Assessment of Permanent Deformation Behavior of Asphalt Concrete by Improved Triaxial Cyclic Compression Testing

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ABSTRACT: For the characterization of the permanent deformation behavior (rutting) of asphalt concrete (AC), the triaxial cyclic compression test (TCCT) is a standardized test method. The test simulates traffic loading by applying a sinusoidal compressive stress in vertical direction and a radial confining pressure, which simulates the confinement of the specimen within the pavement structure. As a result the permanent axial strain versus load cycles is obtained. In the standard test procedure the confining pressure is held constant throughout the test to simplify the test control. However, in reality the confining pressure oscillates in a sinusoidal way with a certain phase lag to the vertical loading due to the viscoelastic characteristics of AC. The phase lag of hot mix asphalt (HMA) depends on the temperature and load frequency. The paper presents an innovative approach to improve the TCCT by implementing sinusoidal confining pressure. Strain gauges are attached directly to the specimen's surface to measure the radial deformation and to obtain the phase lag between the axial loading and the radial reaction. These experiments are carried out for various mixtures at temperatures ranging from 10°C to 50°C and frequencies from 0.1 Hz to 30 Hz. Thus, radial strain and phase lag can be analyzed as a function of temperature and loading frequency. In a second step the sinusoidal confining pressure with the obtained phase lag will be implemented into the test routine and results from standard TCCTs with constant confining pressure versus improved TCCTs with oscillating pressure can be compared and discussed.

KEY WORDS: Performance based test method, high-temperature behavior of AC, triaxial cyclic compression test.

1 INTRODUCTION

The challenge facing designers of flexible road pavements today is the need to fully characterize the thermo-rheological properties of HMA on the one hand while on the other hand also providing a realistic simulation of the traffic- and climate-induced stresses to which pavement structures are exposed over their design lives of 20 to 30 years. Therefore a significant part of European pavement research in the last decade has been dedicated to developing and standardizing performance based test methods for HMAs on the basis of effective mechanical characteristics (Blab and Eberhardsteiner, 2006). These methods are now implemented in European Standards and used for specifying the mix properties within an advanced type testing procedure required to meet customized quality standards for materials defined in tender documents as well as for mix design.

2 PERFORMANCE-BASED LAB TEST

To describe the performance of HMAs entirely three indicators have to be taken into account. It is (1) the low-temperature cracking, (2) the pavement stiffness and fatigue at intermediate temperatures and (3) the permanent deformation at high temperatures (rutting).

The European Standard EN 12697-25 is responsible for cyclic compressions tests to address the high temperature behavior of HMAs. Two methods are implemented in the standard, the uniaxial cyclic compression test with restricted radial strain and the triaxial cyclic compression test (TCCT).

2.1 Reaction of a Flexible Pavement to Traffic Loading

A flexible road pavement that is subjected to loading by a passing wheel exhibits a reaction as shown in Figure 1. The loading F_{ax} itself leads to compressive axial stresses (and strains) within the pavement structure. The axial deformation lags the axial stresses due to the viscoelastic behavior of bituminous bound materials. As each point within the structure is more or less confined in radial direction, no or very limited radial deformation occurs. Further, radial stresses result from this confinement, which lag the axial stresses as well. For cyclic loading these lags can be described as phase angles ($\varphi_{ax,ax}$, $\varphi_{ax,rad}$) which are specific viscoelastic material parameters of AC. According to the theory of viscoelasticity the phase angle depends on the temperature and frequency of loading (Findley et al., 1989).

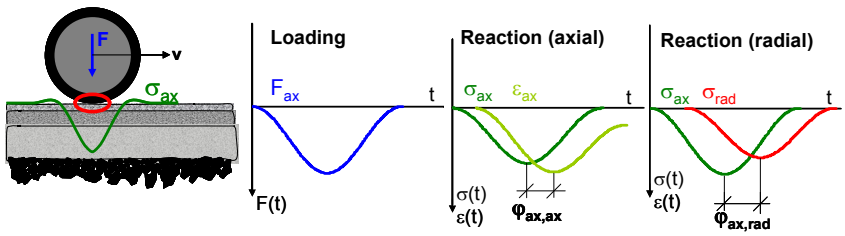

Figure 1: Loading and reaction of a flexible pavement structure due to traffic (schematic)

