Crack propagation in asphalt mixture based on photoelasticity method

Stephan Büchler[1, a], Michael P. Wistuba[1, b]

[1] ISBS, Institut für Straßenwesen, Technische Universität Braunschweig, Braunschweig, Germany

[a] s.buechler@tu-bs.de
[b] m.wistuba@tu-bs.de

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ABSTRACT

The photoelasticity method is a powerful tool for investigating crack propagation during laboratory testing of asphalt materials. In this study, a reflection polariscope is used to detect deformation and cracks on the surface of asphalt mixtures. Six asphalt mixtures commonly used for base course (AC 22), binder course (AC 16) and surface course (AC 8) layers are selected. Notched semi-circular bending specimens are produced from these materials to perform monotonic and fatigue tests. In monotonic tests the specimen is loaded under a constant strain rate until failure. In fatigue tests, a cyclic load with a frequency of 10 Hz is applied until failure. Digital cameras are used to record the tests with a rate of 30 images per second for monotonic tests and 1 image per 2 seconds for cyclic tests. Based on these data, crack propagation is described in function of time. It is observed, that in monotonic tests a minimal deformation of the specimen surface occurs while the load is increased and cracking occurs suddenly at peak load. A similar trend is observed for fatigue tests over a longer period of time. Again cracking occurs near to the end of the tests.

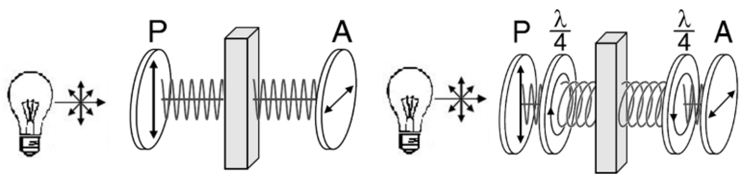
Keywords: Asphalt, Crack propagation, Testing

1. INTRODUCTION

The multilayer theory for asphalt structures assumes that cracks appear at the bottom layer due to bending associated to traffic load. Therefore a basic model was developed to simulate crack propagation in asphalt specimen by the "Institut für Straßenwesen" of the RWTH Aachen.
In order to verify and validate this newly developed model two testing procedures were implemented. The "Institut für Straßenwesen, Technische Universität Braunschweig (ISBS) and the „Professur für Straßenbau des Instituts für Stadtbauwesen und Straßenbau", Technische Universität Dresden (ISSD), proposed two methods based on photoelasticity (ISBS) and on photogrammetry (ISSD) for obtaining an advanced visualization of crack propagation. All works were funded by the research project FE 09/0189/2011/ERB "Numerische Simulation der Rissausbreitung in flexiblen Asphaltbefestigungen Infolge von Verkehrslasten, Teil II".
The results of the photoelasticity technique on crack detection and visualization and propagation are presented in this paper.

2. PRINCIPLES OF PHOTOELASTICITY

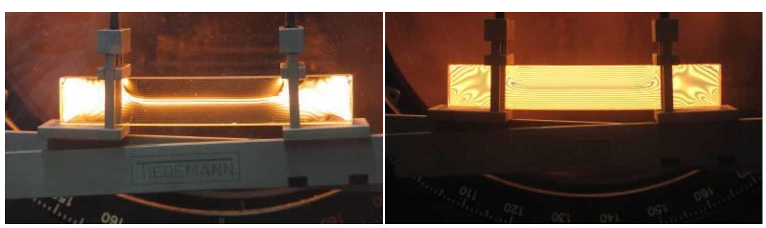
Photoelasticity is not a new measurement technique, see Harris and Jessop (1949) [6]; however, as this technique wasn't yet applied to asphalt materials, a short introduction to photoelasticity will follow. The main principle of photoelasticity is based on the refraction of light rays passing a transparent material under load. To visualize stress patterns at the material surface a polariscope is needed. In principle it consists of a light source and a transparent sample between two polarizing filters, see Figure 1.



a) b)

Figure 1: Principles of photoelasticity a) plane polarized light, b) circular polarized light

The polarizer P converts the light to plane polarized light. The light rays pass the unloaded and transparent sample and hits the second polarizing filter A (analyzer). As the analyzer is rotated by 90 ° with respect to the polarizer, no light can pass through the analyzer and black image is observed. By loading the sample, a certain component of the light rays is refracted, can pass the analyzer and a stress pattern consisting of isochromatics can be seen.
Light rays which are randomly refracted by 90 ° to the polarizer, cannot be seen; black areas will appear. To prevent these areas a quarter wave filter before and after the sample is used to convert the plane polarized light into circular polarized light, see Figure 1. The difference between plane polarized light and circular polarized light is shown Figure 2.



a) b)

Figure 2: View on a sample rayed by monochromatic a) plane polarized light and b) circular polarized light.

