Temperature Correction of Falling-Weight-Deflectometer Measurements

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ABSTRACT: In order to design pavements it is important to know the bearing capacity of the pavement. The bearing capacity can be derived from deflection measurements by a Falling-Weight-Deflectometer (FWD). The deflections next to the load center on asphalt pavements are strongly influenced by the temperature of asphalt layers. To get comparable results, the measured deflections have to be corrected to a reference temperature. The aim of the presented research project was to develop a function for temperature correction of FWD deflections which is suitable for the conditions in Germany. For this, two existing asphalt pavements were instrumented with temperature sensors in the asphalt layer, which continuously log the asphalt temperatures. FWD deflection basins were measured on the instrumented test sections at different temperatures and seasons. In addition 20 more test sections with different thicknesses and asphalt materials were measured by FWD at different temperatures and seasons.

KEY WORDS: FWD, Asphalt, Temperature measurement

1 INTRODUCTION

The shape of deflection basins measured by a Falling-Weight-Deflectometer (FWD) is influenced by several conditions which are not directly related to the overall bearing capacity of the FWD testing point. These conditions can be for example the current water-content of the unbound layers and the temperature of the AC layer. An FWD test only displays the current conditions of the testing point and may change when testing a few hours later. Therefore a consideration of the current nonpermanent surrounding conditions has to be done before data evaluation and interpretation. This is done by correcting the measured data to standard reference conditions.

FWD deflections near the load center are highly dependent on the AC layer temperature. Several international approaches exist to correct the measured FWD deflections to a reference AC layer temperature, e.g. (Chen, Bilyeu, Lin, Murphy 2000) (Kim, Hibbs, Lee 1995) (Park, Kim, Park 2002). In Germany only an algorithm for the temperature correction exists which was developed for Benkelman Beam measurements (Schulte 1984). The transfer of this function to FWD deflections is not possible. Internationally existing algorithms often cannot be transferred without being evaluated, because of differing climatic conditions and construction principles in Germany.

In order to derive a temperature correction algorithm with an empirical approach a wide database is necessary, which contains the temperature situation in the AC layer at a wide range of ambient temperature and weather situation and which also describes the “deflection basin” to “AC layer temperature” relationship at several AC layer temperatures and in different seasons.

2 INFLUENCE ON THE BEARING CAPACITY OF AC PAVEMENTS

The bearing capacity of AC pavements can be described by the FWD deflection basin. The absolute value of the deflections depends on the distance to the load center and the properties and conditions of the bounded and unbounded layers, the subgrade and the combination of these. The deformation behaviour on the surface can be derived from the elastic modulus, the layer thickness and the Poisson number of each layer. As the thickness of each layer depends on the FWD testing station and the Poisson ratio can be assumed constant on uncracked pavements, the elastic modulus is influenced by climate and traffic. The elastic modulus of the layers is therefore influenced by

- in case of AC layers
    - load frequency
    - layer temperature
- in case of unbound layers und subgrade
    - water content
    - layer temperature (in case of temperatures < 0 °C)

These factors have to be considered for the interpretation of FWD testing. In order to be able to neglect the influence of the load frequency all FWD systems measure with a constant load frequency of approximately 10 Hz (Straube, Beckedahl, Huertgen 1996). In order to be able to neglect the water content and the layer temperature of unbound layers, FWD testing in Germany is normally done outside the freeze and thaw period. So the only variable factor which influences the interpretation of the FWD testing is the AC layer temperature.

