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Effect of Gap Width on Interlayer Shear Bond Results

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Abstract: Since the 1990s the Leutner shear test has become the most important device for testing the interlayer shear bond of asphalt pavements. The test device was originally designed by R. Leutner in the late 1970s, but since different countries and laboratories have made modifications or have built their own equipment. Besides others the gap width between the shearing rings has been a matter of modification. Recently this question also appeared in the process of European standardization. This paper shows the results of a laboratory study in which the gap distance was varied between 0 and 5*mm*. It was found that the influence of the gap width depends on the asphalt concrete type of the two layers (mixture type, max. aggregate size, and binder content). In most cases the gap width is negligible, in some cases maximum shear force and stiffness value decreases with increasing gap width. In addition to the shear values at the interface, shear tests were conducted in the material itself. Therefore, the difference between in-layer and interlayer shear properties and behavior is also discussed in more detail.

Key words: *Gap width; Interlayer shear bond; Leutner test.*

Introduction

Developed in the late 1970s the so called Leutner direct shear test has become the most important test for determining the interlayer shear bond between asphalt pavement layers [1]. Although the test arrangement suffers from non-uniform interface shear stresses and the fact that no load perpendicular to the test plain can be applied, its simplicity and easy handling have let to its world wide adaption.

Over the years several countries and laboratories have made modifications or have built their own equipment e.g. [2-7]. Initiated by a modification made in the United Kingdom (UK) [8] the question about the gap width between the shearing rings of the device was raised in the process of European standardization. The reason for the UK modification was due to the difficulty to perfectly align the interface to the shear plane, especially for specimens having irregular interfaces (due to coarse aggregates interlocking or an uneven bottom layer surfaces) [8]. Although the authors state that the modification using a gap width of 5*mm* was beneficial for the testing, no comparison of tests results with different gap widths was given.

This paper describes an investigation in which the bond strength between the different layers of an asphalt pavement was tested varying the gap width between 0, 2.5, and 5*mm*. The paper presents load-deformation properties for the different gap widths focusing on stiffness values, maximum shear stress with corresponding shear deformation. In addition to the shear characteristics at the interface, shear properties were also determined for the material itself in order to discuss the difference between in-layer and interlayer shear behavior, taking into consideration also optical measurement results of an earlier investigation by the authors [9].

It is important to note that this study does not claim providing a broad statistical data basis but intends improving the phenomenological understanding of the mechanisms in interlayer shear testing needed as basics for establishing and developing common standards. It also tries to gather evidence for the following two hypotheses:

(a) the influence of gap width becomes more important in case of weak interlayer shear bond, and
(b) in case of different maximum aggregate sizes of two comparable layers, the layer with the smaller aggregate size should be on top of the one with the larger aggregate size for improved interlayer shear bond.

Materials

For the investigation of the shear strength characteristics, cores obtained from a four layered Swiss motorway pavement were taken (see Fig. 1).

The pavement consisted of a stone mastic surface course material SMA (Stone Mastic Asphalt) with a nominal maximum aggregate size of 11*mm* placed on an asphalt concrete binder course material AC(Asphalt Concrete)-B 22 and an asphalt concrete base course material AC-T 32 with nominal maximum aggregate sizes of 22 and 32*mm* respectively according to the Swiss standard SN 640420. The subgrade material was asphalt concrete AC-S22 with a nominal maximum aggregate size of 22*mm*. Further details of the mixtures are given in Table 1.

Testing

Test Equipment

The tests were conducted using the Leutner shear test equipment shown in Fig. 2. Although this shear device according to the original set-up has no gap between the shearing rings, the gap width could

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Fig. 1. Details of Layers and Material.

Table 1. Mixture Characteristics.

Mixture Type	Binder Grade (Pen)	Binder Content [Mass-%]	Air Void Content [Vol-%]	Layer Thickness [*mm*]
SMA 11	80/100 + Trindad Lake Asphalt	6.4	4.7	40
AC-B 22	55/70	3.9	4.1	80
AC-T 32	55/70	3.6	3.8	105
AC-S 22	80/100	3.3	6.2	90

