Full-Scale Testing of Pavement Response by Use of Different Types of Strain Gauges

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ABSTRACT: From 2002 to 2004 the COST action 347 (European Co-operation in the field of Scientific and Technical Research) was organized under the title “Improvements in Pavement Research with Accelerated Load Testing”, including full-scale pavement tests at a number of European research laboratories. In Lausanne, Switzerland (EPFL) a test pavement of a fully-flexible type was constructed and equipped with strain gauges of different types usually in service in Europe. The loading-facility in Lausanne is an indoor test-pit where road structures can be repeatedly loaded by a linear heavy-pavement-rutting-tester. Within the ALT-program the loading conditions were controlled, comprising a variation of the pavement temperature, a variation of the loading parameters (axle load, tire type and tire pressure, loading speed) and an investigation of the lateral distribution of the responding strains with respect to the load axis. Longitudinal and transversal signals were recorded, that resulted from measurements on the different types of strain gauges and in two different depths: 40 mm and 220 mm from the pavement surface. As a result the shape and the order of magnitude of strains were found for different levels of observation and for defined loading conditions. This makes it possible to comparatively analyse the functionality of the different types of strain gauges on the one hand, and, on the other hand, to derive important information on pavement response that may be used in pavement modelling and performance prediction.

KEY WORDS: Full-scale accelerated pavement testing, ALT, strain measurement, pavement response.

1 INTRODUCTION

Within the framework of full-scale testing of pavement response by use of different types of strain gauges, previous experiments have already been carried out before. In Nardo, Italy, correlations between different techniques of strain measurement were investigated in full-scale for the first time (OECD, 1985). Another experiment took place in Nantes, France, and aimed in comparing different systems for data acquisition (OECD, 1991).

Considering this background and in order to improve the knowledge in the domain of pavement response measurement in Europe, full-scale experiments were organized within the framework of the COST action 347 (COST, 2005). In Lausanne, Switzerland (EPFL) a test section of a fully-flexible asphalt pavement was constructed and equipped with strain gauges of different types (Table 1), making it possible to directly compare the practicability of application of different systems and to favor the transfer of knowledge between the different countries involved. Additionally, exchange of knowledge was encouraged by a number of Short Term Scientific Missions that have been organized and funded by the European Community.

Consequently, the in-service functionality of the different systems for strain measurement was checked under controlled loading and temperature conditions. The comprehensive test program, detailed in section 2, aimed in finding information on pavement response in the full-scale domain that may be used in pavement modelling and performance prediction.

Table 1: Types of used strain gauges

User-code	Type	Manufactured by	Gauge factor	E [MPa]	Resistor [Ohm]
LAVOC	KYOWA KM-120-H2-11W1M3	Kyowa Electronic Instruments Co. Ltd.	2.0	2800	120
ETHZ	KYOWA KM-120-H2-11W1M3	Kyowa Electronic Instruments Co. Ltd.	2.0	2800	120
LCPC	KYOWA KM-120-H2-11W1M3	Kyowa Electronic Instruments Co. Ltd.	2.0	2800	120
BAST	HBM 1-LY11-10/350A	Hottinger Baldwin Messtechnik GmbH, Germany	2,1	20000	175 (=350/2)
CEDEX	MM EA-06-10CBE-120	Vishay Measurements Group Inc. Raleigh,North Carolina	2,07	165	120
TU DELFT	KM-100HAS	Tokyo Sokki Kenkyujo Co. Ltd.	2	40	350
LAVAL	Fiber optic strain gauge	Fiso Technologies Inc. Quebec, CAN	-	-	-

2 FULL SCALE TESTING

The ALT-facility at EPFL consists of an indoor test-pit where full-scale road structures can be constructed and repeatedly loaded with a linear heavy pavement-rutting tester. The load axle tracks forwards and backwards linearly on a total length of approximately 4 meters. As concerns this study, the test pavement was instrumented by a total number of 63 strain gauges placed in two different levels as depicted in Figure 1.