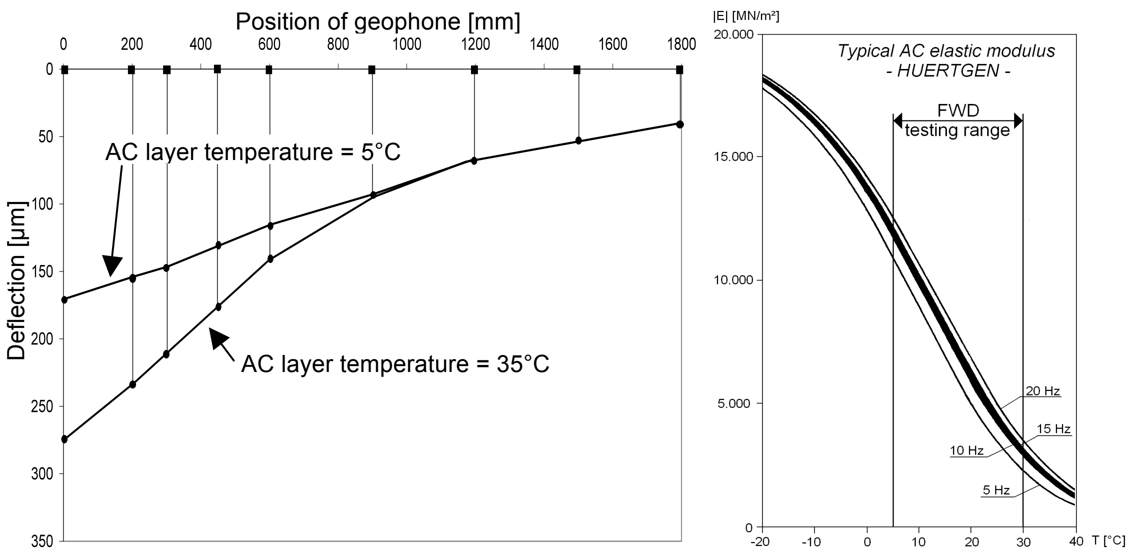

Figure 1: Influence of AC layer temperature on FWD deflection basin and calculated AC elastic modulus

FWD testing in Germany is limited from 5 °C to 30 °C AC layer temperature by an official paper (FGSV 2003). To give an example for the influence of the AC layer temperature, several FWD tests were done at the same position. Figure 1 (left) shows the testing results and the temperature dependency of the AC elastic modulus (right). In this example the AC layer temperature creates a center deflection range of 40 % of the maximum value. Figure 1 (right) shows the temperature and frequency dependency of the AC elastic modulus demonstrated by calculated values.

In order to consider the AC layer temperature for the interpretation of the FWD testing, the deflections influenced by the AC layer temperature needs to be corrected to a reference temperature. For the climatic conditions in Germany a reference temperature of 20 °C can be chosen (FGSV 2005).

3 FIELD TESTING

In order to examine and evaluate the qualitative and quantitative influence of the AC layer temperature on the deflection basins measured by the FWD, several field tests were done over more than one year. In order to continuously measure the AC layer temperature gradients, two existing asphalt pavements were instrumented with thermocouples in the asphalt layer, which continuously log the asphalt temperatures. FWD deflection basins have been measured on the instrumented test sections at different temperatures and seasons. In addition 20 more test sections with different thicknesses and asphalt materials have been measured by FWD at different temperatures and seasons. Meteorological data and results from drill core evaluations make the analysis complete. Furthermore all measured data will be used for other research projects concerning pavement design.

All chosen test sections had to meet several demands:

- specific AC layer thickness (five test sections each): 18, 22, 26 and 30 cm (± laydown tolerance)
- flexible pavement: AC layer and subbase on subgrade (no hydraulically bound layers / no overlays)
- Surface course: asphalt concrete or stone mastic asphalt
- minimum length of each section: 500 m
- classified roads, freeways
- roads built in recent years, maximum age of 10 years
- no distinctive surface distresses
- no exceeding traffic impact during FWD measurements

Two test sections where chosen for the installation of the thermocouples. They had to meet additional demands:

- homogenous field conditions on a length of 50 m each
- no random shading of the section (for example: parking vehicles)
- no longitudinal gradient
- no embankment, cut or cut and fill profile

About 50 test sections were first looked up into a national database, visited and at last reviewed if they could fulfill the mentioned demands.

3.1 AC layer temperature logging stations

Thermocouples were installed in different depths of the AC layer at two test sections to measure the AC layer temperature gradients. The total AC layer thickness of the test sections were 22 cm (Station 1) and 28 cm (Station 2). The thermocouples were installed in depth range from 0 to 20 cm and 28 cm respectively. The horizontal position of the thermocouples is midlane. The test sections are located in the northwest of Germany and have a linear distance of 94 km to each other. Figure 2 shows the local details of each test section.

The thermocouples were installed in April 2007. In order to install the thermocouples, two overlapping drill cores were taken and the thermocouples were fixed with thermoconducting glue into a channel which was vertically milled into the drill hole. Afterwards the drill cores were put back into the hole, fixed with installation foam and sealed at the top. The data logger, connected with a wire to the thermocouples, is placed at the side of the road and logs the temperature in a text file on a SD-Memory card every minute. The data logger runs on battery.

The thermocouples were built for the special needs of the project. They basically consist of an aluminum head in a non-thermoconducting compound, see figure 3. The AC layer temperature is only measured at the tip of the aluminum head, so that the influence of the installing drill core is as little as possible.