As asphalt specimens are not transparent, the principle of photoelasticity is not directly applicable. An alternate method has to be used: the reflection method (Figure 3).

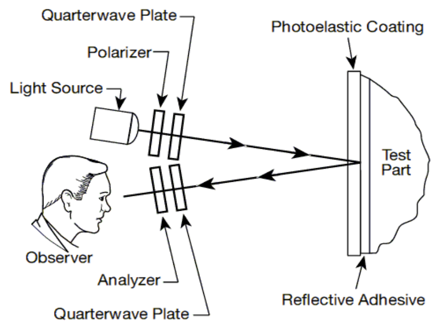


Figure 3: Principle of the reflection polariscope [8, 9, 10]

A photoelastic coating is applied on the specimen surface. This coating consists of a transparent sheet of high-elongation material, such as rubber, with a thickness of 3 mm and a modulus of elasticity of 4 MPa. This photoelastic coating is glued to the specimen through a reflecting adhesive which consists of glue with reflecting particles having a small modulus of elasticity equal to 7 MPa. By this small modulus even small deformations can be transferred from the specimen to the photoelastic coating. Caused by this deformation within the coating layer the light rays are refracted and deformation can be visualized by the polariscope.

3 MATERIALS

Three types of asphalt mixtures commonly used in Germany were selected for the experimental phase: a base layer AC 22, a binder layer AC 16 and a surface layer AC 8. Two asphalt binder contents were used for each asphalt mix design; hence six different asphalt mixtures were produced, see Table 1.

Table 1: Binder contents for asphalt mix design

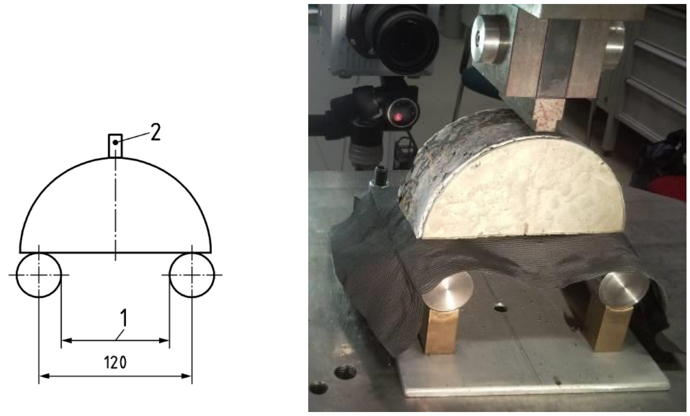
	lower content [M.-%]	higher content [M.-%]
AC 22	4.1	4.6
AC 16	4.5	5.0
AC 8	6.2	6.7

Specimens were prepared with a roller compactor according to EN 12697-33 [3] capable of compacting asphalt mixture slabs up to a size of 50 x 70 cm². Then specimen with a diameter of 150 mm and a thickness of 60 mm were cored out of the slabs and grinded on the front sides to obtain a smooth surface. Afterwards each core was sawn in the middle and notched (width: 2 mm; depth: 10 mm). After drying, each specimen was coated with a transparent layer of photoelastic material.

4. TEST METHODS

4.1 MONOTONIC SEMI-CIRCULAR BENDING TEST

Semi-circular bending (SCB) tests were selected for the experimental phase, based on previous research [7] or [2]. SCB tests were performed according to the European specifications EN 12697-44 [4]; a schematic sketch of the test is be presented in Figure 4.



a) b)

Figure 4: a) Monotonic semi-circular bending test and b) experimental setup with coated specimen

Specimens were first conditioned at 5°C for 4 hours and tests performed at room temperature of 20°C. Load was applied in deflection control mode with rate of 5 mm/min. The stress at the tip of the notch was calculated according to EN 12697-44 [4]. Each test was filmed with 30 pictures per second for a maximum duration of 20s. Then single picture-frames were extracted and used for interpreting the results.