2.2 The Triaxial Cyclic Compression Test (TCCT)

To address the deformation behavior at high temperatures, the TCCT simulates the situation on the road. A cylindrical specimen (recommended minimum: h = 200 mm, d = 100 mm) is situated in a triaxial pressure cell between two load plates. The cell is filled with an incompressible medium (e.g. water) which is pressurized and creates the radial confining pressure. To protect the specimen from the medium, it is surrounded by a latex membrane. According to EN 12697-25 and as shown in Figure 2, the axial (wheel) loading is simulated by a sinusoidal compressive load F_{ax}:

$$F_{ax}(t) = \left[\sigma_{rad} + \sigma_a \cdot [1 + \sin(2\pi f t)]\right] \cdot A_{sp} \tag{1}$$

$F_{ax}(t)$	axial loading with respect to time
σ_{rad}	radial confining pressure
σ_a	amplitude of axial loading stress
f	frequency of loading [Hz]
t	time
A_{sp}	cross-section of the specimen

To simplify the test control a constant radial confining pressure σ_{rad} is applied to the specimen to simulation the confinement within the pavement structure. As a reaction axial and radial strain with respective phase angles can be derived.

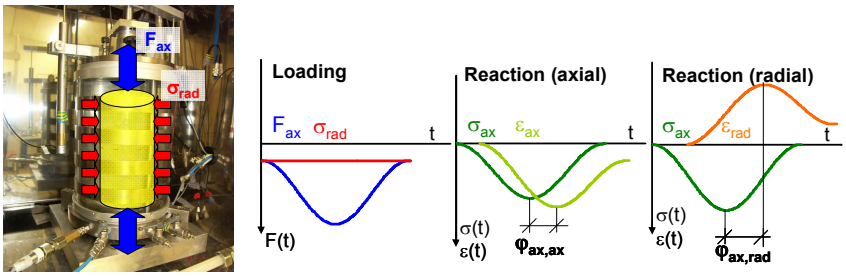

Figure 2: Loading and reaction of an HMA-specimen in the TCCT (schematic)

Depending on the type of HMA-layer (surface or base) different test parameters are given by the European Standard EN 13108-20 (see Table 1). The standard TCCT results in a relationship between the permanent axial deformation $\varepsilon_{ax,perm}$ vs. the number of load cycles N. The creep rate f_c in micro strain per load cycle indicates the resistance of the HMA to permanent deformation at high temperatures. A high value of f_c stands for low rutting-resistance vice verse. (EN 12697-25, 2006)

Table 1: TCCT parameters (EN 13108-20, 2006)

	Surface Layer	**Base Layer**
Test temperature	50°C	40°C
Radial confining pressure	150 kPa	50 kPa
Amplitude of axial loading	300 kPa	200 kPa
Frequency of loading	3,0 Hz	3,0 Hz

Compared to the actual stress situation in the pavement under a passing wheel with the TCCT, the constant confining pressure σ_{rad} is a simplification which has an influence on the result itself since the 3-d state of stress in the specimen is different from that in a road pavement. By applying a cyclic confining pressure with a certain phase angle, the test procedure will simulate the state of stress in a more realistic way and thus the permanent deformation behavior in more reliable way. The challenge is therefore to (1) measure the radial deformation and (2) to determine the phase angle $\varphi_{ax,rad}$ which is not only dependent on the temperature and frequency of loading but also the binder and the mix type itself.

3 APPROACH

To improve the TCCT by implementing cyclic confining pressure, an extensive testing program using the simplified TCCT and uniaxial cyclic compression tests (UCCT) is carried out on different ACs. The axial loading, the radial and axial deformation are recorded and analyzed to obtain the phase angle $\varphi_{ax,rad}$. This phase angle is then used as an input value for phase lag between the axial loading and the cyclic confining pressure in the improved TCCT. Results of simplified and improved TCCT will be compared and analyzed. The approach is also depicted in Figure 3.

