Measuring pavement response – Design, development and application of sensors and data evaluation for test and in-service pavements

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ABSTRACT: The main task of pavement engineers is the design and construction of pavement structures being able to resist traffic loads and climatic impacts over the design operating life. Pavement design is mostly based on empirical or mechanistic-empirical models. Monitoring pavement response and performance over a long period of time is essential for establishing these methods. Furthermore, mechanistic-empirical or analytical models need adequate material parameters as input. Material parameters are usually determined in dynamic laboratory tests, which in nature depend on the boundary conditions of the specific test method. Thus, these parameters are often more test-specific parameters rather than material parameters and often boundary test conditions are not consistent with in-situ conditions.

Accelerated testing and response measurements on instrumented full-scale pavements are suitable methods to bridge the gap between performance monitoring of pavement structures, laboratory testing and analytical methods. Usually they are the only means to validate theoretical models by measuring the mechanical response induced by traffic and climatic impact. Though a large number of tests on instrumented full-scale pavements have been conducted worldwide, the appropriate measurement of stresses, strains and deformations in pavement structures still remains a difficult task. Despite of the difficulties response measurements can provide important information to validate analytical models or to define adequate boundary conditions for dynamic laboratory tests of pavement materials.

This paper gives a short overview over the basic principles of pavement instrumentation and sensor design and shows examples and evaluations of selected response measurements to heavy vehicle and FWD loading at the full scale pavement test facility at the Federal Highway Research Institute BASt in Germany. Focus is on the evaluation of redundant sensor arrangement and statistical evaluation regarding the variations and scatter. Finally, an outlook is given on an improved sensor design and improved data acquisition techniques for long-term response measurements on in-service pavements.

KEY WORDS: Pavement instrumentation, pavement sensors, full scale testing, in-situ measurements, pavement response

1 INTRODUCTION

Pavement response measurements serve a number of tasks in pavement engineering:

- Gain general information about the structural behaviour of entire pavement structures under various loading and boundary conditions

- Derive mathematical relationships between loading, boundary conditions and response, e.g. wheel load or speed and strain/stress, influence of lateral wander, temperature, water content of granular layers etc.
- Perform (long-term) monitoring of structural performance to detect and describe deteriorations like loss of stiffness due to cracking, loss of layer adhesion, change of stiffness due to water intrusion in granular layers etc.
- Validate, improve or confirm mechanistic models
- Compare response and performance of different pavement structures
- Derive realistic boundary conditions as input for dynamic laboratory tests with special regard to loading frequencies, loading time and load amplitude
- Correlate measured strains and stresses with deflection parameters e.g. from the Falling Weight Deflectometer (FWD) or other deflection measurement systems as the Traffic Speed Deflectograph (TSD) to improve the interpretation of deflections
- Compare or calibrate deflection measurement systems as the FWD or TSD with deflections from pavement embedded instruments like Multi-Depth-Deflectometer (MDD), surface-embedded accelerometers or geophones
- Assist in back-calculation of pavement layer stiffness

Apart from the mechanical properties environmental and climatic effects are also of essential importance. In the following, this document focuses only on sensors for mechanical response measurements.

For the structural design or residual life assessment of pavements surface deflections are often measured to compute the layer stiffness in a back-calculation process and compute stresses and strains in a forward-calculation process based on the layer structure and the back-calculated stiffness. All these mechanistic procedures employ mechanistic models to describe the relationship between the load, geometry (layer system), displacements, stresses and strains including the material stiffness.

FWDs are usually employed to measure surface deflections. On the pavement side, MDDs, geophones and accelerometers can provide absolute displacements, deflection velocities or accelerations respectively. While MDDs provide absolute vertical displacements, deflection velocities from geophones or deflection accelerations from accelerometers require the signals to be integrated once or twice respectively to compute vertical displacements. Accelerometer signals have been compared to FWD deflections and applied successfully (Ferne 2009), but the data processing requires careful consideration (Arraigada 2007).

Each embedded sensor poses a discontinuity of the structure and a disturbance of the material and its stiffness which is impossible to avoid, but to minimise. At the same time sensor like strain gauges and pressure cells should be large enough to cover a representative element of the in fact inhomogeneous pavement material. Based on experience and common practice a reasonable recommendation for the minimum size of the sensitive element is about 2-3 times the maximum grain size of the surrounding pavement material. This is also recommended by manufactures of strain gauge patterns and common practice in experimental structural analysis. The tensile and compressive stiffness of asphalt strain gauges should be lower than that of the surrounding material to allow for an adequate deformation of the gauge and prevent a constraint of the surrounding structure. Asphalt stiffness changes with temperature and loading frequency and covers a broad range of E-Moduli which cannot be covered by a material used for sensors. Therefore the axial stiffness of an asphalt strain gauge is recommended to be lower than 500 MPa which is the approximate asphalt stiffness at temperatures about 40 °C. Concrete stiffness does not significantly depend on temperature and loading frequency and thus the axial stiffness of a concrete strain gauge could be higher but ideally not exceeding 5,000 MPa. Another critical design parameter for pavement sensors is the resistance against heat (up to 250 °C when placed in mastic asphalt) and dynamic mechanical impact during placement while the operating conditions are usually much more moderate.