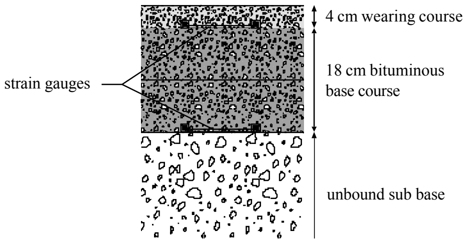

Figure 1: Vertical position of the strain gauges in the test pavement

A plan view of the test section is given in Figure 2, representing the lower level of the base layer (-220 mm). The gauges were installed in both directions, longitudinally (reference) and transversally with regard to the direction of traffic loading. Testing conditions were changed as detailed below (the reference loading case for the subsequent analysis is given in brackets):

- 3 temperatures (measured @ -40 mm): 5°C (low), 15°C (reference) and 30 °C (high)
- 2 axle loads: 80 kN and 115 kN (reference)
- 2 tires: super single tire 385 mm (reference) and dual tire
- 2 tire-pressures: 8 bar (reference) and 10 bar
- 2 speeds: 3km/h (low speed) and 11 km/h (high speed, reference)
- Lateral wandering of the load axle: from -50 to +300 mm (reference = 0 mm: the lateral position of the center of the wheel corresponds to the lateral position of the gauge)

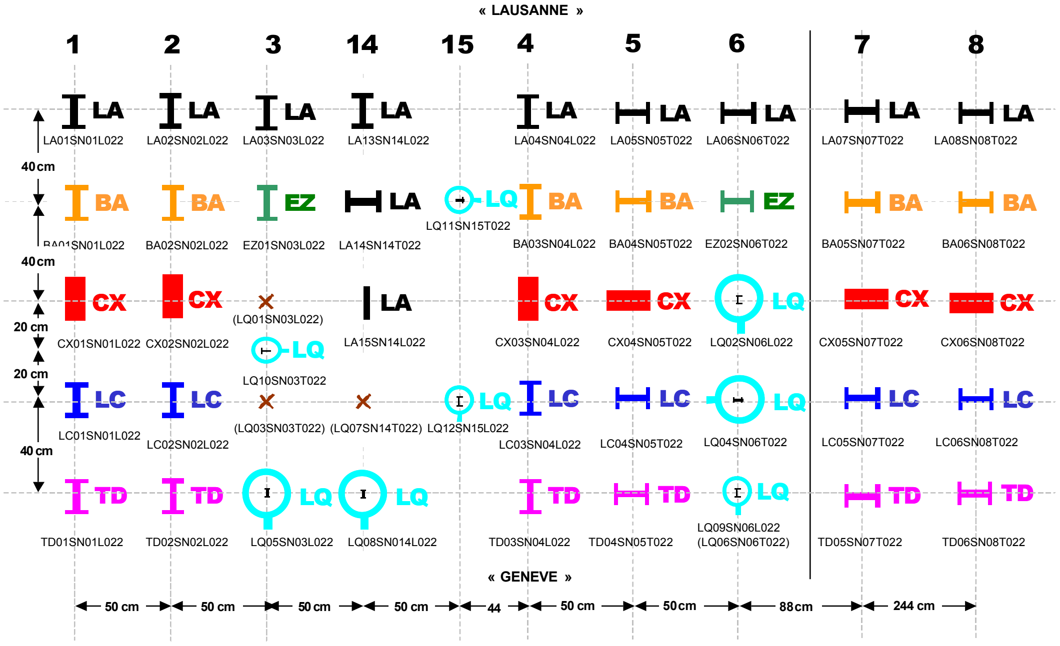

Figure 2: Plan view of the test section.

3 PAVEMENT RESPONSE FROM DIFFERENT TYPES OF STRAIN GAUGES

In the following, selected results of the strain measurements at a level of -220 mm (bottom of the base course) are presented. More detailed information is given in Wistuba et al. (2005).

3.1 Maximum tensile strains

For the reference loading case the maximum tensile strains from longitudinally placed strain gauges are represented in Figure 3, giving the maximum values referring to the lines of loading (Figure 2). The average maximum strain of the individual types of gauges varies between 80.6 µε and 175.1 µε. For reasons of comparison, an analytical pavement model and the reference loading case were simulated with VEROAD (Korkiala-Tanttu 2003), giving a maximum tensile strain at the bottom of the base course of 80 µε.