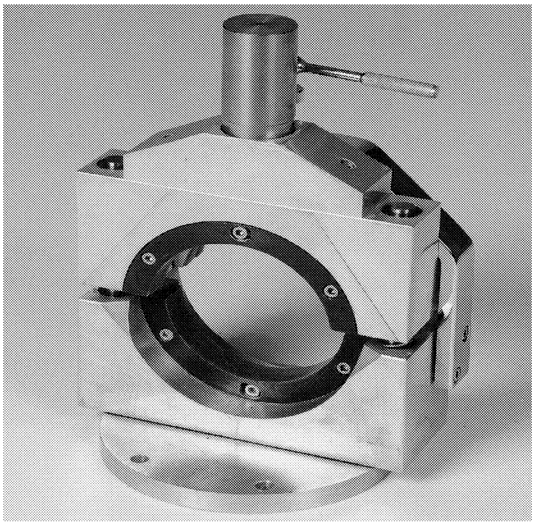


Fig. 2. Leutner Shear Test Equipment.

be modified for test purpose using a bolt spacer. In addition to the original 0*mm*, gap widths of 2.5 and 5.0*mm* were used for testing.

Note that the test equipment used for bond testing was slightly different to the one used for optical measurements (see Fig. 3). The test device in Fig. 3 is the so called Layer-Parallel Direct Shear (LPDS) test device [9], an EMPA (Eidgenössische Material Prüfungs- und Forschungsanstalt, Federal Laboratories for Material Testing and Research) modified version of equipment developed in Germany by Leutner [1]. The modified LPDS test device with hydraulic clamping mechanism fits into an ordinary servo-hydraulic Marshall machine and allows testing of cores with a diameter of about 150*mm* as well as rectangular specimens of 150 × 150*mm*. The application of a normal force perpendicular to the shear plane is not possible. One part of the core (up to the shear plane to be tested) is laid on a circular u-bearing and held down with a well defined pressure by a semicircular pneumatic clamp. The other part, the core head, remains unsuspended. Shear load is induced to the core head by a semicircular shear yoke with a deformation rate of 50*mm*/min, thus producing fracture within the pre-defined shear plane. For the evaluation of the influence of the velocity on the adhesion properties, a deformation rate of 2.5*mm*/min was evaluated additionally. The EMPA modified LPDS has a long clamping and supporting length such that the clamping of the specimen is simple, fast, and well defined. Earlier investigations showed that both test devices deliver comparable results [2].

Test Procedure

The tests were carried out at the standard loading rate of 50*mm*/min and the standard temperature of 20°C. Before testing, all cores with a diameter of 150*mm* were conditioned in a temperature controlled chamber.

Both the shear characteristics at the interface and within the individual layers were determined.

For every gap width configuration between 5 and 7 cores were tested. Testing was done by successively shearing in the interfaces of each core. The in-layer shear tests for the lower layers were conducted on the remaining core parts, while the surface layers were glued onto concrete cores to enlarge the specimens and enable the testing of layer thicknesses beneath 30*mm*.

From the Leutner test the shear force F as a function of shear deformation w measured as the vertical displacement of the upper shear ring was obtained. Nominal shear stress can be determined by dividing the max. shear force by the cross section area of the core. Additional to the shear force, the maximum slope from the diagram of shear force F versus shear deformation w was used to define the maximum shear "stiffness" value $S_{\max}$ as follows:

$$S_{\max} = \frac{dF}{dw} \quad where \quad \frac{d^2F}{dw^2} = 0 \quad and \quad \frac{d^3F}{dw^3} < 0 \tag{1}$$

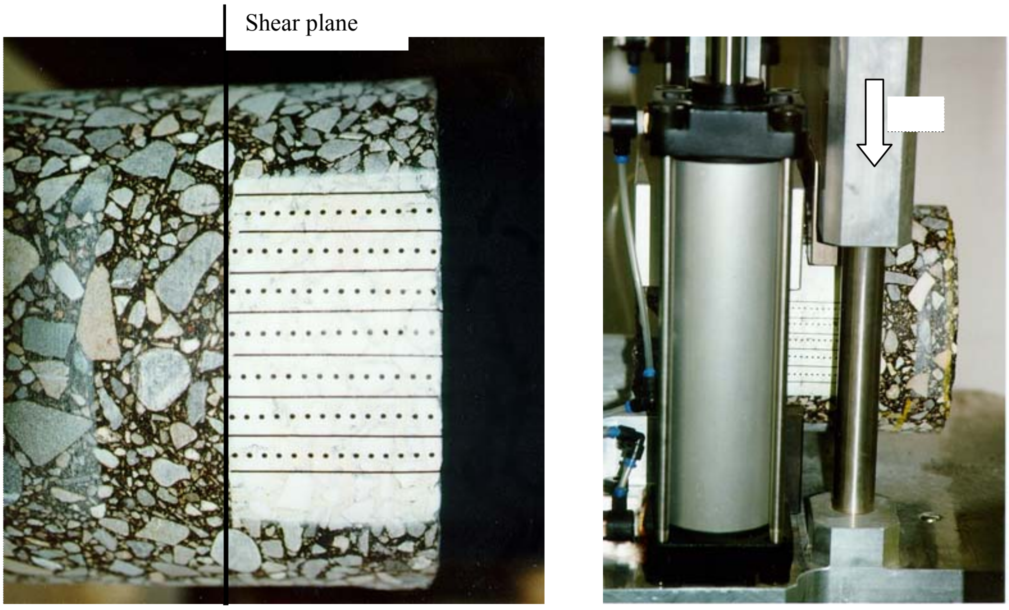
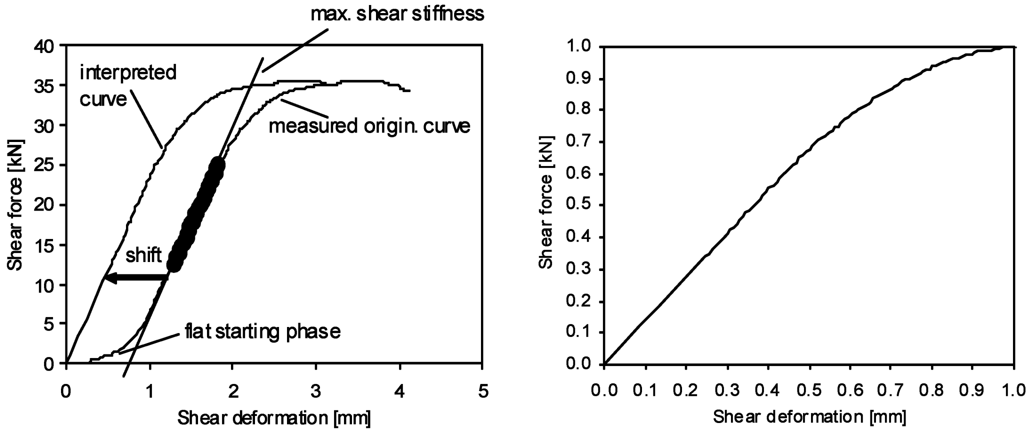


Fig. 3. Test Specimen with Markings in the Shearing Zone (left). To the Right the Specimen Fixed in the Test Device.



(a) (b)

Fig. 4. Method to Determine Mean Shear Force - Shear Deformation Curves.

where:

dF = differential shear force

dw = differential shear deformation

From the single measurements of shear force and shear stiffness the mean values and standard deviation as well as the mean shear force-deformation curves were determined. In order to determine the mean curves, the following 3-step procedure was applied:

(1) In a first step, the flat starting phase of the measured original curves was replaced by the tangent defined as the calculated maximum shear stiffness value from Eq. (1). After that, the whole curve was horizontally shifted into the origin of the coordinate system as shown schematically in Fig. 4(a). This was done for all single curves.

(2) In a second step, the single curves were normalized such that both a maximum shear force and corresponding deformation of "1" was obtained. This was done by dividing the coordinates of the individual shear force and deformation points of each curve through maximum shear force and the corresponding deformation coordinate as shown in Fig. 4(b). Next, all normalized curves were summed up and divided by the number of curves (average).

(3) In a last step, the mean curve was determined by multiplying the normalized mean curve with the mean maximum shear force and the associated mean deformation. The maximum shear stiffness value was calculated from linear regression in the steepest part of the curve.

Test Results

Shear Force

In Table 2 and Fig. 5, the mean maximum interlayer and in-layer shear forces and stresses for all investigated interfaces and mixture types for gap widths of 0, 2.5, and 5.0*mm* are shown. In Fig. 5, the standard deviations are also given.

For the interface between SMA and AC-B the shear forces

Table 2. Results from Shear Testing.

Shear Plane	Gap Width [*mm*]	Force [*kN*]	Stress [*MPa*]	Deformation [*mm*]	Stiffness [*mm*]
SMA 11/AC-B 22	0	43.2	2..4	2.3	25.6
	2.5	39.2	2.5	2.4	20.4
	5	37.0	2.1	2.5	20.8
AC-B 22/AC-T 32	0	43.6	2.5	1.8	30.2
	2.5	44.3	2.5	1.9	29.5
	5	43.6	2.5	1.9	29.2
AC-T 32/AC-S 22	0	26.0	1.5	0.9	30.5
	2.5	27.6	1.6	1.0	31.4
	5	19.3	1.1	0.8	26.8
In SM A 11	0	29.5	1.7	4.4	11.3
	2.5	26.0	1.5	3.2	12.9
	5	29.3	1.7	4.2	12.8
In AC-B 22	0	36.6	2.1	3.0	21.6
	2.5	33.6	1.9	3.0	21.2
	5	35.8	2.0	2.9	21.5
In AC-T 32	0	39.8	2.3	2.4	25.3
	2.5	40.6	2.3	2.2	28.8
	5	42.0	2.4	2.4	27.7

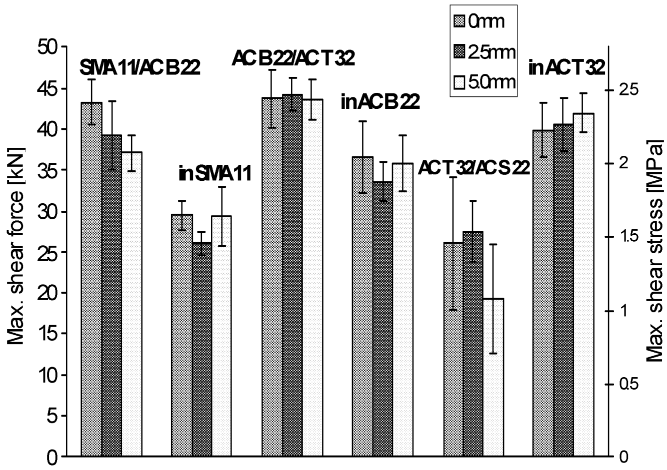


Fig. 5. Mean Values of the Max. Interlayer and In-layer Shear Forces with Gap Widths of 0, 2.5, and 5.0*mm*, Mean Value and Standard Deviation.

decrease with increasing gap width, while for the interface between AC-B and AC-T the values show no significant difference. In the case of the AC-T/AC-S interface, a tendency towards a decrease at a gap width of 5.0*mm* can be found. The observation of decreasing shear forces with increasing gap width could be explained by the fact that with increasing gap width, the shear plain is less concentrated at a certain location and therefore the failure happens at the weakest place of the specimens leading to lower shear forces.

It is interesting to note that in the presented case the gap appears to play a more dominant role for interlayer shear properties in cases where both layers show comparatively clear differences in composition and mechanical properties. This is true for SMA 11 and AC-B 22, which are very different in terms of aggregate size, binder grade, and binder content, as well as in the case of AC-T 32 and AC-S 22, which are different in terms of binder grade and air void content.

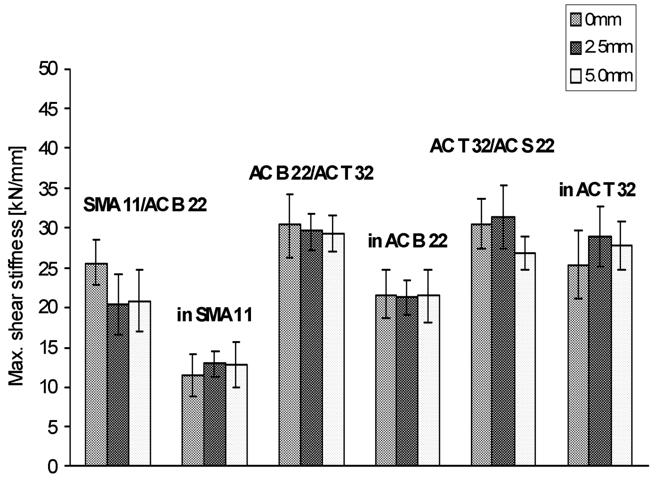


Fig. 6. Mean Values of the Max. Interlayer and In-layer Shear Stiffness Value with Gap Widths of 0, 2.5, and 5.0*mm*, Mean Value and Standard Deviation.

Regarding the in-layer shear forces, no significant systematic influence of the gap width could be observed: In the SMA the mean max. shear forces for 0 and 5.0*mm* are identical, the value for a 2.5*mm* gap is slightly smaller. This behavior can also be found for the second layer (AC-B 22), while for the AC T 32 layer the mean shear force increases with increasing gap width.

Shear Stiffness Value

Table 2 and Fig. 6 show the mean maximum interlayer and in-layer shear stiffness values for all investigated interfaces and mixture types for gap widths of 0, 2.5, and 5.0*mm*. In Fig. 6 the standard deviations are also given.

Regarding the shear stiffness value, the findings are similar to the ones for the shear forces: for the SMA/AC-B and the AC-T/AC-S interface, the shear stiffness value determined with a 5.0*mm* gap width

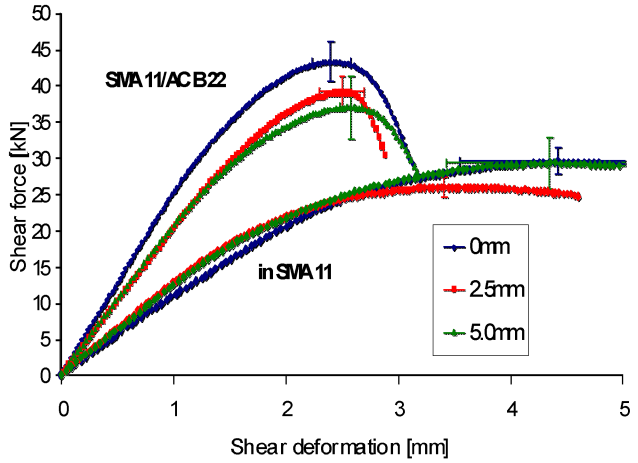


Fig. 7. SMA 11/AC-B 22 Mean Shear Force-Deformation Curves with Standard Deviation for Gap Widths of 0, 2.5, and 5.0*mm*.

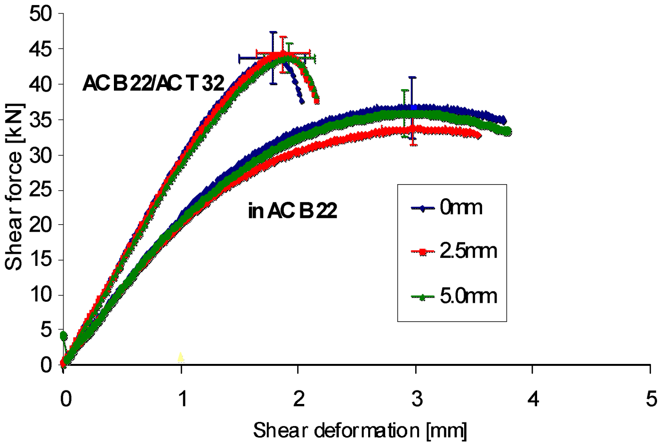


Fig. 8. AC-B22/AC-T322 Mean Shear Force-deformation Curves with Standard Deviation for Gap Widths of 0, 2.5, and 5.0*mm*.

was lower than the one with 0*mm* gap width. Again, for the AC-B/AC-T interface, no dependency on the gap width can be observed.

For in-layer testing, the differences are negligible: the in-layer shear stiffness value within the AC T 32 appears slightly higher than for a 0*mm* gap when testing with 2.5 and 5.0*mm* gaps, while for the in-layer testing of the SMA 11 and AC-B 22, no difference could be found.

General Considerations

From Figs. 5 and 6 the gap width appears to be less critical for in-layer than interlayer shear tests. Assuming that a properly produced asphalt layer material by itself should have a better internal micro-structural interlock than the interlock expected between the two layers, this finding suggests that the better the interlock between the layers or within the asphalt layer material, the lesser the influence of the gap width on the shear test results. This means that in cases of comparatively poor interlayer bond, the gap width may well influence the results and can therefore not be ignored. Standardization should therefore opt for narrow gap width tolerances.

Considering the influence of the gap width, in the case of this study, the interlock between AC-B 22/AC-T 32 (layer with small on layer with large maximum aggregate size) appears better than that between AC-T 32/AC S 22 (layer with large on layer with small maximum aggregate size). Likewise the influence of the gap width would imply that the interlock between SMA 11 and AC-B 22, despite small on big maximum aggregate size, is relatively weak. This may be due to the fact that SMA has a thicker binder film than that of the AC and a gap graded gradation that does not interlock so ideally with the AC. The reduced ability to interlock also shows up when the in-layer results for SMA are compared with the two other AC in-layer shear properties (AC-B 22 and AC-T 32), with SMA providing clearly lower force and stiffness values than AC.

Interlayer and in-layer shear behavior

In Fig. 7 the mean shear force - shear deformation curves for the interlayer testing between the stone mastic asphalt surface course SMA 11 and the asphalt concrete binder course AC-B 22 as well as the in-layer testing in the SMA 11 surface course layer are depicted. Fig. 8 shows the same curves for the AC-B/AC-T interlayer and the AC-B 22 in-layer testing.

Regarding the difference of interlayer and in-layer shear behavior, the qualitative difference between the curves is noteworthy: in-layer curves are flatter (less stiff) and show more deformation than interlayer curves. Further, the scatter of deformation is larger than the one of shear force respectively.

It has been found earlier [6] that the interlayer adhesion behavior between surface and binder courses is often less ductile (and therefore stiffer) than the in-layer shear behavior of the pavement. This has been explained by the fundamental difference between both shear behaviors. The in-layer shear properties depend on the micro-structural interlock of the components. Due to the inhomogeneities of the material and depending on compaction and composition, the interlock and contact forces between the individual components are only fully mobilized if some deformation and reorientation of the aggregates within the material has been possible. This process takes place during the whole shear test but becomes more dominant with increasing load. Hence, this type of behavior is based on a successive process with ductile appearance. The interlayer shear behavior, on the other hand, is governed by the adhesion of two planes, which means that the whole plane has to be moved at once to produce shear failure. After local adjustment at the beginning of the test, which was eliminated in this study by using the tangent and shifting the curve, the interlayer system tends to react stiff and failure occurs almost suddenly without large deformations.

Optical measurements

The difference between interlayer and in-layer testing are depicted in Fig. 9 showing optical measurements of the shear testing [9]. These optical measurements had been conducted to determine the vertical and horizontal deformation during the shear test and compare

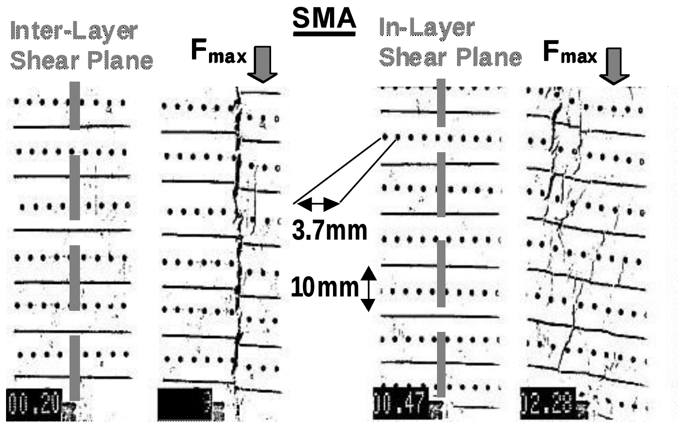


Fig. 9. Optical Measurements during Inter-layer and In-layer Shear Testing of a Pavement with SMA 11 Surface Courses at 20°C from [9]. View of the Situation at the Start of the Test and When Cracks Appear.

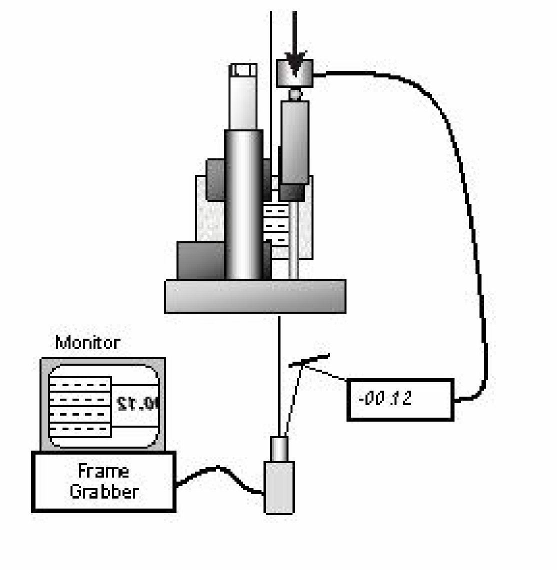


Fig. 10. Schematic Drawing of Test Set-up.

the deformation behavior of interlayer and in-layer testing. In order to be able to measure several points on the test specimen at the same time, the markings drawn on the specimen (Fig. 3) were taken during the shearing action with a camera. In this process the analogue force signal was blend in by using a mirror so that it was possible to correlate the measured deformation and the effective force. In Fig. 10 the test set-up of the optical measurement is shown.

During shear testing the specimens suffer displacements not only in the vertical in-plane shear direction but also in the horizontal or axial direction. This is due to dilatancy and load eccentricity effects. