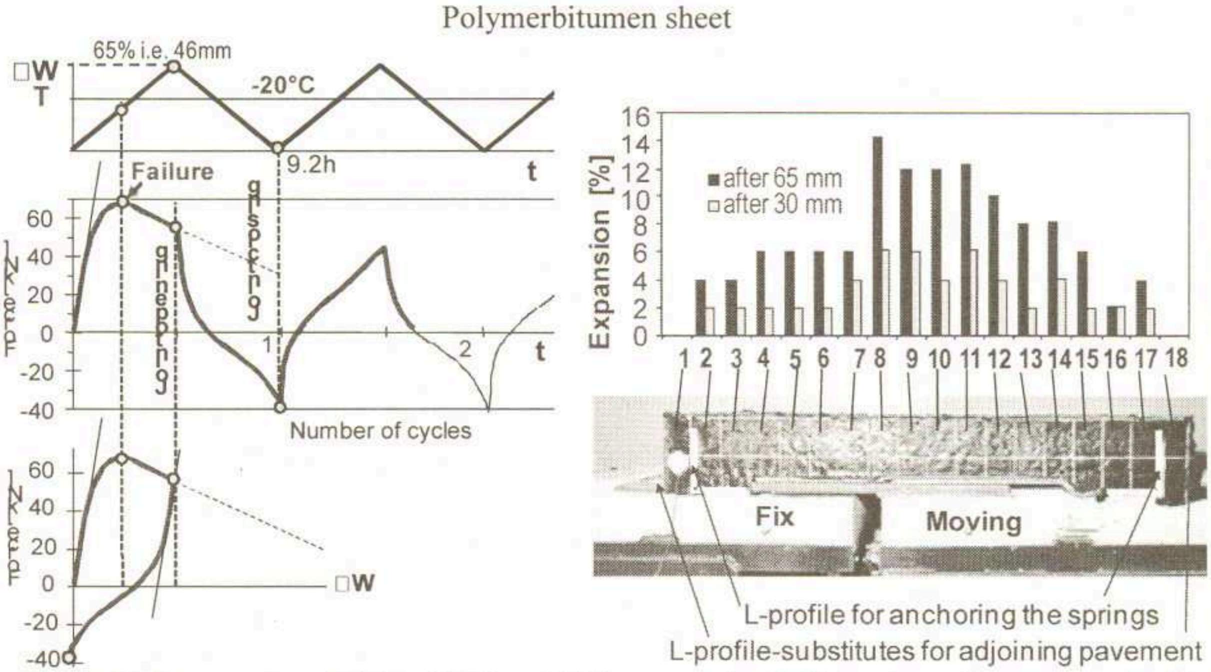


Figure 19 Test results of S7 at –20°C and 9.2hr per cycle (left); horizontal expansion in S9 at joint openings after 30 mm and 65 mm at –20°C (right)

Investigations of in-situ performance of S9 and S7 BEJs on bridges after about 1-6 years took place together with different experts, comprising visual assessment of cracking in the asphaltic joint filling material, lateral debonding, between joint and pavement, blistering, material dislocation, local deepening of surface, water tightness, etc. (Figure 20).

Generally, the different plug joints were in good condition. However, it has to be kept in mind that the assessment was not conducted at minimum temperatures (important for cracking) for practical reasons. Apart from a few defects, such as lateral debonding at the bridge parapet and in the centre line of the motorway in case of two relatively new sites, the condition of the inspected BEJs for large joint movements was rated as satisfactory. Based on visual assessment, all BEJs fulfilled their functionality as joint sealing. Hence, it could be concluded that the new type of BEJ for large movements showed promising performance in the laboratory and on site. The springs embedded in the BEJ material fulfilled their function to enforce a homogeneous longitudinal strain distribution within the plug joint during joint movements.

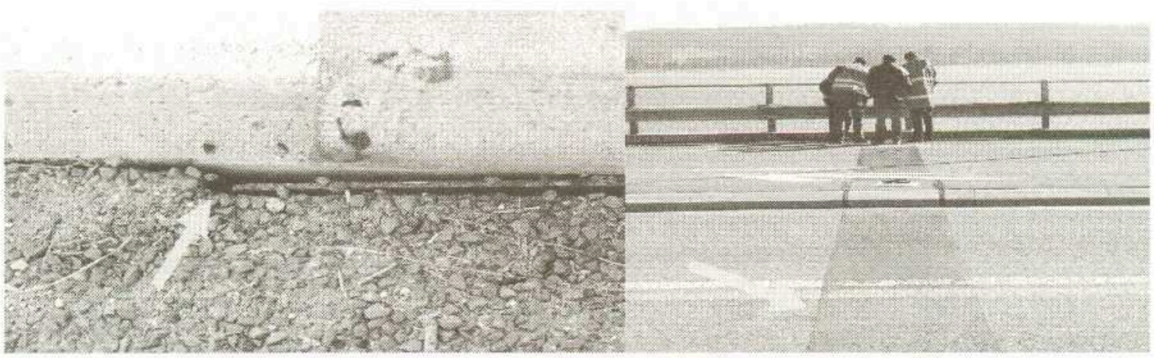


Figure 20. Edge de-bonding between asphaltic joint filling material and lateral metal plate (left); accumulation of binder at the surface edging.

CONCLUSIONS

Various investigations on low-noise bituminous plug joint systems (BEJ) for concrete bridges were presented. These investigations served as basis for guidelines by the Swiss Federal Road Office (ASTRA 806.315.d, 2005) and have certainly promoted the development of BEJ systems for small and large joint movements with good performance in moderate, alpine and Mediterranean climate. They also helped to eliminate poor systems, thus narrowing down the market to carefully engineered innovative products and reducing risks of BEJ failure for the last 10 years. This is promising news, since the advantage of noise reduction with systems for total joint movements up to 100mm together with the advantage of easy replacement and repair makes these type of plug expansion joints an attractive option in densely populated urban areas.

Most BEJs on inspected bridges in Switzerland showed good performance under traffic over several years. Cracking and debonding were the most common defects detected during visual inspections. Some surface cracking may be attributed to aging effects in the top zone of the BEJ-filling, as observed with the high frequency torsional rheometer placed on one of the bridges during a period of three years. Field survey and performance evaluation showed that long term behavior of BEJ joints in terms of rutting and cracking is generally still not at the same level as for asphalt pavements. On the other hand, MMLS3 testing demonstrated that rutting behavior in the BEJ filling similar to the adjacent MA pavement can be achieved. However, further research and development is certainly needed.

BEJ systems require careful construction, installation and quality assurance in order to fulfil their function. Careful construction means systems that do not produce stress concentrations from mechanical movement aids or from the sliding plate kit which may result in premature failure.

The system should be placed at moderate temperatures and under dry conditions. Particular focus should be given to the interfaces between the BEJ filling material and the adjacent surfaces. Solvents may have counterproductive effects in preparing the contact areas on the side of the BEJ-tanking and should therefore not be used for both technical and environmental reasons. In addition, "over"- and "under"-heating of the filling material should be avoided, since it can cause degradation of the polymer in the binder and insufficient adhesion respectively.

In order to avoid water infiltration from the sides of the BEJ-tanking, pavements with air void content below 6 Vol-% should be used. This is also important with respect to the risk of moisture damage and stiffness reduction in the pavement when exposed to temperature cycles and fast repeated mechanical loading in the laterally confined coaxial shear test CAST where open graded pavement mixes with 25 Vol-% may show 20 times higher water sensitivity as compared to a mix with 6 Vol-%.

Test procedures used in these investigations proved appropriate for laboratory and field performance assessment. As an example, good correlation with expert rating from visual inspections and GPC analysis in terms of polymer degradation was found. Systems testing such as the joint movement simulator JMS for low temperature behavior and the MMLS3 rut tester for elevated temperatures appeared useful tools. MMLS3 was also very appropriate for field testing and revealed that partial renewal of the BEJ surface material can only be considered as a temporary solution and should be evaluated very carefully

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