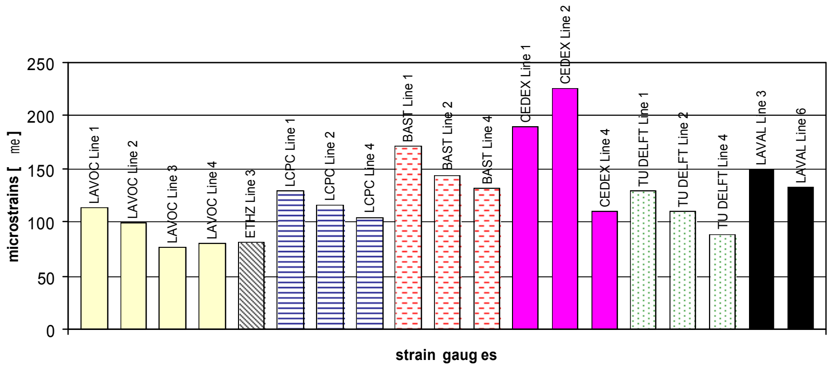

Figure 3: Maximum tensile strains for longitudinal strain gauges of different types.

Even though the observed maximum strain values vary significantly, the sensibility to temperature behaves more or less equally for all types of gauges (Figure 4). Maximum strain ratios in function of temperature, i.e. 5/15°C and 30/15°C, are given in Figure 5.

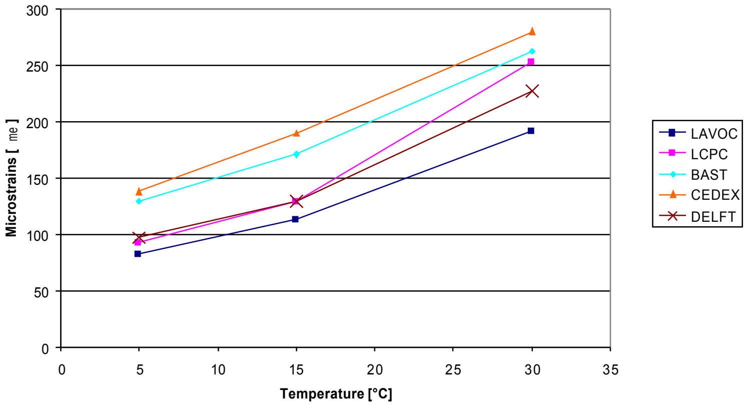

Figure 4: Influence of the temperature on the maximum tensile strains measured in line 1.

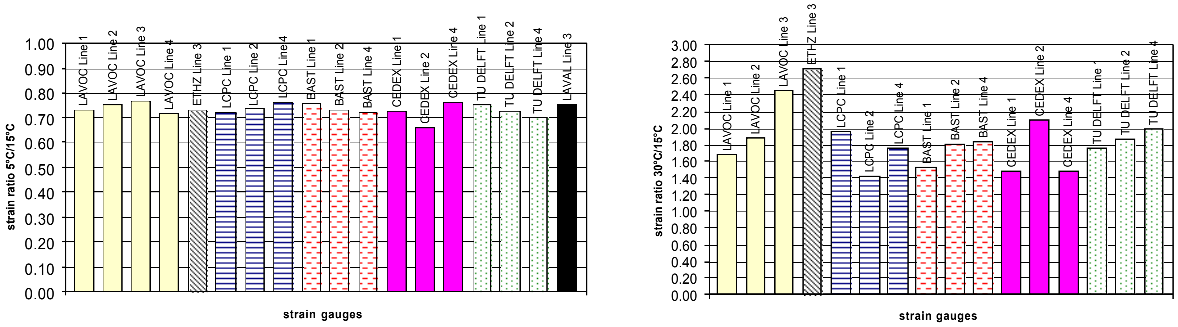

Figure 5: Ratios of maximum strains in function of temperature.

3.2 The shape of signals

The shape of the signal is similar for all loading cases: compressive strains from the approaching wheel, than important tensile strains during its passing and finally compressive strains when the wheel moves away. Resulting signals for the reference loading case are shown in Figure 6: Shape of the longitudinal signal for the reference loading case at 15°C in line 1.. The gauge of CEDEX shows no compression peak in the end, which may be due to the flat, anchor-less shape of the gauge.

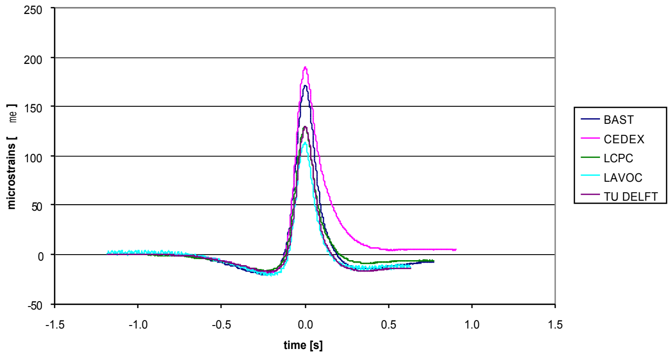

Figure 6: Shape of the longitudinal signal for the reference loading case at 15°C in line 1.

3.3 Transversal gauges

Signals from transversally placed gauges give tensile strains only. Figure 7 shows the results for the reference loading case. Measured maximum strains again underestimate the analytically calculated value of 110 με (Korkiala-Tanttu 2003). Again the shape of the signal is similar for all types of gauges, but the maximum strain values are different. In general, transversal values are smaller than the related longitudinal values measured simultaneously. The ratio of transversal to longitudinal maximum strains is represented in Figure 7. The temperature seems to be more influent on transversal strains: the higher is the temperature the higher is the ratio transversal strain/longitudinal strain.

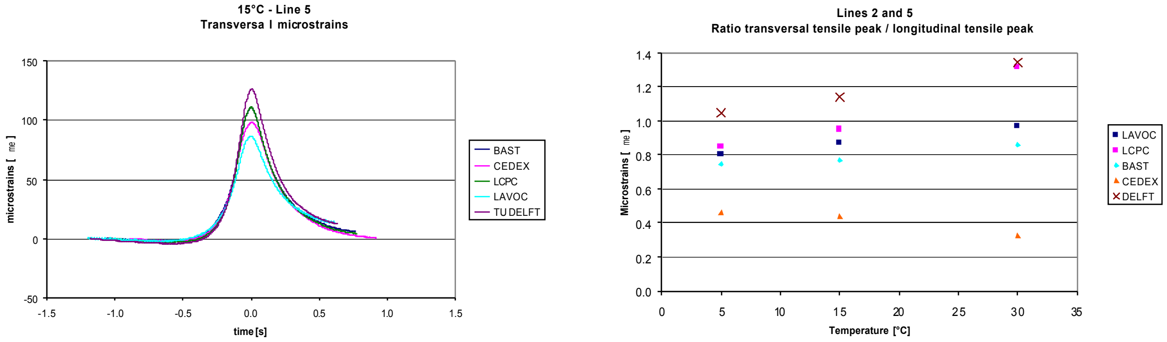

Figure 7: Reference loading case – transversal microstrains at 15°C

4 SPECIFIC FINDINGS

4.1 Analyses of traffic speed and loading frequency

When a pavement is loaded by a passing wheel, vertical and horizontal stresses are applied. The shape of this signal of response changes depending on the location in the road structure. At the surface and in the wearing course, compressive strains are predominant. According to Huang (2004), the vertical contact pressures can be characterized as a haversine function. Contrary, at the bottom of the base course, important tensile strains are measured (Figure 8).

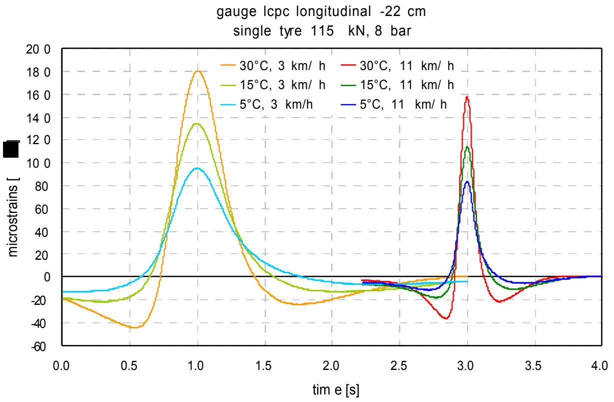

Figure 8: Signals from strain measurements at the bottom of the base course.