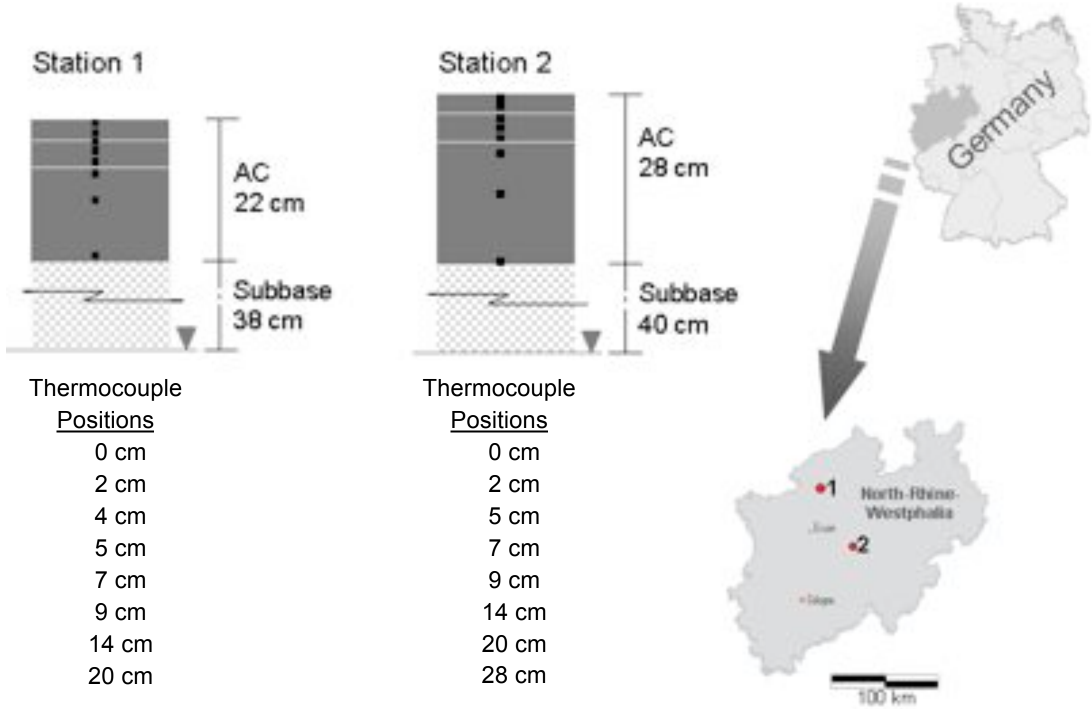

Figure 2: Test site location and inventory data of the Temperature-Logging-Stations (TLS)

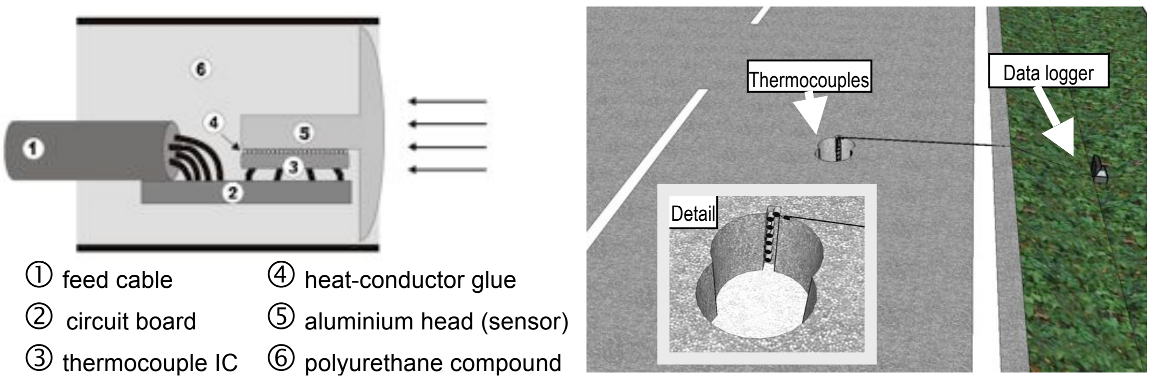

Figure 3: Thermocouple and TLS

3.2 FWD testing

The FWD testing was done at different AC layer temperatures and in different seasons (spring, summer and autumn). Repeating measurements were done next to the temperature logging station (TLS) and at the 20 test sections.