4.2 CYCLIC SEMI-CIRCULAR BENDING TEST

Samples and experimental design of the cyclic semi-circular bending tests are similar to the monotonic semi-circular bending procedure. In this test a cyclic sinusoidal load was applied to the specimen with a frequency of 10 Hz. The amplitude of the applied load was selected based on the maximum load used for the monotonic tests (see Table 2). The minimum stress level was fixed to 0,1 MPa.

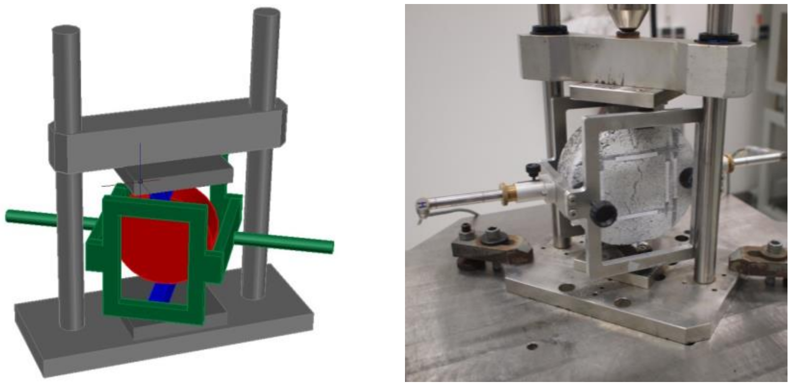
Table 2: Applied load as terms of stress at the tip of the notch

	binder content 1 [M.-%]	amplitude 1 [MPa]	binder content 2 [M.-%]	amplitude 2 [MPa]
AC 22	4.1	2.9	4.6	3.2
AC 16	4.5	2.2	5.0	2.2
AC 8	6.2	2.4	6.7	2.5

As the duration of the tests was up to 28 minutes and beyond the storing capacity of the cameras, picture/frames were recorded only every 2 seconds.

4.3 CYCLIC INDIRECT TENSILE TEST

The cyclic indirect tensile tests (ITT) were performed according to the European specifications EN 12697-24 [11]. A schematic sketch and the experimental setup are presented in Figure 5. A special frame for measuring the horizontal deformations was constructed, to take a look at the middle range of the specimen.



a) b)

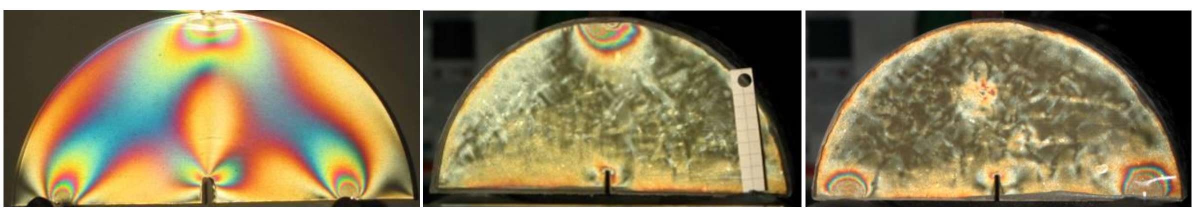
Figure 5: a) Sketch for Cyclic Indirect Tensile Test and b) experimental setup with specimen

For this test cored specimen (diameter 150 mm) were used. They were conditioned and tested at room temperature of 20 °C. Tests were performed in stress control mode with a frequency of 10 Hz. Pictures were taken every 2 seconds, similar to the cyclic semi-circular bending test.

4 VISUALIZATION

4.1 MONOTONIC SEMI-CIRCULAR BENDING TEST

In Figure 6 the difference between a homogenous elastic specimen (plexiglass) and an asphalt specimen (AC 8) is shown. For the plexiglass an accumulation of ischromatics can be observed at the three points of the load application, which are connected by an area of a single isochromatic. A clear pattern can be also identified at the tip of the notch, which expand and propagate to the top of the specimen. These patterns are confirmed by literature [1] and [5]. For the asphalt specimen accumulations of isochromatics only under the top or bottom loading points were observed.



a) b) c

Figure 6: a) Visualized isochromatics in a homogeneous and elastic specimen and b) and c) nearly no isochromatics on an asphalt specimen AC 8 under load.