Soil and earth pressure cells are commonly designed according to two principles. On basis of the hydraulic principle external pressure is transferred via a sensitive area of the cell case via a liquid inside the cavity of the cell. The uniform pressure of the liquid is then measured with a pressure sensor. As the liquid and the metal case have different thermal extension properties, any change in temperature will produce compressive stress inside the cavity. Thus, pressure cells based on the hydraulic principle are not generally suitable for long-term measurements under varying temperature. Alternatively, a compensation of the stress signal has to be employed whether by the use of electronics or a calibration procedure.

Another technical principle is the measurement of the deformation of the sensitive part of the cell case caused by external pressure e.g. by strain gauge patterns. The strain is related to the external pressure via a calibration procedure. Sensors based on this principle are generally suitable for long-term measurements. Both principles are suitable for dynamic measurements. For completeness, the vibrating wire technology has to be mentioned but will not be further explained. The vibrating wire technology is generally not suitable for measuring short-term dynamic response induced by traffic loads. More information can be found in Rabe (2011b).

2 BAST FULL SCALE PAVEMENT TEST TRACK AND 1ST GENERATION SENSORS

2.1 The BASt full scale pavement test track

The current configuration of the BASt full scale pavement test track comprises eight different asphalt pavement structures according to the German pavement design guideline RStO. About 200 strain gauges, pressure cells and thermocouples were installed in total according to the principle shown in Figure 1. The structure and instrumentation of three selected sections 3, 7 and 8 which are further examined in this paper are shown in Figure 2.

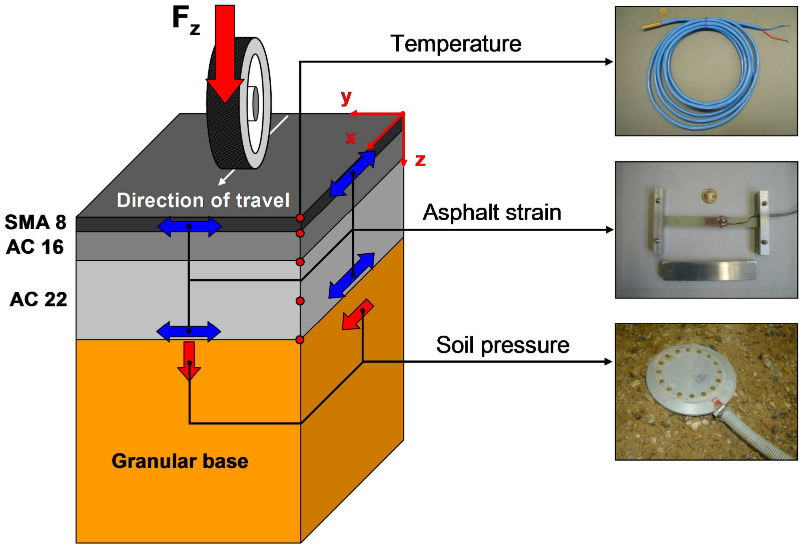


Figure 1: Sensor arrangement in the BASt full scale pavement test track (Rabe 2007).

A comprehensive test programme including response measurements under various heavy vehicle configurations under variation of speed, load, tyre types and -pressure and lateral wander was performed. Accelerated testing of selected sections employing the recently purchased Mobile Load Simulator MLS10 is currently in progress.

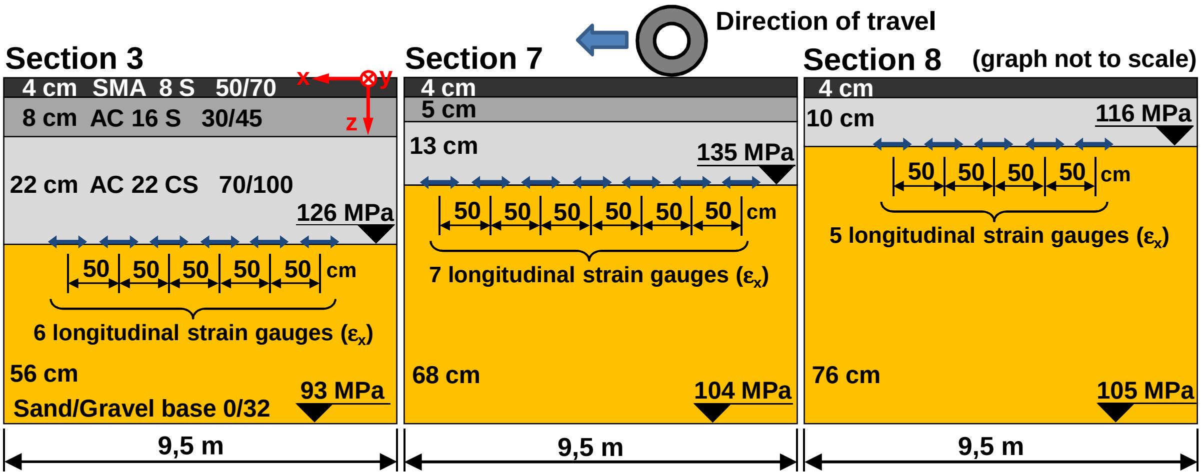


Figure 2: Structure, layers and material properties of three instrumented pavement sections at the BASt full scale pavement test track with embedded longitudinal strain gauges placed at the bottom of the asphalt base.

2.2 Asphalt strain gauges

The asphalt strain gauges employed in the BASt full scale pavement test track are in-house developments and follow the common design principle of pavement strain gauges. A strip of fibre-reinforced epoxy-resin serves as carrier for strain gauge patterns. The strain gauge patterns are arranged on both sides of the strip in a quarter-bridge circuit which ideally should compensate for unwanted flexural strain. Tension and compression forces in asphalt are transferred via aluminium anchors from the surrounding material to the carrier strip where the tensile and compressive strains are measured by the strain gauge pattern.

The E-Modul of the epoxy-resin was determined to be around 20,000 MPa. The strip and the strain gauge pattern are protected with an aluminium case cover to protect against mechanical impact and heat during placement and compaction. The dimensions of the sensor are length x width x height = 150 x 75 x 15 mm. The epoxy-resin strip itself has thus no contact to the asphalt and thus no shear stress/strain can be transferred from the surrounding material to the strip. This is a difference of the BASt strain gauge compared to other strain gauges (e.g. Dynatest, CTL). The teflon-shielded wires are heat resistant up to 250 °C.

The signal of the strain gauges was set to zero in the unstressed state shortly before a vehicle pass or FWD drop so that any offset due to pre-stressing of the strain gauges or temperature-induced strains were deleted. Figure 3 shows examples of Dynatest PAST-2AC and CTL ASG asphalt strain gauge as well as the BASt asphalt strain gauge of the 1st generation embedded in flexible cement mortar on a crushed stone base 0/45 mm.

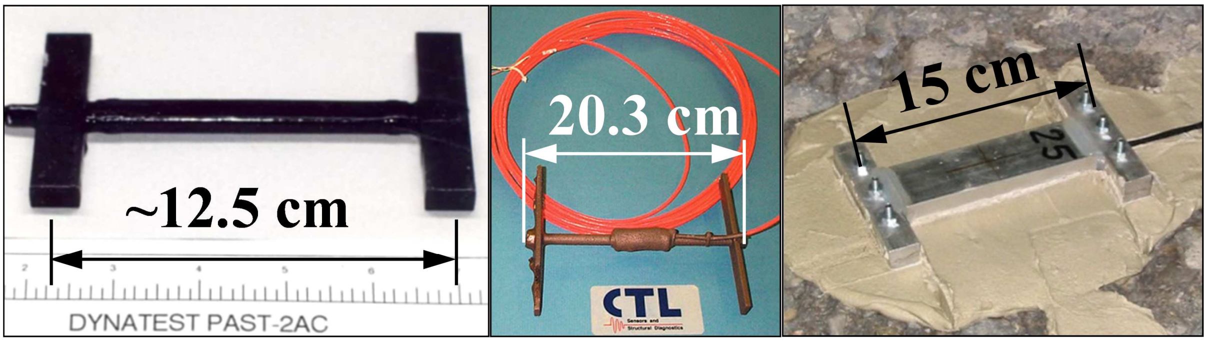


Figure 3: Dynatest PAST-2AC- (left), CTL- (centre) and BASt1st generation- (right) asphalt strain gauges (www.dynatest.com, www.CTLGroup.com, Rabe 2007).

2.3 Soil/earth pressure cells

The soil pressure cells installed in the current test track are based on the hydraulic principle of a cavity entirely filled with silicon-oil which transfers the pressure from the sensitive area of the cell to a pressure sensor inside the cavity. The dimensions of the cell are diameter x height = 150 x 15 mm. Aluminium was chosen as case material for manufacturing reasons.

A calibration procedure was conducted prior to placement by applying a uniform air pressure to the pressure-sensitive area of the cell and comparing the air pressure measured by an external sensor and the pressure of the silicon oil. The signals of both sensors proofed to be congruent and linear along the entire measurement range of up to 3,000 mbar.

The disadvantage of the hydraulic principle is the temperature-sensitivity of the pressure cell due to the different thermal expansion properties of the case material and the silicon oil. An expansion due to warming-up produces compressive stress inside the oil-filled cavity without any external pressure acting on the cell. For the short-term measurement of response to heavy vehicles and FWD loads on the granular stress the temperature dependency of the soil pressure cells was non-relevant because the signal was offset before the truck or FWD triggered the data acquisition. More details can be found in Rabe 2007 and Rabe 2011b.

The stiffness ratio between cell and surrounding material is also of essential influence. In the normal case of a relative stiff cell embedded in a relative soft material the effect of arching leads to stress concentration on the cell and thus to higher stress values measured.

3 PAVEMENT RESPONSE MEASUREMENTS

3.1 Pavement response to heavy vehicle loading

Figure 3 shows typical sensor signals in a 22 cm strong 3-layer asphalt pavement at the bottom of the asphalt base course and on top of the granular base induced by a single-tyred steering wheel with a static wheel load of 3.5 tons at creep speed of 2 – 3 km/h.

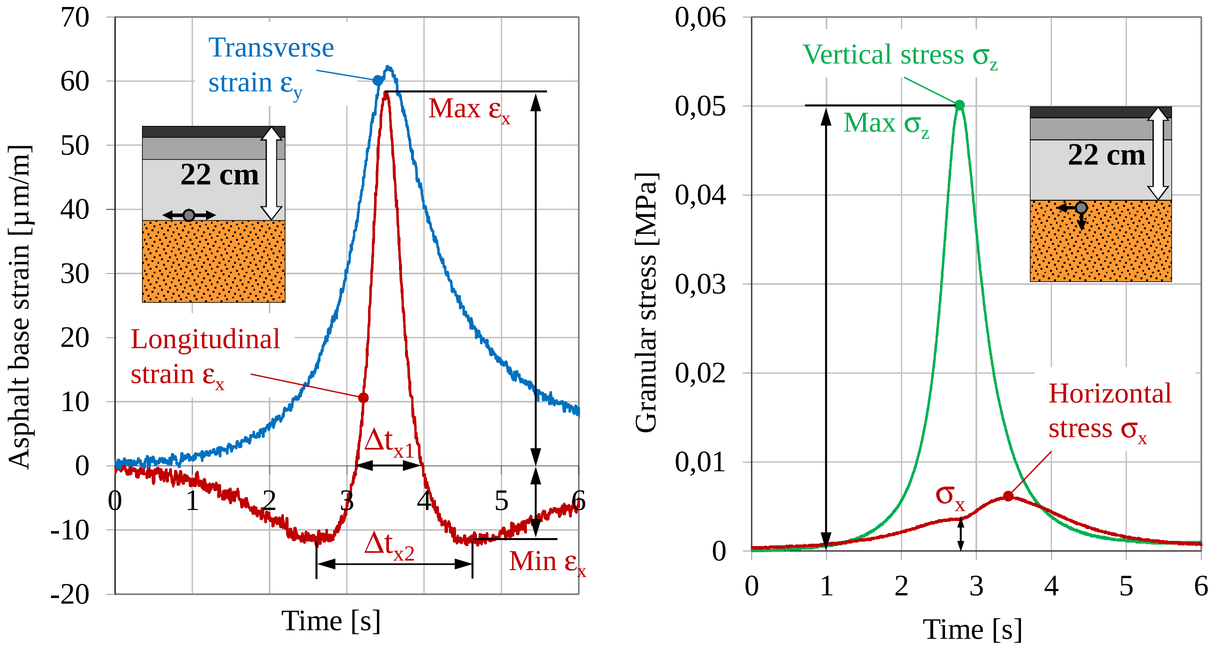


Figure 3: Asphalt base strains in a 22 cm asphalt package in longitudinal x- and lateral y-direction (left) and granular base stress in vertical z- and horizontal x- (right) direction induced by a 3.5 ton single-tyred steering wheel at creep speed.

Following general observations can be made from the signals:

- Longitudinal asphalt base strains are characterized by an alternating compression - tension - compression pattern during a wheel pass.
- In transverse direction only tension strains occur at the bottom of the asphalt package. The duration of the lateral tensile strain is significantly higher than in longitudinal direction, resulting in a lower lateral loading frequency compared to the longitudinal direction.
- The comparison of the duration of the tension in longitudinal and lateral direction shows that due to a passing wheel the asphalt stiffness in longitudinal direction is higher than in lateral direction which produces an "orthotropic" material behaviour.
- The loading time from zero to peak strain and the unloading time from peak strain to zero are different with a longer unloading time, confirming the viscoelastic material behaviour of the asphalt.
- Only compression stress occurs on top of the granular base in vertical and horizontal direction with the vertical peak strain being significantly higher (up to 10 times).
- At the peak of the vertical stress directly underneath the wheel the horizontal stress signals show a recession with a local minimum directly under the wheel.
- Peak values of response signals can be used to compare the measurements against calculations in theoretical models. The duration and shape of the signals provide important information on the loading times and the corresponding frequency and therefore the corresponding asphalt stiffness. By determining the frequencies on basis of the loading times, appropriate elastic moduli can be derived from the master curves of asphalt samples as input for structural calculations.

3.2 Pavement response to FWD loading – Multiple sensor arrangement and evaluation

To gain more information about the variations and the scatter, asphalt strain gauges were placed in a row of 5 to 7 sensors at longitudinal spacing of 50 cm in the outer wheel path of pavement sections 3, 7 and 8, respectively. FWD loading was performed on each sensor location by varying the load in four stages with 30, 50, 70 and 90 kN target loads. Figure 4 shows the strains from seven asphalt strain gauges (ASG) in section 7 with 22 cm total asphalt thickness at different FWD target loads. The mean value serves as representative "true" strain.

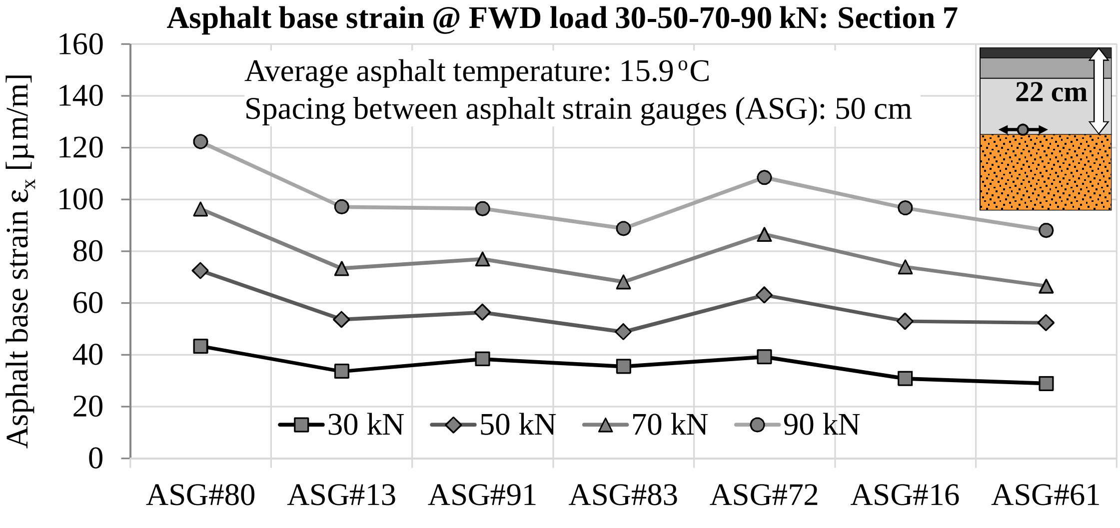


Figure 4: Asphalt base strains from seven strain gauges at the bottom of a 22 cm asphalt package on granular base at four FWD load levels in section 7.

Figure 5 shows the normalised centre deflections and asphalt strains. Both parameters were normalised with regard to the mean values of all seven sensors and FWD points, respectively, so that the difference in variations can be directly compared. It can be seen that the variation in normalised asphalt strains along all sensors is greater than the variation in deflections - which is an evidence of the relative homogeneity of the structure. This leads to the conclusion that the main reason for the variations in measured strains is the variation of the sensor characteristics and not the inhomogeneity of the pavement structure.

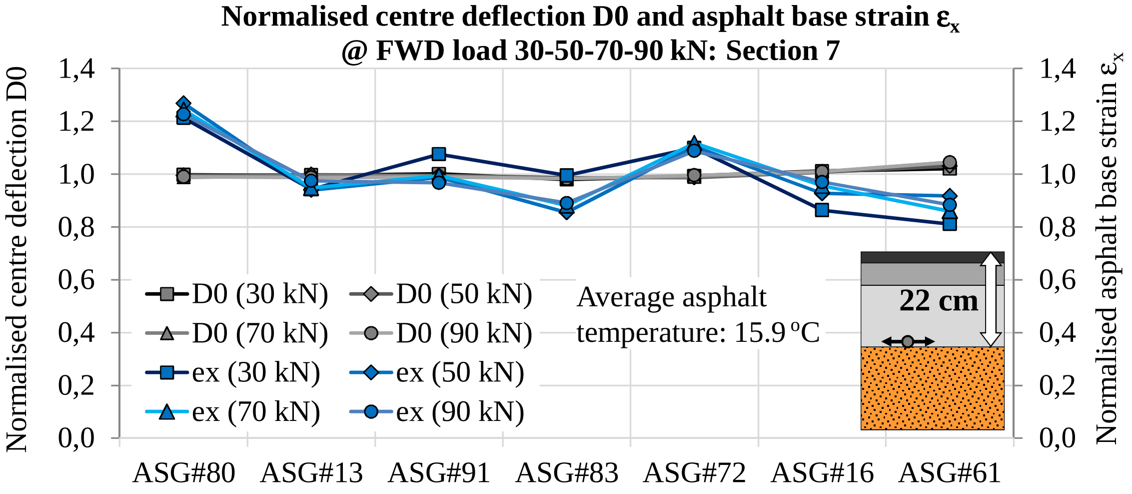
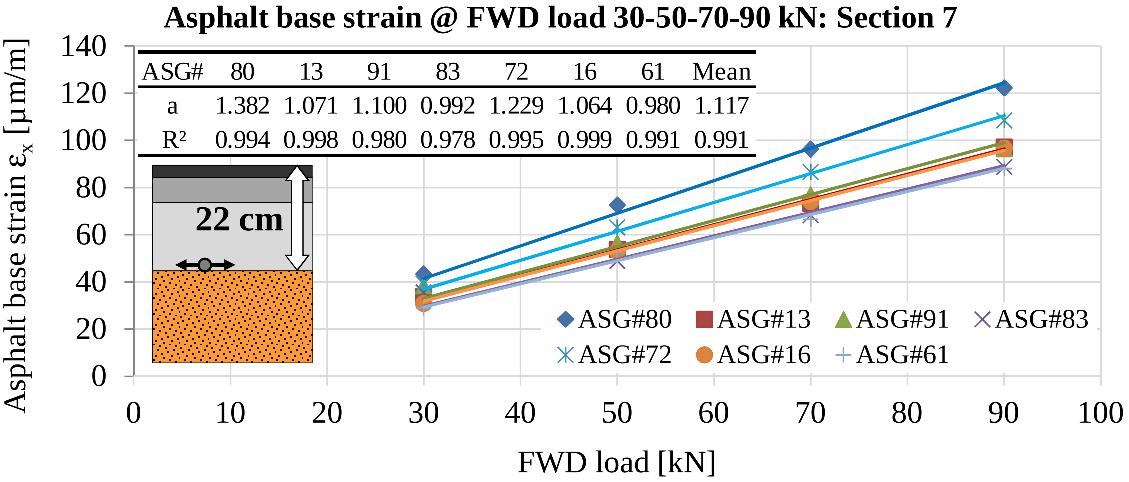


Figure 5: Normalised centre deflections and asphalt base strains at the bottom of a 22 cm asphalt package on granular base at four FWD load levels in section 7.

The relationship between the FWD load and the measured response (asphalt base strain ε_x) in the three aforementioned sections with multiple strain gauges is shown in Figure 6. A linear regression analysis was performed, including four load levels and the resulting measured strains with the linear regression $\varepsilon_x = a * F_{FWD}$ being forced through zero. With all R^2 values exceeding 0.978 the linear regression shows to be an appropriate model in this case, valid for asphalt temperatures around 15.9 °C.



ASG#	80	13	91	83	72	16	61	Mean
a	1.382	1.071	1.100	0.992	1.229	1.064	0.980	1.117
R²	0.994	0.998	0.980	0.978	0.995	0.999	0.991	0.991

Figure 6: Linear regression $\varepsilon_x = a * F_{FWD}$ between FWD load and asphalt base strains at the bottom of a 22 cm asphalt package on granular base in section 7.

The analysis shows a remarkable variation in the measured strains along all sensors of up to 24 % of the mean value and a significant load-strain relationship for all sensors.

Although the number of redundant sensors is limited to 5, 6 and 7 respectively, a statistical analysis was performed on the asphalt peak strain values to show the variation along the sensors. Table 1 shows the statistical evaluation and the variation of asphalt peak strains at 50 kN FWD load and the coefficient a of the linear regression $\varepsilon_x = a * F_{FWD}$ (asphalt strain ε_x vs. FWD load). Deviations from the mean value of all sensors per section up to 29 % may occur. It has to be mentioned that the variations include the structural variations within the pavement section as well as the variation of the sensor characteristics, the latter is considered the main reason as already explained before. A thorough calibration of each sensor after manufacturing should therefore reduce the scatter and improve the reliability of the results.

Table 1: Statistical evaluation of the relationship between measured asphalt base peak strains ε_x and applied FWD loads in all three pavement sections 3, 7 and 8.

Section	Asphalt-thickness [cm]	No. of sensors [-]	Asphalt base strains @ 50 kN FWD load [µm/m]							
			Mean	Min	Max	St.Dev.	Q5%	Q95%	Min/ Mean	Max/ Mean
3	34	6	38.4	29.6	49.5	7.4	29.8	47.6	0.77	1.29
7	22	7	57.2	48.9	72.5	8.1	49.9	69.7	0.86	1.27
8	14	5	88.9	70.2	102.4	13.2	73.1	102.1	0.79	1.15

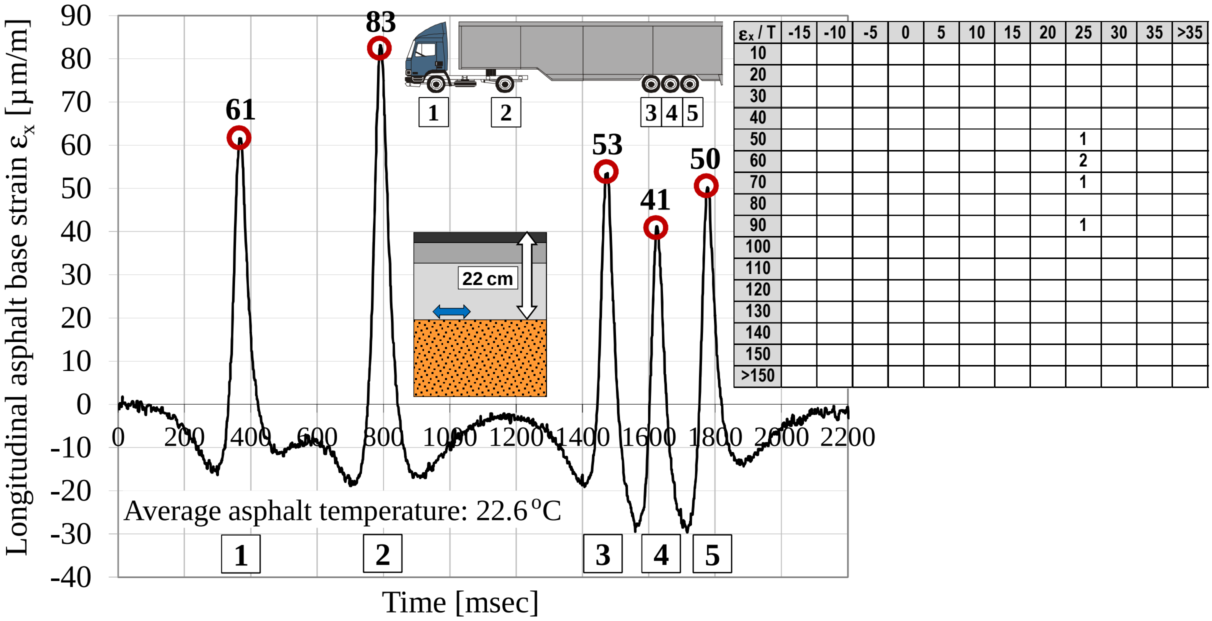
Section	Asphalt-thickness [cm]	No. of sensors [-]	Linear regression coefficient (FWD load vs. strain ε_x)							
			Mean	Min	Max	St.Dev.	Q5%	Q95%	Min/ Mean	Max/ Mean
3	34	6	0.761	0.557	0.980	0.154	0.573	0.944	0.73	1.29
7	22	7	1.117	0.980	1.382	0.143	0.984	1.336	0.88	1.24
8	14	5	1.758	1.349	2.083	0.286	1.409	2.059	0.77	1.18

4 ESSENTIAL ASPECTS OF LONG-TERM RESPONSE MEASUREMENTS IN IN-SERVICE PAVEMENTS AND 2ND GENERATION OF PAVEMENT SENSORS

4.1 Essential aspects of long-term response measurements in in-service pavements

For an envisaged automated long-term response measurement in in-situ pavements following two data acquisition methods are under consideration:

- A continuous start-stop short-term recording of response signals under controlled loading or in-situ traffic at vehicle speed up to 90 km/h. Based on the test track experience a minimum sampling rate of 4 kHz is required to obtain satisfying quality of response signals under vehicle speed of up to 90 km/h. Due to the high amount of data the transfer and storage capacity poses a “bottleneck” and make continuous long-term measurement impossible without any intelligent data reduction. This method requires loading and measurements at regular intervals to detect changes or deteriorations in the pavement structure.
- Due to these limitations, an acquisition of selected peak values of stresses and strains seems to be an adequate alternative. To reduce the amount of data to be transferred the new sensor design includes an integrated processing and memory unit that allows for peak search and classification according to peak strain value and temperature. The memory requirements for a classification table are small and the data can be transferred at regular intervals from the sensor. The principle is shown in Figure 7:



ε_x / T	-15	-10	-5	0	5	10	15	20	25	30	35	>35
10												
20												
30												
40												
50									1			
60									2			
70									1			
80												
90									1			
100												
110												
120												
130												
140												
150												
>150												

Figure 7: Example of asphalt base peak strain detection in a 22 cm asphalt pavement section induced by a 5-axle truck and semitrailer to show the peak strain value picking for the classification of long-term measurements on in-service pavements.

4.2 Improved sensor design for long-term in-situ measurements

To cater for the boundary conditions and the advanced needs for conducting measurements with pavement sensors like asphalt strain gauges and soil pressure cells on in-service roads over a longer period of time - ideally with an automated data acquisition - an improvement of the sensor design was necessary. While the dimensions and the structure remained unchanged, the main innovations were the integration of electronic circuits inside the strain gauges and the pressure cells to enable data processing, storage and adaption of the measuring range after installation. The 2nd generation of pressure cells was designed using the circular pressure-sensitive surface as a bending plate with no liquid inside the cavity and flexural strains being measured on the inner surface using four strain gauges integrated in a full bridge circuit allowing compensation for temperature effects. The main improvements are the following:

- The carrier strip for the strain gauge patterns serves also as board for the electronic circuits, processing and memory unit. Four strain gauges were integrated into a full-bridge circuit to allow for temperature compensation.
- An amplifying circuit was integrated to amplify the signal directly at the source. This provides a better signal/noise ration quality for the data to be transferred.
- A microprocessor-memory unit with was integrated to enable data processing like peak detection and classification for data reduction.
- A temperature sensor and a 4-20 mA industry standard interface were integrated.
- A bi-directional interface is planned to be integrated in the 3rd generation of sensors to enable the adjustment of the measurement range after the placement of the sensors and a bi-directional data transfer. This should allow for adjusting calibration factors and setting an optimal measurement range even after installation.
- Strain gauges have proven to resist at least 1,000,000 load cycles in dynamic tests.

The asphalt strain gauge and soil pressure cell of the 2nd generation with case and electronics are shown in Figure 8:

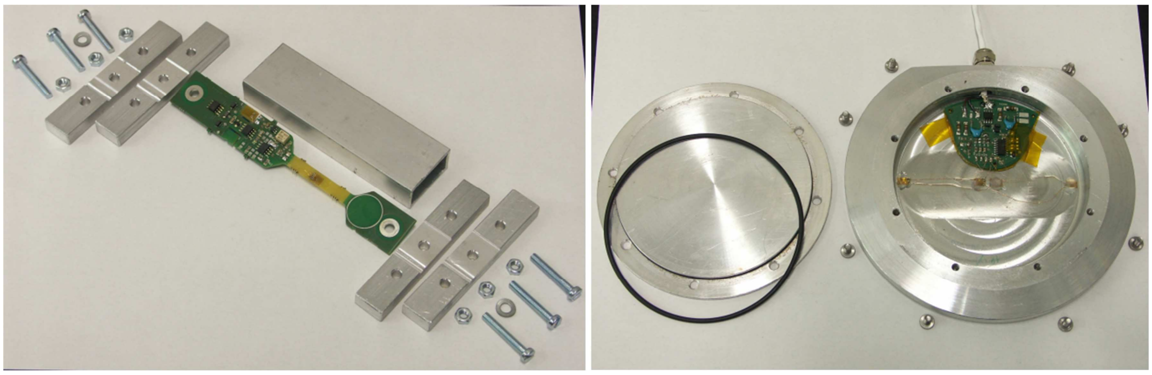


Figure 8: BASt asphalt strain gauge (left) and soil pressure cell (right) of the 2nd generation with aluminium case and anchors, sealing and electronic board.

5 SUMMARY, CONCLUSIONS AND OUTLOOK

Pavement response measurements are a powerful tool in pavement engineering providing important data for detecting pavement deterioration and validation of response and performance models. A careful design and choice of sensor technology as well as a proper calibration combined with redundant arrangement of sensors will reduce uncertainties and improve reliability. Following results can be summarised from the tests described:

- The relationship between load and measured strain is confirmed to be linear.
- A redundant arrangement of sensors is essential for statistical evaluations.
- Signals provide essential information about loading time, amplitude and frequency.
- Long-term response measurements require intelligent data reduction and classification.

Research at BASt is going on in the fields of validation of response measurements and improvement of sensor design with regard to long-term in-situ measurements under real and simulated traffic.

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