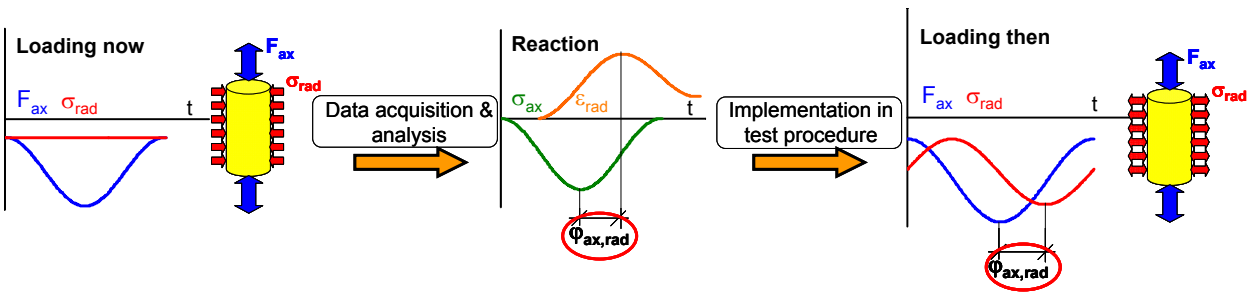

Figure 3: Approach to implement cyclic confining pressure in the TCCT

3.1 .Measuring Radial Deformation

To measure the radial strain of a cylindrical specimen and in consequence to assess $\varphi_{ax,rad}$, different devices based on different methods are available. For this purpose, the measuring device has to fulfill the following requirements:

- Temperature range: 0 to 60°C
- Total radial strain: > 5%
- Qualified to measure repeated loading with a frequency of up to 30 Hz
- Exact and reliable measurement of cyclic radial deformation
- Fits into the triaxial cell with its limited space

In a first step three systems were implemented and analyzed regarding their capability to fulfill above requirements (Kappl, 2007). They are depicted in Figure 4.

None of the systems was suited for the analysis of radial strain in the TCCT. The device based on extensometers fulfills the first four requirements excellently. Due to the dimensions of the device, it does not fit into the triaxial cell and could not be used. The system which measures on the basis of a rosette of steel springs with strain gauges is a compact system that fits into the triaxial cell. But the sealing which protects the strain gauges gets damaged due to the large strains that occur when attaching to the specimen. The third system based on linear variable differential transformers (LVDTs) is first of all too sluggish to record the cyclic radial deformation (see Figure 5). Still, it is a suitable device to obtain the cumulative strain for standard TCCTs, but it cannot be used for an analysis of phase lags. Furthermore, the device as the two other systems mentioned is also attached to the specimen on the outside of the latex membrane. This membrane reacts viscoelasticly itself and therefore influences measured radial the phase lag.

Figure 4: Chain-extensometer (left), steel spring device (middle), LVDT device (right) (Kappl, 2007)

3.2 Introducing Strain Gauges

As the mentioned devices did not lead to satisfactory results regarding radial strain analysis, another approach was needed to analyze the cyclic radial deformation successfully. As strain gauges have been employed on other inhomogeneous materials like concrete for decades, a new method was developed how to attach a strain gauge directly to an AC-specimen. As indicated in Figure 5, it records the cyclic radial deformation perfectly.

The major advantage to the three methods described in chapter 3.1 is that for the first time a measuring device is attached directly to the surface of the specimen and not outside the latex membrane. To protect the strain gauge from water, it is coated with a sealing based on silicone rubber. To guarantee reliable and repeatable measurements with strain gauges, each component of the system was optimized, including the adhesive, type of bonding, length of the strain gauge and the geometric setup.