For measurements at the bottom of the base course, the longitudinal signal of response can be fitted in good approximation by means of a sinusoidal function, as found in this study and exemplarily illustrated in Figure 9. This matter of fact may be useful for accelerated loading tests on asphalt specimens, especially for laboratory fatigue testing, where the repeated bending strains at the bottom of the base course resulting from traffic loading can be simulated in an accelerated way by means of a sinusoidal load. Thus, an interrelation between the speed of traffic loading and the speed of application of the sinusoidal load, expressed by the frequency of the sinusoidal function, is of special interest.

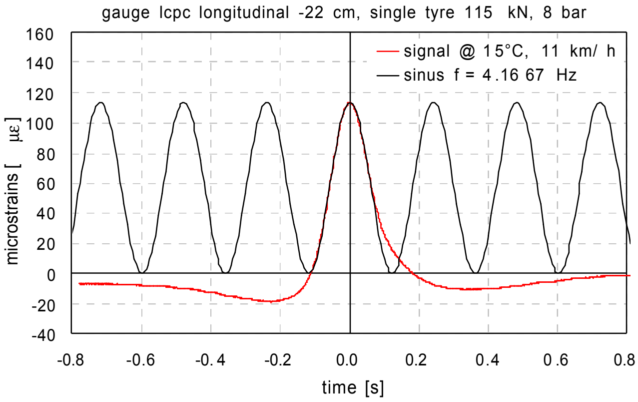

Figure 9: A sinusoidal function fits the longitudinal strain signal of an axle load, measured at the bottom of the base course.

The shape of the fitting sinusoidal signal depends on the loading parameters, i.e. axle load, pavement temperature, speed of loading, and the related pavement depth of the signals' origin. In order to assess the importance of the loading speed under ordinary temperature conditions (about 20 to 30°C), and for probable ranges of the heavy vehicle's axle load (around 100 kN) and of the base layer's thickness (around 200 mm), strain data from measurements under controlled loading and temperature conditions were analyzed (see Table 2). In a first step, strain signals recovered from selected controlled strain measurements at the bottom of the base course of both, of the laboratory ALT test track and of real motorway road pavements, were fit by means of sinusoidal functions (an example is illustrated in Figure 9). Consequently, the loading speed related to the specific strain signal, was plotted over the frequency of the fitting sinusoidal function. Finally, an interrelation of speed and frequency was found. The result of this analysis for all loading cases of Table 2 is represented in Figure 10, where a linear regression between loading speed and frequency is shown. For finding the linear regression in Figure 10, all data plotted as crosses remained unconsidered. These additional data, given for verification purpose only, are recovered from strain measurements on trafficked roads, where no detailed information on traffic load and exact pavement temperatures was available.

Table 2: Load cases of selected strain data, used for analysis of the interrelation between traffic speed and load frequency.

data origin LAVOC	depth [mm]	temperature [°C]	axle load [kN]	tire type & pressure	traffic speed [km/h]
ALT test track*	-220	+30	115	single tire, 8 bar	3
					11
motorway A**	-160	+30	90	single tire, 8 bar	40
					60
					80
motorway B***	-160	+20	90	single tire, 8 bar	40
					60
					80

* EPFL, Halle Fosse; ** A9, Exit of the tunnel of Sierre; *** A9, Middle of the tunnel of Sierre

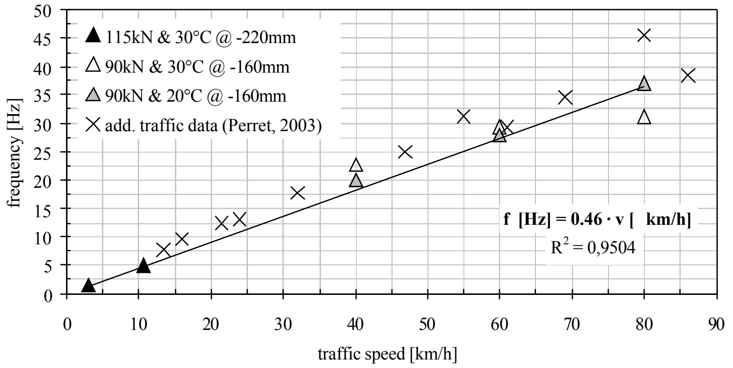

Figure 10: Interrelation of traffic speed and frequency of loading.

Additionally, the influence of the temperature of the pavement on the resulting frequency of the sinusoidal function was studied from strain data that were performed on the ALT test track under controlled loading and temperature conditions. Even though the range of applied loading speeds is very small (due to limitations of the ALT facility), a temperature change from 5 to 30°C influences the frequency ratio up to 10%, if expressed by the ratio of the frequency at the given temperature and the frequency at a reference temperature of 15°C (Table 3).

Table 3: Influence of temperature on the frequency ratio for a reference temperature of 15°C

	frequency ratio $f_{temp}/f_{15°C}$		
temperature / speed	5°C	15°C	30°C
3 km/h	0.90	1.00	1.09
11 km/h	0.92	1.00	1.10

4.2 Time-shift between signal and load

During strain measurements at the bottom of the base course a time-shift Δt was noticed between the passing of the wheel and the response of the strain-gauge (Figure 11). Hence, the maximum tensile strain is registered, when the wheel has already passed the gauge.

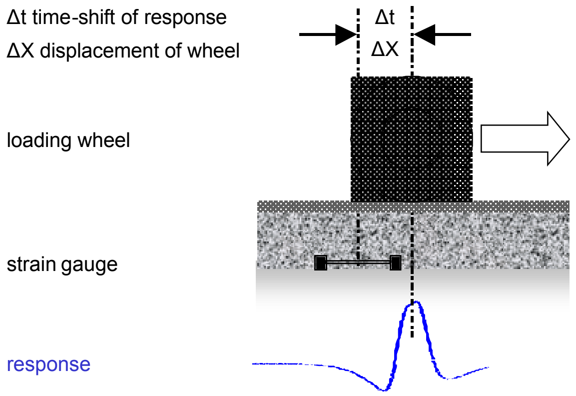

Figure 11: Illustration of time-shift of response Δt, between the passing of the wheel and the maximum tensile strain at the bottom of the base course.

Due to the visco-elastic behavior of bituminous material the time-shift depends on the pavement's temperature. The higher the temperature the bigger is the time-shift. For 5, 15 and 30°C temperature and for a reference loading case (11 km/h loading speed, 115 kN axle load, 8 bar tire pressure, single tire) the time-shift was determined for strains resulting from different types of strain gauges placed at the bottom of the base course at a level of –220 mm from the pavement surface longitudinally and transversally to the direction of loading. The registered time-shift Δt is about 0,05 to 0,09 seconds. It is notably bigger for transversal than for longitudinal strains and this difference increases with the temperature.

However, the time-shift of different types of gauges varies within a very small order of magnitude. Hence, for practical reason of interpretation, the time-shift is converted into the displacement of the moving wheel, which is related to the time-shift. This is possible, because during the strain measurements the movement of the wheel is registered with the help of an encoder. The displacement ΔX is the distance between the strain gauge and the position of the wheel, at the time the maximum strain of this gauge is registered. In the following always the displacements of the different types of gauges are comparatively analyzed.

The displacements for the reference loading case (given above) for all registered strains are given in Figure 12 and Table 4, where the absolute and the mean values together with the standard deviation are shown.

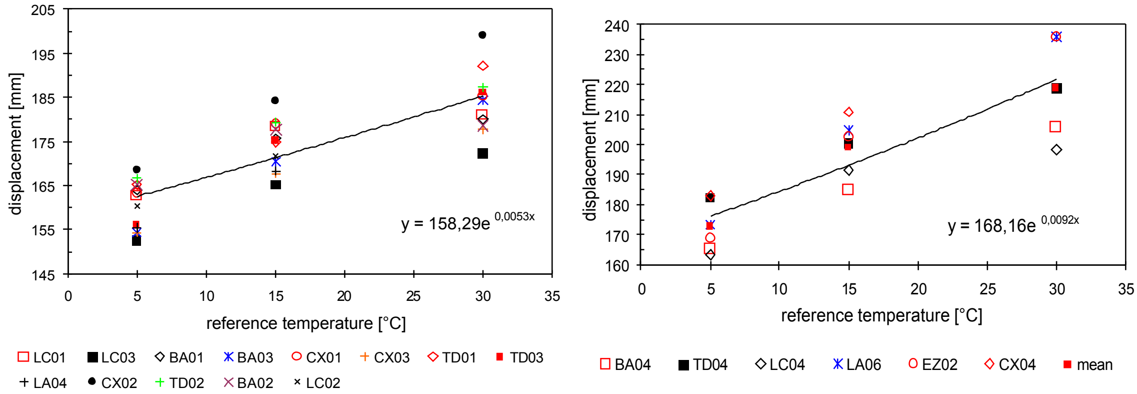

Figure 12: Displacement of longitudinal and transversal strains at –220 mm.