The varying appearance of this accumulations may be caused by several effects. One observed effect is the compression of the glue at the top, transmitting its deformation to the refracting coating material. But as main reason, the planeness of the specimen is to be seen. The cored and cut specimens are not as plane as the counter bearing or the load stamp. So it may happen, that the main part of the load will be transferred at the rear side of the specimen, resulting in nearly no deformations at the front and therefore no visible isochromatics.

Nevertheless all tested specimen showed nearly no deformation (and therefore stresses) up to the point of crack. Figure 7 shows the development of deformation (and stress) during a test for a AC 8.

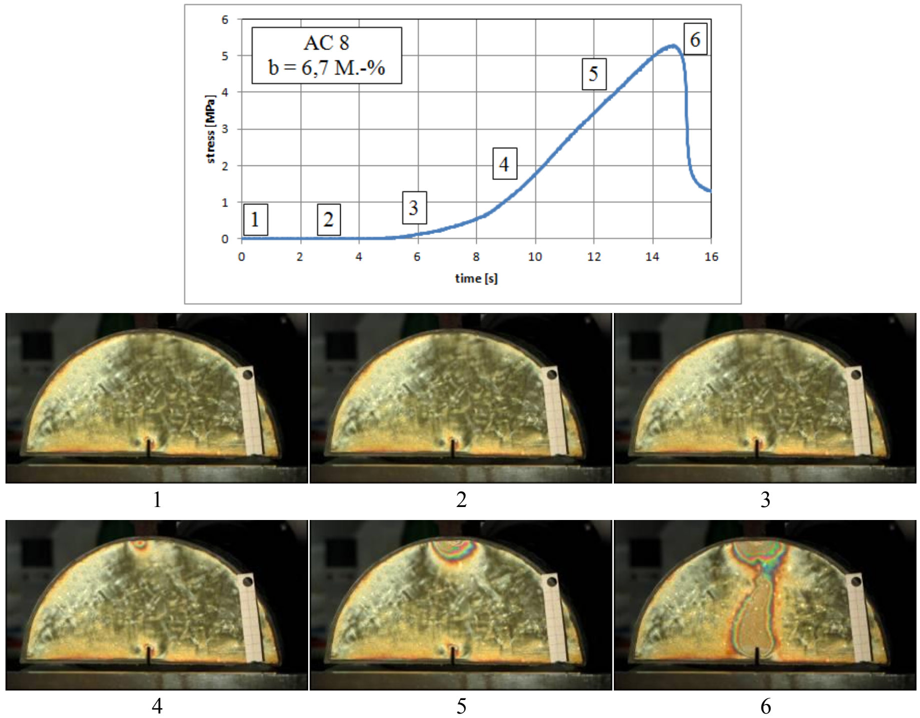


Figure 7 Visualization of the deformation evolution during a monotonic bending test (AC 8)

In Figure 8 the crack propagation is presented; the crack propagates from the tip of the notch and reaches the top of the specimen within half a second.

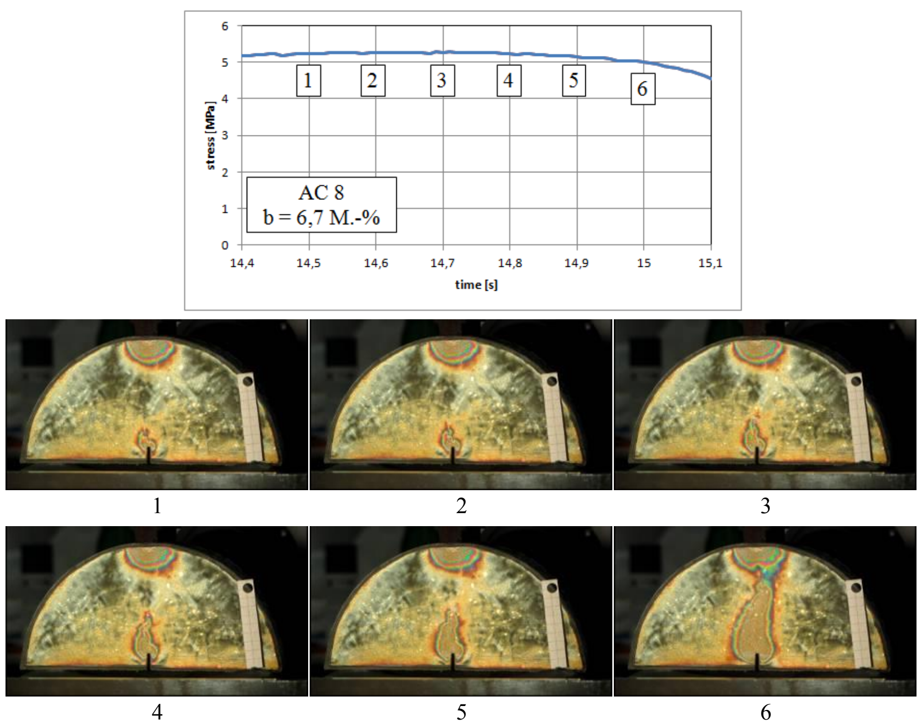


Figure 8: Crack propagation in a monotonic bending test (AC 8)

The propagation of the crack does not follow the ideal line of maximum stress, straight to the top of the specimen (see Figure 8). The crack is deflected by single grains constituting the aggregate skeleton of the mixture. At failure the crack has reached the top of the specimen which is entirely cracked. An exact cracking line cannot be directly observed behind the coating surface, as the coating still holds the specimen together. Only large deformation will tear the coating apart (Figure 10). Observing the test, the crack seems to appear very fast, a quasibrittle failure happens. By analyzing the series of pictures obtained for each test, the crack propagation is not linear. It will start with a slow movement and increases exponentially, as shown in figure 9.

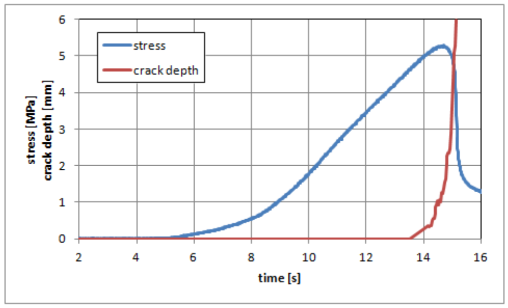
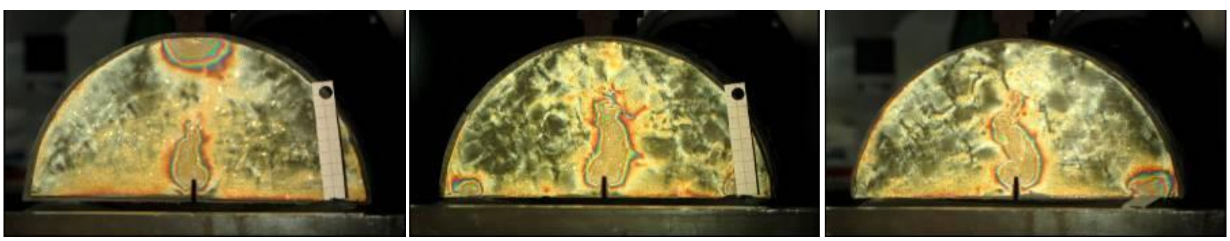


Figure 9: Crack growth for asphalt mixture AC 8

For this tests, data recording and image recording were manually synchronized. There was no synchronization by an electrical signal or similar. The convenient conformity of stress and crack growth, shown in figure 9, will happen only in a few cases. Mostly a correct assignment of time and crack growth is not possible. So further investigations in crack growth were not made.

Overall no statistically significant effects of the asphalt binder content could be observed on the crack initiation and propagation. Asphalt mixtures AC 22 and AC 16 showed a similar behavior with respect to crack propagation, with small differences associated to the crack path which showed limited deflection from a straight line for the mixture prepared with larger aggregates. Figure 10 shows the difference during cracking for the three asphalt mixtures investigated.

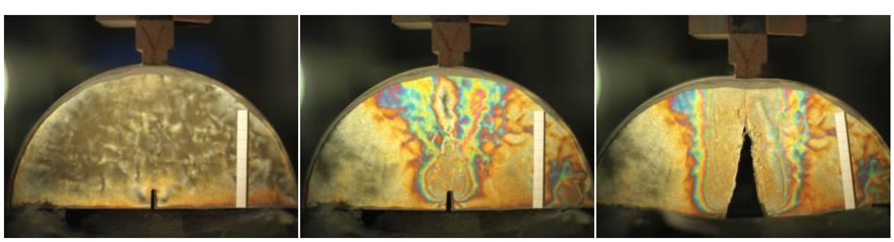


a) b) c)

Figure 10: Crack line for asphalt mixtures a) AC 8, b) AC 16 and c) AC 22

4.2 CYCLIC SEMI-CIRCULAR BENDING TEST

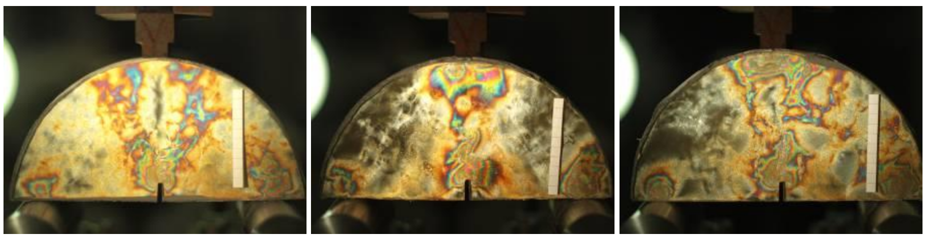
The visualization of the cyclic tests resulted in pictures are comparable to the monotonic tests. Up to 10% of the test duration no strain or stress could be observed in the specimen. Then small patterns of isochromatics occurred at the top of the specimen. This patterns of isochromatics increased slowly until 80 % - 90 % of the test duration. Then cracking occurred at the tip of the notch and propagated slowly (with respect to the monotonic tests) till the top of the specimen. Figure 11 shows an AC 8 after 258 load cycles without any significant (permanent) strain. After 12,900 load cycles the crack is developing and propagates through the specimen, showing a typical pattern observed in three-point bending tests. Finally, after 200 additional load cycles the specimen failed.



a) b) c)

Figure 11: Isochromatic patterns in a cyclic semi-circular bending test, after 258 load cycles (a), after 12,900 load cyles (b) and after 13,100 load cycles (c)

While the crack was propagating the isochromatic pattern showed a V-shape above the crack. In the middle of the specimen a strainless zone could be detected. In the monotonic tests (Figure 5a) this zone could also be identified, but its size is significantly smaller compared to what observed for cyclic loading. The specimens prepared with mixtures having larger aggregates (AC 16 and AC 22) showed this patterns only basically. The location of single grains has a large impact on the crack pattern (see Figure 12). On the other hand, the AC 8 mixture showed consistently a V-shape pattern with a strainless zone above the notch or the crack. This V-shape could also be observed in a calculated (elastic) stress distribution by Krans et al. 1996 [10]. This accordance indicates, that the crack growth theory, described in [5] or [7], can be verified and the calculation of the stress intensity factor K in the crack tip could be possible.



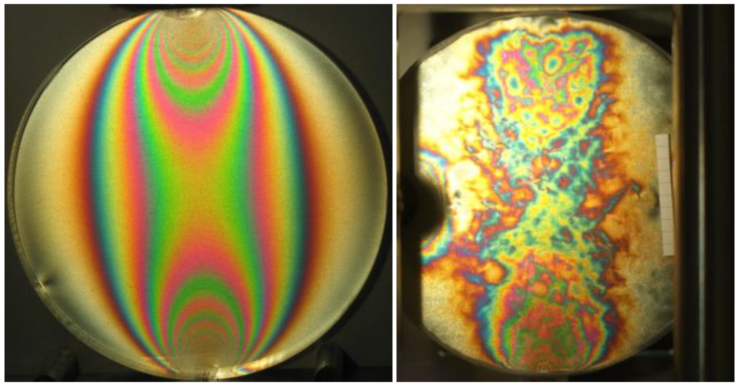
a) b) c)

Figure 12: Isochromatic patterns in a cyclic semi-circular bending test at ~90 % of the test duration. AC 8 (a), AC 16 (b) and AC 22 (c)

As the timing of the camera was not exactly fixed on two second (it scatters around approximately 0.2 s), the pictures were taken randomly around the 2 second interval. So at the time a picture was taken, the load could vary from minimum load to maximum load. But there was only little effect to the patterns by this load difference.

4.3 CYCLIC INDIRECT TENSILE TEST

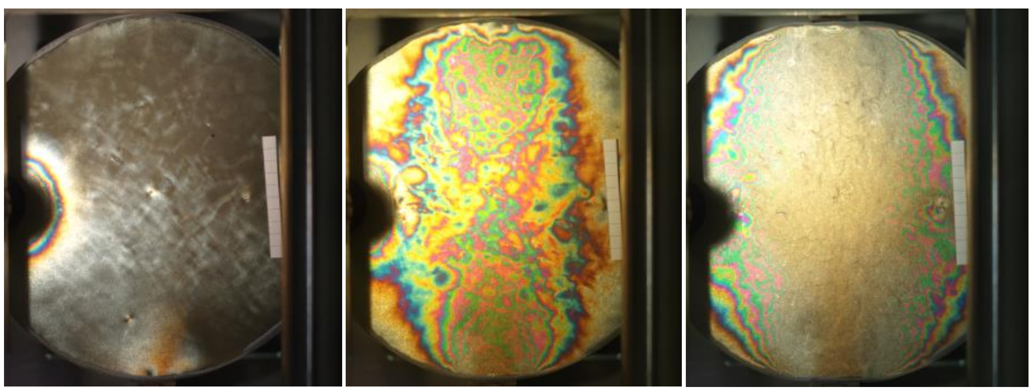
The difference between a homogenous elastic specimen (plexiglass) and an asphalt specimen (AC 8) is shown in Figure 13. For the plexiglass an accumulation of ischromatics can be observed at the top and bottom points of the load application (pressure). The left or right side of the plexiglass is stressless (dark region) with an increasing number of isochromatics to the center (tensile). The asphalt specimen shows a similar pattern, but it is deflected by single grains constituting the aggregate skeleton of the mixture.



a) b)

Figure 13: a) Visualized isochromatics in a homogeneous and elastic specimen and b) isochromatics on an asphalt specimen AC 8 after 300 load cycles.

Figure 13 and Figure 14 (same specimen) show the development of patterns in a single test. Soon after 600 load cycles no clear pattern can be observed, up to failure at 4,700 load cycles. Even the cracks can’t be observe behind the coating surface, as the coating still holds the specimen together (similar to monotonic semi-circular bending tests).



a) b) c)

Figure 14: Isochromatic patterns in a cyclic indirect tensile test, at start (a), after 600 load cyles (b) and after 4,700 load cycles (failure) (c)

This development of patterns was characteristic for all conducted tests. The deformation in the middle zone of a specimen exceeds the range of the coating for resulting in a clear pattern. Overall it was not possible to detect a crack or to visualize a crack propagation.

5 SUMMARY

In this paper the possibility of using photoelasticity to visualize and evaluate deformation and crack propagation of asphalt specimen was investigated. A reflection polariscope was used to observe strain patterns on the surface of asphalt mixture specimens. Three asphalt mixtures commonly used in Germany with two different binder contents, were selected to perform monotonic and cyclic (fatigue) semi-circular bending tests on notched specimens and to perform cyclic indirect tensile test on cylindrical specimen. The deformation patterns (isochromatics) were recorded through digital cameras, acquiring 30 images per second for monotonic tests and every two second an image for fatigue tests.

During monotonic testing, very little deformation on the specimen surface could be visualized as load increased. As peak load was reached, cracking occurred suddenly, suggesting a typical quasibrittle behavior. Fatigue tests showed similar trend, but over a longer time. First strain patterns appear after 10 % of the test duration, but cracking occurred at the end of the tests and needed an additional number of load cycles to reach complete failure.

Cyclic indirect tensile tests showed large deformation in the middle zone of specimen. After a short number of load cycles clear isochromatic patterns were visualized. At failure no patterns were observed and cracks couldn’t be detected.

The technique of photoelasticity, based on the use of a reflection polariscope, showed the possibility to visualize deformation at the surface of asphalt specimen. Cracks can be detected and their propagation can be recorded for further analysis. For future research an improved test equipment should be used and correlations to homogenous materials and the link to stress calculation models should be investigated.

ACKNOWLEDGMENTS

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