The FWD testing next to the TLS were done at four testing points (TP 1-4), see figure 4. The spacing between the positions was chosen so that the towing vehicle did not shade the next testing position when standing at the one before. The FWD testing next to the TLS was done with three 50 kN drops followed by three 90 kN drops. The FWD testing on the 20 test sections was done with 25 m spacing between the testing positions. The first testing position of each test section was marked. Each test section has 21 FWD testing points. Each testing position was tested with three 50 kN drops. The AC layer temperature was recorded at the beginning of each test section with a mobile temperature logging system. This system consists of five thermocouples which were put into small drill holes (diameter 8 mm) at 4, 8, 12, 16 cm depth and at the surface. The temperature data was recorded with a notebook.

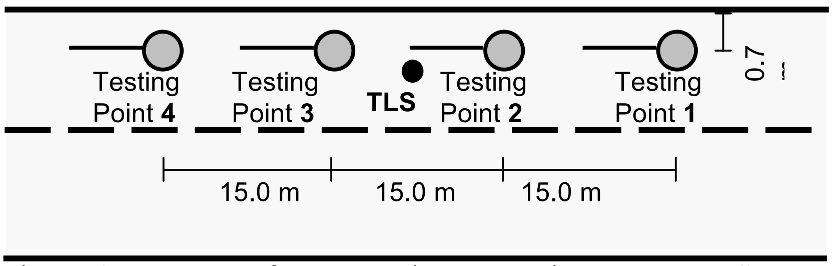

Figure 4: Test setup for repeated FWD testing next to TLS

4 DISCUSSION OF RESULTS

4.1 Temperature measurements

The AC layer temperature gradient measurements were done continuously from April 2007 to April 2008 and beyond. The measured spectrum and frequencies of the AC temperatures in 0, 5 and 20 cm depth are shown in figure 5. One of the main questions to be answered was, if the temperature gradients significantly depend on the AC layer thickness. Therefore the recorded temperatures from the two stations, AC layer thickness 22 and 28 cm, were compared to each other in different ways.

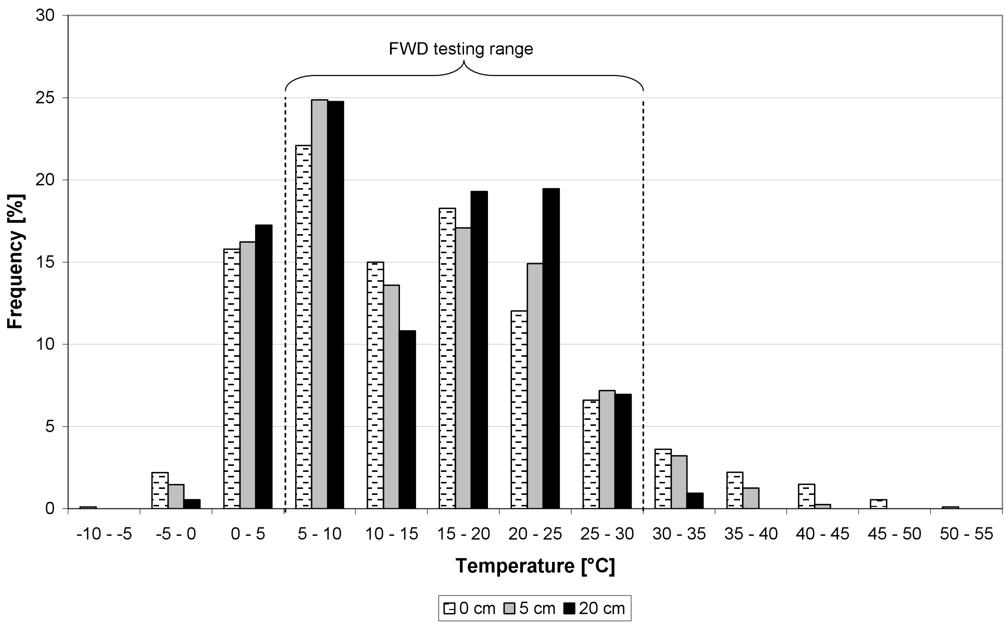

Figure 5: Measured AC temperature distributions at Station 1

First the daily curves of each station and depth were compared to each other, see figure 6, and then the temperature gradients of each station were compared to each other. The slope of the gradients is nearly the same regardless of the AC layer thickness. Even though the stations have a distance of 94 km to each other and have different surrounding conditions, the daily curves look fairly similar, so that the measured data can be assumed as plausible.

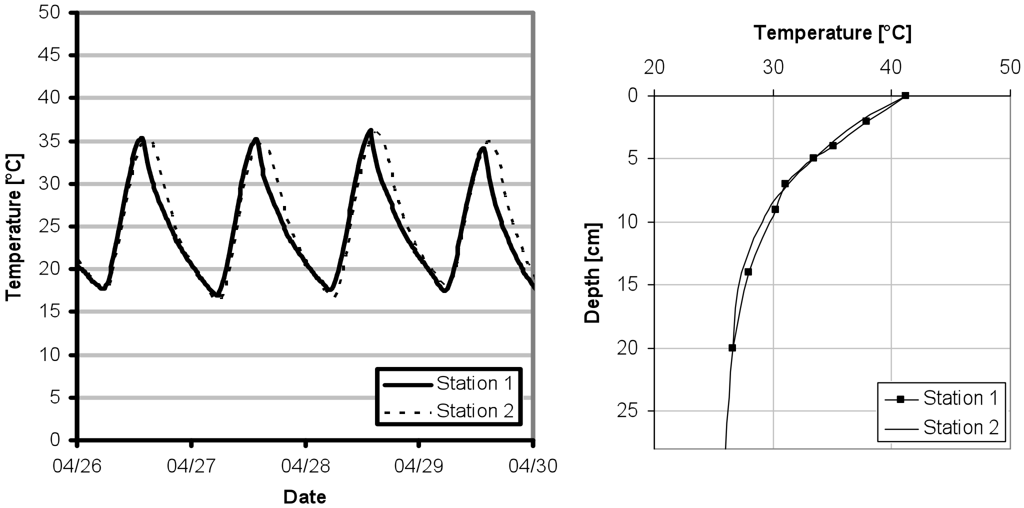

Figure 6: Comparison of daily curves at 7 cm – sunny period and temperature gradients

In combination with the meteorological database the daily temperature curves of the AC surface temperature can be characterized. There are three typical daily curves of the AC surface temperature, see figure 7 and figure 8. The three types can be described with the maximum and minimum daily AC surface temperature, daily sunshine duration and daily global radiation.

4.2 FWD testing

The FWD testing next to Station 1 and Station 2 were done at a temperature range from 5 to 30 °C (at 5 cm depth). The measured deflection basins next to Station 1 and Station 2 (TP 1) are shown in figure 9. The analysis of the deflection basins (TP 1-4) shows that the relative influence of the AC temperature on the deflections is independent from the AC layer thickness, see table 1.

Several questions have to be answered in order to derive a temperature correction algorithm for FWD deflections: What has to be done to get the actual AC layer temperature? Does the temperature correction have to be dependent from the FWD load level and from the AC layer thickness? Up to which distance from the load center should the deflections be corrected to the reference temperature?

4.2.1 In situ AC layer temperature measuring

The best way to describe the AC layer temperature is to measure the whole temperature gradient from the top to the bottom at every FWD testing position. In case of the usual proceeding of FWD actions it is not possible to integrate this kind of detailed temperature measurement.

To check how the actual AC layer temperature can be measured best during FWD actions, AC layer temperature measurements in small drill holes (diameter 8 mm) were done next to the TLS. Several parameters have been tested. The results show that there is no difference in using water, glycerol or measuring in a dry hole when the thermocouple is placed close to the bottom of the drill hole. No sealing at the top is necessary if the thermocouple has nearly the same diameter as the drill hole. To be on the safe side, one has to wait at least 15 minutes until the AC temperature measurement is no longer influenced by the drilling heat, or until the temperature reading has been stable for over more than a minute. Additional measurements, up to two hours after drilling a hole, have shown that the open drill hole can be still be used if one allows the thermocouple about five minutes to reach the temperature of the drill hole.

To derive a representative depth for the temperature probe a regression analysis of the measured temperature and deflection data was done. The analysis showed that there is a strong correlation (≥ 97 %) of the AC temperatures measured from 5 to 9 cm depth and the center deflection. With a view to practicality the AC temperature at 5 cm was chosen as a representative depth. The AC temperatures above are significantly influenced by sudden changes of weather while it is difficult to make drill holes at deeper layers at low temperatures.

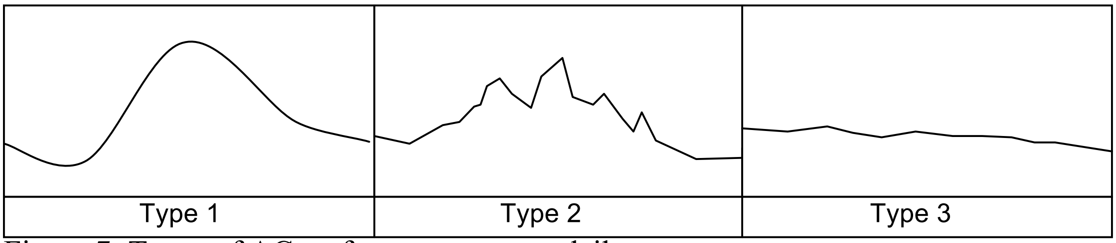

Figure 7: Types of AC surface temperature daily curves

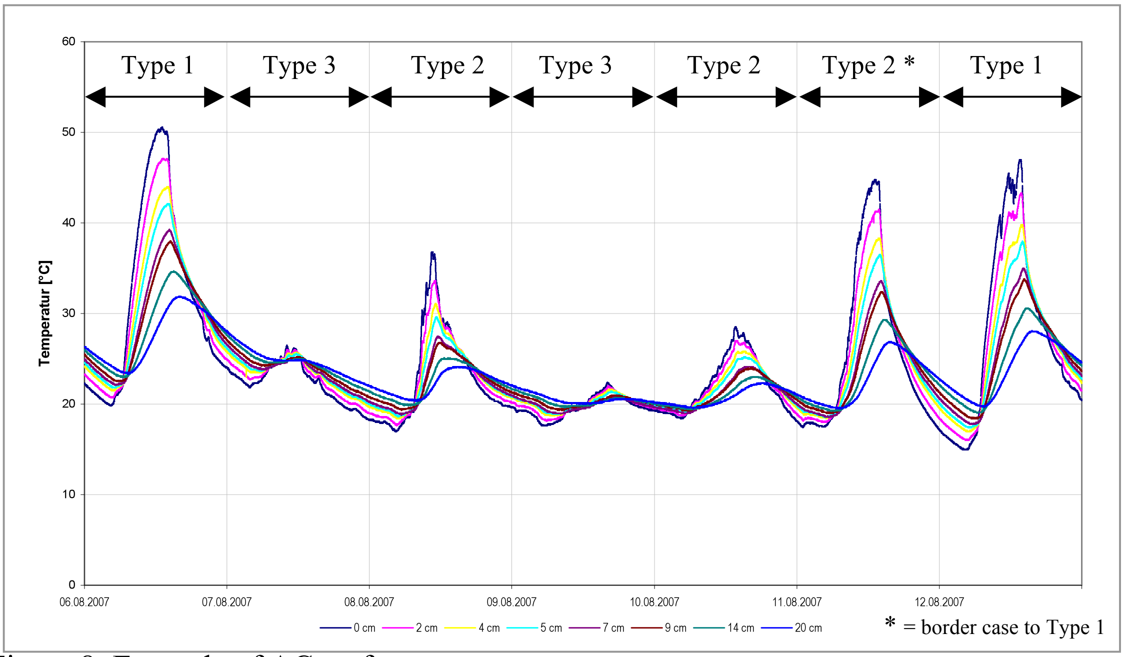

Figure 8: Example of AC surface temperature types

4.2.2 Load level dependency

Figure 10 shows the measured load center deflections at 50 kN and 90 kN at different AC layer temperatures. There is a linear dependency between the deflections without an AC layer temperature influence. Therefore a temperature correction of deflections can be done independently from the FWD load level.

4.2.3 AC layer thickness dependency

To evaluate whether the temperature correction of FWD deflections has to be dependent from the AC layer thickness, the measured deflection basins at the two TLS were compared to each other. Even if the absolute, temperature dependent, change of the center deflection at Station 2 (AC layer thickness = 28 cm) is much smaller than at Station 1 (AC layer thickness = 22 cm) the relative change is similar, see figure 9 and table 1. Therefore the AC layer thickness can be neglected in case of temperature correction of deflections.

Table 1: Absolute and relative influence of the AC temperature on center deflection

Station	Testing Point	Spectrum of center deflection (AC temperature range of 30 °C at 5 cm depth)	Relative influence of AC temperature on center deflection at a AC temperature range of 25 °C (5 – 30 °C) (100 % = center deflection at 30 °C)
1	TP 1	Δ = 118 µm	66 %
	TP 2	Δ = 132 µm	63 %
	TP 3	Δ = 195 µm	70 %
	TP 4	Δ = 93 µm	72 %
2	TP 1	Δ = 21 µm	60 %
	TP 2	Δ = 21 µm	62 %
	TP 3	Δ = 20 µm	67 %
	TP 4	Δ = 37 µm	62 %

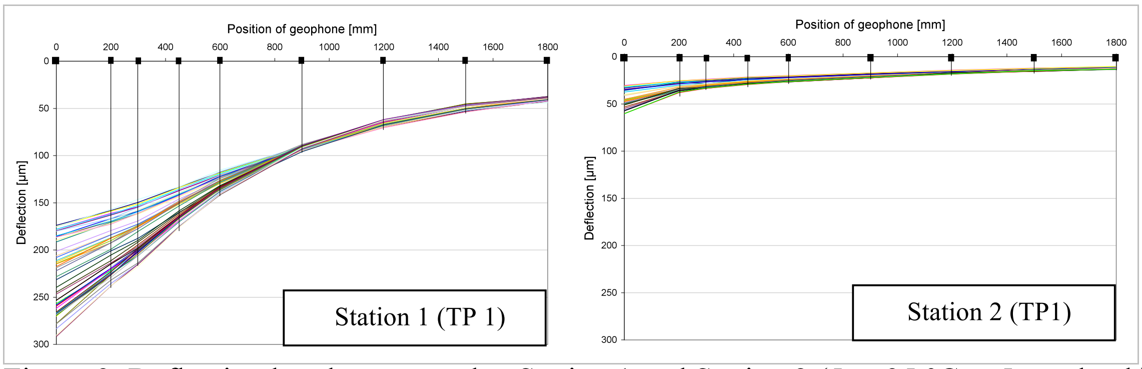

Figure 9: Deflection bowls measured at Station 1 and Station 2 (5 to 35 °C at 5 cm depth)

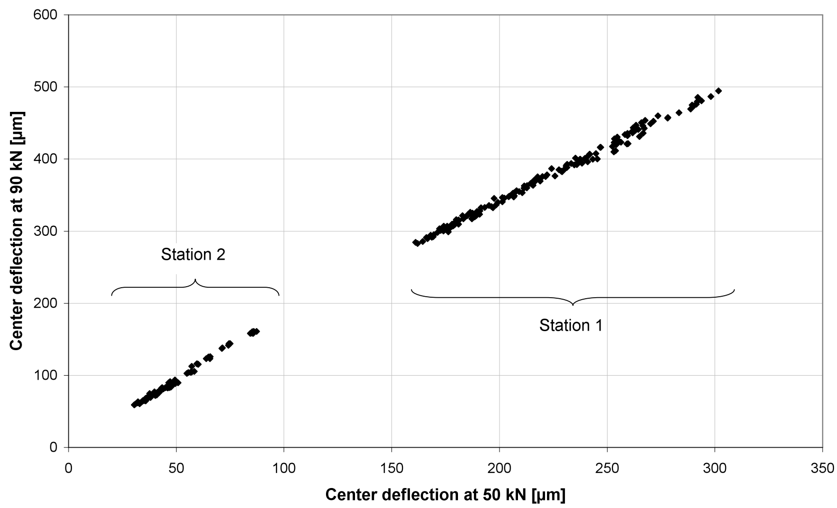

Figure 10: Load level dependency

4.2.4 Distance to load center

As seen in figure 9 the impact of the AC layer temperature on the deflection basin decreases with increasing distance to load center. A graphical analysis and correlation analysis of the data measured at Station 1 und 2 was done to define the influenced distance to load center. Only distances to the load center which are typical for FWD testing in Germany were analyzed (0, 200, 300, 450, 600, 900, 1.200, 1.500 and 1.800 mm). The correlation analysis (AC temperature at 5 cm to deflection at various distances) showed that there is a strong correlation of 91 to 95 % up to 600 mm from the load center. The analysis of the measured deflections bowls at different AC temperatures, see figure 9, showed that the deflections at 600 mm are still influenced by the AC temperature while the deflections at 900 mm or more are not influenced. The correlation analysis and graphical analysis showed that the deflections up to a distance of 600 mm from the load center needed to be considered for temperature correction.

5 TEMPERATURE CORRECTION OF FWD DEFLECTIONS

The temperature correction formula for FWD deflections was derived from the measured data at Station 1 and Station 2 and afterwards verified by the measured data from the mentioned 20 test sections. The chosen reference AC layer temperature was 20 °C.

Regression analysis was used to get a reference deflection at 20 °C for every testing position next to Station 1 and Station 2 and for every distance to the load center up to 600 mm. Then a temperature correction factor was calculated for every single deflection using the data from Station 1 and Station 2, see figure 11. Afterwards several regression analyses were done to get a temperature correction formula for each geophone position up to 600 mm. These analyses showed that there is a linear relationship between the AC layer temperature and the FWD deflections. The analyses also showed that higher significance could be achieved when using separate functions for the AC layer temperature range below and above 20 °C. Furthermore the analyses showed that separate functions for small deflections below 20 °C are necessary to enhance the significance. For the temperature correction of FWD deflections the measured deflections are multiplied with a temperature normalisation factor to get deflections at the reference temperature of 20 °C:

$$D_{20,i} = (a - b \cdot T) \cdot D_{T,i} \tag{1}$$

$D_{20,i}$ = Deflection of geophone i at 20 °C [µm]
a, b = Factors depending on
- geophone position
- AC layer temperature range (<20 °C or >20 °C)
- small or large deflections (criterion depends on geophone position / only < 20°C)

T = AC layer temperature at 5 cm [°C]
$D_{T,i}$ = measured FWD deflection at AC layer temperature T of geophone i [µm]

Criteria		Geophone position	Factor *a*	Factor *b*
AC Temperature < 20 °C (large deflections)	if > 140 µm	1 @ 0 mm	1.3052	0.0152
	if > 130 µm	2 @ 200 mm	1.2784	0.0139
	if > 120 µm	3 @ 300 mm	1.2317	0.0115
	if > 110 µm	4 @ 450 mm	1.1779	0.0089
	if > 100 µm	5 @ 600 mm	1.1158	0.0058
AC Temperature < 20 °C (small deflections)	if ≤ 140 µm	1 @ 0 mm	1.5183	0.0259
	if ≤ 130 µm	2 @ 200 mm	1.4308	0.0215
	if ≤ 120 µm	3 @ 300 mm	1.3102	0.0155
	if ≤ 110 µm	4 @ 450 mm	1.3131	0.0156
	if ≤ 100 µm	5 @ 600 mm	1.2392	0.0122
AC Temperature > 20 °C		1 @ 0 mm	1.3005	0.0153
		2 @ 200 mm	1.2713	0.0137
		3 @ 300 mm	1.2709	0.0133
		4 @ 450 mm	1.2303	0.0110
		5 @ 600 mm	1.1600	0.0077

5 CONCLUSIONS

In this paper the empirical procedure of the continuous measurement of temperature gradients within two different asphalt pavements for over more than one year and the analysis of these temperature gradients concerning their effect on the FWD bearing capacity measurements is presented. The discussion of results shows that the daily temperature curves can be characterized into three types and that the temperature gradients are independent from the AC layer thickness. These results will be part of a following research project concerning, amongst others, typical temperature distributions for the design of AC pavements in Germany.

From the results of this investigation, the following conclusions were made concerning the temperature correction of FWD deflection basins: The temperature correction of deflection basins can be made without the knowledge of the AC layer thickness. Deflections up to a distance of 600 mm from the load center are influenced by the AC temperature. The FWD load level has no impact on the temperature dependency of the deflections. The AC layer temperature at a depth range from 4 to 9 cm strongly correlates with the FWD deflections. The AC temperature at 5 cm was chosen to correct the measured deflections to a standard temperature of 20 °C. A new function for temperature correction of FWD deflection basins has been presented. The function is dependent on the geophone position, the AC layer temperature range and the size of the deflections.

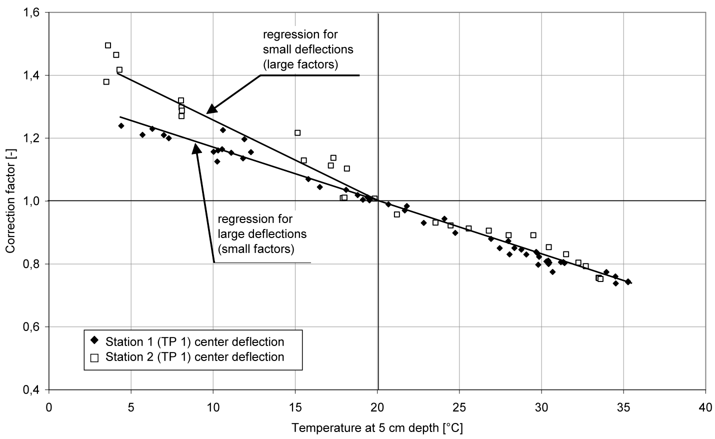

Figure 11: Correction factors (Station 1 (TP 1) and Station 2 (TP 1)) with regression lines

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