Table 4: Displacements for longitudinal and transversal strains (reference loading case 11 km/h loading speed, 115 kN axle load, 8 bar tire pressure, single tire).

<table>
<tr><th colspan="16">longitudinal strains at the bottom of the base course (-220 mm)</th></tr>
<tr><th>°C</th><th>LC01</th><th>LC02</th><th>LC03</th><th>BA01</th><th>BA02</th><th>BA03</th><th>CX01</th><th>CX02</th><th>CX03</th><th>TD01</th><th>TD02</th><th>TD03</th><th>LA04</th><th>mean</th><th>s.d.</th></tr>
<tr><td>5</td><td>162.87</td><td>160.33</td><td>152.81</td><td>163.99</td><td>165.29</td><td>154.38</td><td>163.32</td><td>168.64</td><td>154.38</td><td>165.29</td><td>166.73</td><td>156.18</td><td>155.32</td><td>160.73</td><td>5.65</td></tr>
<tr><td>15</td><td>178.54</td><td>171.73</td><td>165.38</td><td>175.53</td><td>177.76</td><td>170.41</td><td>178.90</td><td>184.19</td><td>167.76</td><td>174.86</td><td>179.33</td><td>175.40</td><td>168.35</td><td>174.47</td><td>5.55</td></tr>
<tr><td>30</td><td>181.24</td><td>-</td><td>172.48</td><td>180.03</td><td>178.44</td><td>184.34</td><td>185.19</td><td>199.07</td><td>177.69</td><td>192.06</td><td>187.36</td><td>186.22</td><td>-</td><td>184.01</td><td>7.66</td></tr>
<tr><th colspan="16">transversal strains at the bottom of the base course (-220 mm)</th></tr>
<tr><th>°C</th><th>EZ02</th><th colspan="2">LC04</th><th colspan="3">BA04</th><th colspan="3">CX04</th><th colspan="3">TD04</th><th>LA06</th><th>mean</th><th>s.d</th></tr>
<tr><td>5</td><td>168.84</td><td colspan="2">163.21</td><td colspan="3">165.65</td><td colspan="3">183.01</td><td colspan="3">182.83</td><td>173.42</td><td>172.83</td><td>8.53</td></tr>
<tr><td>15</td><td>202.27</td><td colspan="2">191.54</td><td colspan="3">185.33</td><td colspan="3">210.89</td><td colspan="3">200.74</td><td>204.58</td><td>199.23</td><td>9.26</td></tr>
<tr><td>30</td><td>235.70</td><td colspan="2">198.15</td><td colspan="3">206.04</td><td colspan="3">-</td><td colspan="3">219.34</td><td>235.74</td><td>219.00</td><td>17.04</td></tr>
</table>

According to these results, the response behaves similar for different types of strain gauges. The displacement is about 150 to 170 mm at 5°C, and 170 to 200 mm at 30°C temperature. The mean displacement varies about 6 mm at 5°C, up to 8 mm at 30°C. If temperature is raised from 5 to 30°C, the mean displacement is increased by approximately 14% for longitudinal strains and 27% for transversal strains. The difference between the gauges increases with the temperature, for longitudinal gauges from 16 mm at 5°C up to 27 mm at 30°C and for transversal gauges from 20 mm at 5°C up to 38 mm at 30°C. Apart from the pavement temperature, also the loading speed is an important parameter of influence. The speed of the ALT-facility can be changed from approximately 11 to 3 km/h. However, even this small change in loading speed significantly influences the displacement ΔX: if speed is reduced from 11 to 3 km/h, the displacement for longitudinal gauges is reduced about more than half (Figure 13). It is expected, that also the thickness of the layer has an important influence on the displacement ΔX, assuming an increase with the thickness. However, in order to verify this assumption, further measurements of gauges in different depths and/or analytic analyses with a finite-element-model are recommended. Factors which are of hardly any influence on the extent of the shift are the axle-load, the tire pressure and the type of tire. This assumption is concluded from the analysis of strain data from one selected type of gauge (LC-gauge-type), and for a reference temperature of 15°C (Figure 14).

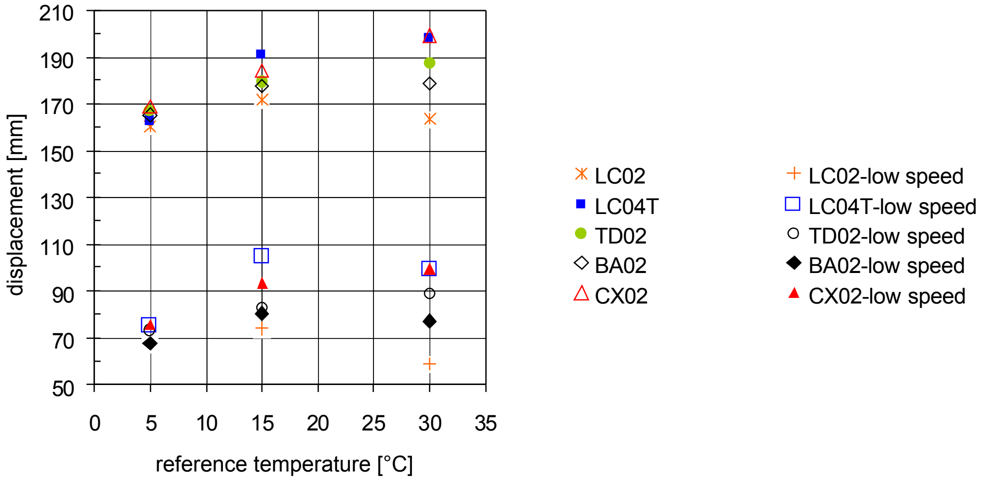

Figure 13: Displacement for different loading speeds: low 3 km/h and reference speed 11 km/h.

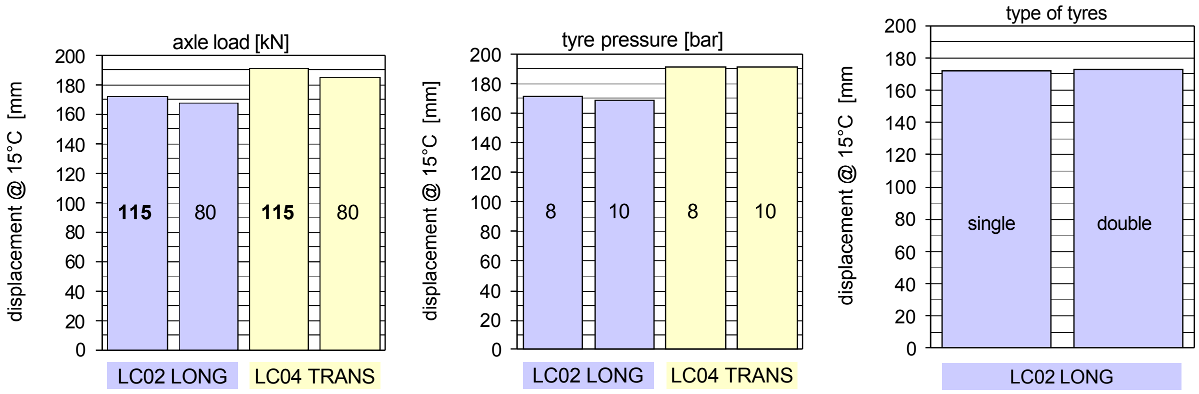

Figure 14: Displacements for different axle-loads (80 vs. 115 kN), different tire-pressures (8 vs. 10 bar), and for different type of tires (single vs. double tire).

5 CONCLUSIONS

From this study it can be concluded, that different techniques of strain measurements may give different results, especially as regards absolute strains. All different types of gauges can be exploited within a confidence interval.

In addition, it was possible, through specific findings, to present an interrelation between the traffic speed and the frequency of loading, which is of special interest for laboratory fatigue testing. It was also found that the maximum tensile strain occurs when the wheel has already passed the gauge. This time-shift mainly depends on the loading speed and the temperature of the pavement.

In conclusion, strain measurements in bituminous layers considerably improve the knowledge in domain of pavement response. Associated analytic analyses with finite-element-models can express the measured visco-elastic behavior of the materials.

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