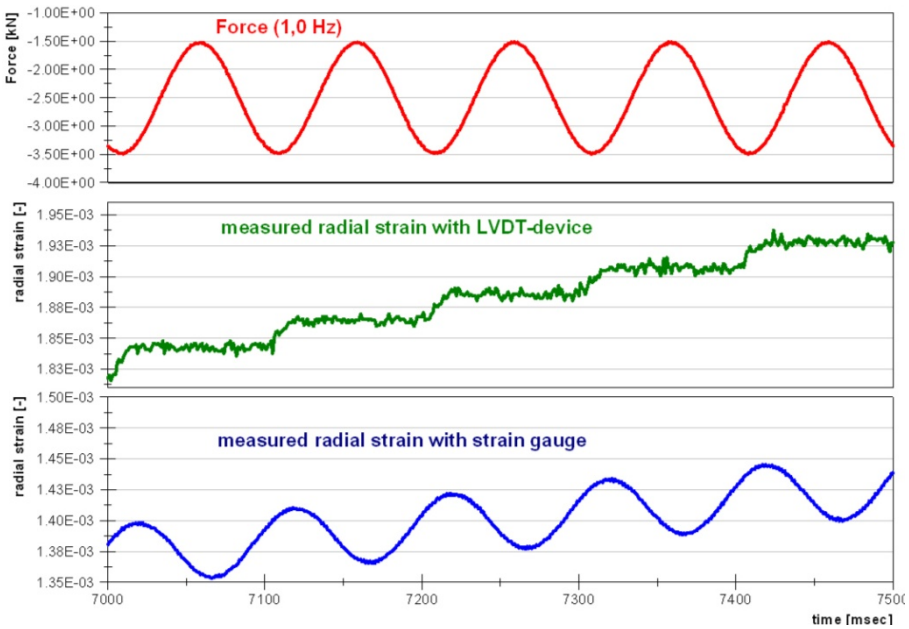

Figure 5: Measured radial deformation with LVDT-device (green) vs. strain gauge (blue)

3.2.1 Adhesive

The only adhesive we found suitable for a surface like AC-specimens is a two component adhesive which is also used when working with concrete. A solid acrylpolymere is mixed with a liquid monomer mixture based on methyl acryloester. The working limits regarding the temperature are -200°C and +80°C and the adhesive shows an extensibility of more than 10%. At room temperature the hardening time is about 15 minutes. The material exhibits a Young's modulus after hardening of around 13,000 N/mm² (HBM, 2009). All parameters of the adhesive are suitable for the type of tests carried out in the project. The only challenge is the high modulus of the adhesive which can be problematic at higher testing temperatures due to low stiffness of HMAs.

3.2.2 Type of bonding

From literature (Hoffmann, 1987) it is known, that the bonding quality of the strain gauge to the specimen is most important for correct and reliable readings. The strain gauge must be bonded force- and form-fit to the specimen. This is usually accomplished by adhering the device in a holohedral way to the surface. However, due to the high stiffness of the adhesive compared to the stiffness of HMAs, a holohedral bonding results in incorrect readings. The system of strain gauge and adhesive works like a restraint and prevents deformation.

As the strain gauges are only used for measuring strain due to tension, a different method of bonding is used. The strain gauge is attached to the specimen only punctually at both ends of the device. Figure 6 shows a specimen with an attached strain gauge. The adhesive area should be large enough, so that the force can be transmitted into the device without being too concentrated and not too large which would have a similar effect as holohedral bonding. The optimal area depends on the size of the largest aggregate used – in the present case with an AC11 (11 mm largest aggregate) a 2.0 cm by 1.5 cm area symmetrical around the end of the strain gauge showed best results.

3.2.3 Length of strain gauge

The minimum length of the strain gauge depends on the size of the largest aggregate fraction. Strain gauge manufacturers recommend that the length of the strain gauge should be more than 4- to 5-times the size of the largest aggregate fraction in the mix (Hoffmann, 1987). Thus it can be guaranteed that the recordings represent an average strain rather than a non-

representative strain between one specific stone and the mastix due to too short strain gauges.

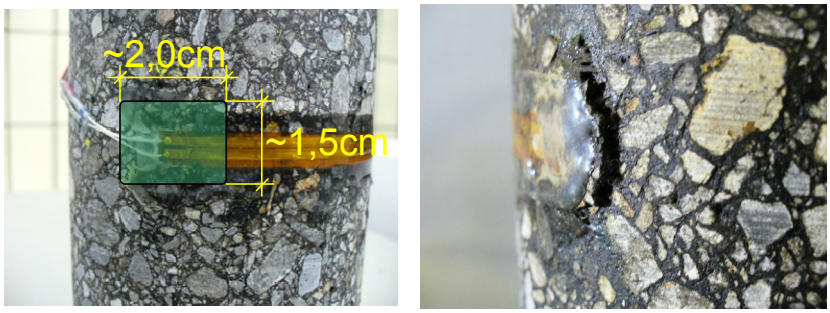

Figure 6: Adhesive area on specimen (left), typical damage due to small bonded area (right)

For the measurements strain gauges with an active, strain sensitive length of 100 mm and 150 mm respectively are used and results were compared. No significant difference was found in the results between both types, neither with regard to the recorded total radial strain nor to the calculated phase angles.

3.2.4 Geometric setup of strain gauges

Two setups of strain gauges were compared. In one case two strain gauges with a length of 100 mm were attached to the surface of the specimen each covering about one third of the perimeter. In the other case one 150 mm strain gauge was used covering about half the perimeter of the specimen. Again, comparative TCCTs were carried out with both setups to isolate any influence of the geometric setup. No difference was found in the results. Therefore the single strain gauge setup was used as it is less time consuming to prepare the specimen for testing. In all cases the strain gauges are attached at half height of the specimen as we expect a homogeneous state of stress in this region of the specimen.

3.2.5 Radial strain limits

With a thermo-rheological material like HMA, the test temperature has a significant effect on material parameters like the dynamic modulus E*. Especially at high temperatures, the binder itself exhibits more fluid-like characteristics. To prevent the adhesive area from getting separated from the rest of the specimen like shown in Figure 6, the total radial strain should be limited to 1% especially at high temperatures and the adhesive area should never be smaller than indicated in Figure 6.

3.3 Regression used for Analysis

To be able to analyze the phase lag analytically, the recorded data from tests must be represented by a regression functions which allows to find roots in an analytical way. For a stress-controlled test like cyclic compressions tests the advanced sinusoidal function

$$f(t) = a_1 + a_2 \cdot t + a_3 \cdot \sin(2\pi f \cdot t + a_4) + a_5 \cdot \sin(4\pi f \cdot t + a_6) \tag{2}$$

was found to deliver best results by (Kappl, 2007). The function takes into account a linear term to describe cumulative permanent deformation, as well as two sinusoidal terms to describe the oscillating part. A detailed discussion about different regression functions can be found in (Kappl, 2007).

4 MATERIALS

In this first stage of the project, one mix design (AC11 pen70/100) with a variation in the binder content is studied to systematically analyze the influence of this mix parameter on the phase angle $\varphi_{ax,rad}$. In Table 2 the variation of the mix design parameters for the AC11 pen70/100 are shown.

Table 2: Variation in the mix design of AC11 pen70/100

binder content [M%]	5.0	5.3	5.6
air void content [V%]	3.0	3.0	3.0

5 TEST PROGRAM AND RESULTS

To identify the viscoelastic behavior of the AC under cyclic compressive loading, in a first test phase (chapter 5.1) assumptions of the viscoelastic theory regarding the independence of viscoelastic parameters to the state of stress were verified. In the second test phase (chapter 5.2) the test temperature and frequency were varied for each tested material.

5.1 Test Phase #1

According to the theory of viscoelasticity, viscoelastic parameters should not be influenced by the state of stress applied. To prove this assumption, TCCTs at 30°C were performed at the AC11 pen70/100 at three different deviatoric stress levels. Figure 7 provides information on the test setup and the results. “sig_m” stands for the mean axial stress, “sig_a” for the axial stress amplitude and “sig_rad” for the constant confining pressure. “sig_d” is the resulting deviatoric stress. Three specimens were tested for each deviatoric stress level. However, the highest loading setup produced too large radial strains, so only one test was performed successfully at a limited frequency range.

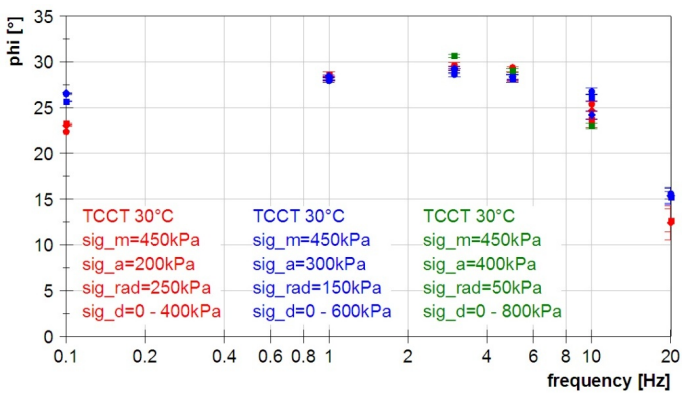

Figure 7: Phase angle between axial loading and radial deformation $\varphi_{ax,rad}$ at different deviatoric stresses for AC11 pen70/100 – frequency in logarithmic scale

5.1.1 Results

In Figure 7 different colors assign different deviatoric stress levels. For each frequency, the last 20% of the oscillations were used for analysis. So it is guaranteed that the test data was taken from a steady state with constant phase angles. The markers in the diagram show the mean value of the phase angle $\varphi_{ax,\ rad}$ for each specimen at each frequency. Additionally the standard deviation is depicted as a bar. From the results it can be concluded that the state of stress has indeed no influence on the viscoelastic parameters. Thus in the test phase #2 the

10°C and 30°C tests were carried out uniaxially, since uniaxial tests are much easier and quicker to carry out. Still the 50°C tests are carried out with confining pressure according to the stress levels in EN 13108-20.

5.2 Test Phase #2

In the second test phase the main influences on $\varphi_{ax,rad}$ are isolated. Besides the influence of frequency and temperature, the impact of the binder content on the phase angle was investigated. Tests were carried out at 10°C, 30°C and 50°C (see Table 3) at a frequency sweep shown in Table 4. However, the 0.5 and 30.0 Hz frequency packages were only added at a later stage of the project. For each material at least two specimens per temperature were tested.

Table 3: Test set-up regarding stress-levels

Temperature [°C]	10	30	50
Test type	UCCT	UCCT	TCCT
sig_m [kPa]	600	250	450
sig_a [kPa]	500	150	300
sig_rad [kPa]	0	0	150

Table 4: Test set-up regarding load frequency and number of load cycles

Frequency [Hz]	0.1	0.5	1.0	3.0	5.0	10.0	20.0	30.0	0.1	0.5	1.0
Load cycles [-]	25	50	200	600	1000	1000	1000	1000	25	25	100

5.2.1 Results

The results regarding the binder content are displayed in the diagrams in Figure 8. Each diagram represents a test temperature, each marker in a diagram the mean value of the phase angle $\varphi_{ax,rad}$ for one test at a certain frequency.

Again the phase angle was obtained from the last 20% of each frequency package to make sure that the test is in a steady state. The bars around each marker show the standard deviation. Each color marks one binder content (5.0, 5.3, 5.6 M%). From the results it can be concluded that the binder content has no evident influence on the phase angle. Still, as the bituminous binder is responsible for the viscous characteristics of HMAs, it is believed that the binder content does have an influence on the viscoelastic parameters. Thus we will vary the binder content in a larger range (± 0,5 M%) in the second stage of the experimental program to verify the present results.

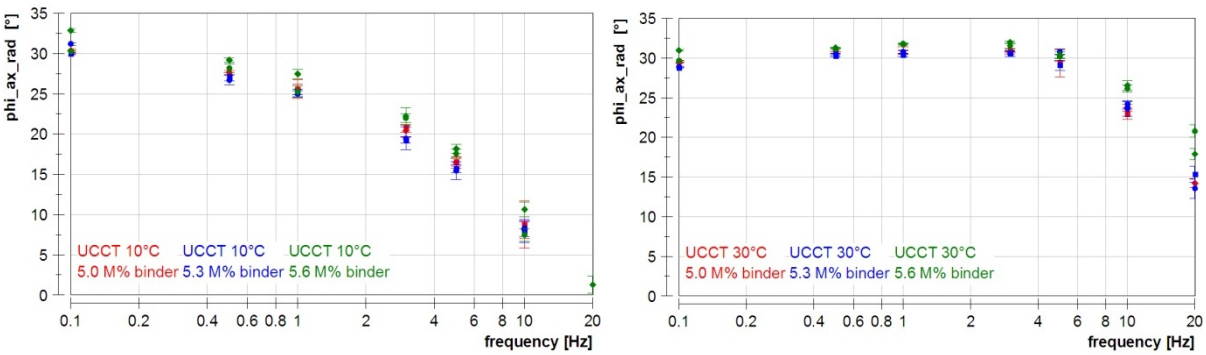

Figure 8: Impact of binder content on phase angle for 10°C (left), 30°C (right) for AC11 pen70/100 – frequency in logarithmic scale.

As expected, temperature and frequency have a crucial impact on the viscoelastic

parameters as HMAs are considered thermo-rheological materials. The left diagram in Figure 9 presents the results. The setup of the diagram is the same as for Figure 8, except that the different colors match different temperatures.

Interestingly enough, the phase angle which represents the rate of elastic vs. viscous behavior is not directly proportional to the test temperature. The highest phase angles occur at a test temperature of 30°C. This is consistent with analysis done for stiffness-tests at HMA-specimens (Blab and Eberhardsteiner, 2006). If results from these tests are presented in the black-space (norm of the dynamic modulus $|E^*|$ vs. phase angle φ), the maximum phase angles never occur at the highest temperatures.

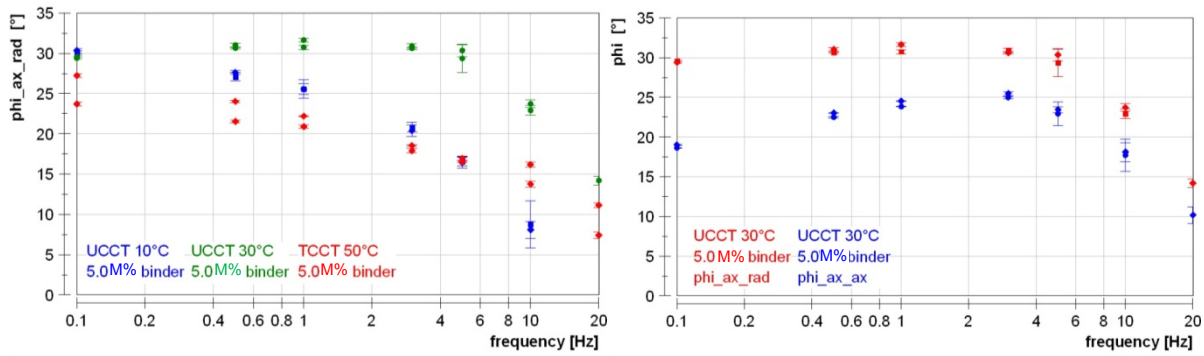

Figure 9: Impact of test temperature on the phase angle (left) and comparison of phase angle $\varphi_{ax,ax}$ and $\varphi_{ax,rad}$ (right) for AC11 pen70/100 – frequency in logarithmic scale.

By comparing the phase angle between axial loading and axial deformation $\varphi_{ax,ax}$ and the phase angle between axial loading and radial deformation $\varphi_{ax,rad}$,the two phase angles show a difference of 4° to 11°. $\varphi_{ax,rad}$ is always the larger one. The right diagram in Figure 9 shows an example. The present assumption is that this effect is associated with the anisotropy of the material. Right now the cylindrical specimens are drilled out of an HMA plate perpendicular to the direction of compaction. In the second stage of the project, specimens will also be drilled out in the actual direction of compaction results will be compared to validate the assumption.

Thus, for the improvement of the standard TCCT by implementing a cyclic confining pressure according to Figure 3 the phase angle $\varphi_{ax,rad}$ at 50°C and 3 Hz is needed. For the AC11 pen70/100 with 5.0 M% binder content a mean value of 18.2° with a standard deviation of 0.46° was found. These numbers were derived from tests carried out on four different specimens.

6 CONCLUSIONS AND NEXT STEPS

From the present stage of the project, we conclude the following:

- Strain gauge technique successfully implemented – high accuracy of measurement directly on the surface of the specimen
- Mathematical approach to derive phase angles from measured data developed
- Test setup optimized to obtain repeatable material parameters

The first test phase shows:

- No influence of deviatoric stress on viscoelastic material parameters – rheologically simple material behavior
- Radial phase lag strongly dependent on temperature and frequency; no or moderate influence of binder content

- Maximum phase lag at a temperature of 30°C – analogue to stiffness tests
- Difference in axial and radial phase lag depending on temperature and frequency between 4° and 11°.

Some issues about the test device can be optimized. The most important part is the adhesive which is very stiff and could be replaced by an adhesive with a similar stiffness like the specimen. This is necessary to prevent any influence of the adhesive on the results especially at high temperatures. There are two component adhesives which allow the user to change the stiffness by changing the mix of the components. Right now the hardening of these adhesives at room temperature takes high contact pressures and a fairly long time.

The test program will be carried on in a second stage. It will include an AC11 with SBS-modified binder at different binder contents and also different contents of air voids to analyze any influence of this mix design parameter. Functional relationship between the phase angle and mix parameters should be obtained.

The cyclic confining pressure with $\varphi_{ax,rad}$ will be implemented to improve the TCCT and results of the standard and the improved TCCT will be compared and analyzed.

In a parallel project other viscoelastic parameters, i.e. the phase angle $\varphi_{ax,ax}$, the elastic (E_1) and viscous part (E_2) of the dynamic modulus E^* obtained from the TCCTs and UCCTs are also analyzed. More information on the viscoelastic behavior of HMAs at high temperatures is going to be gathered from this project. The main objective is to find functional relationships between mix parameters and the viscoelastic parameters.

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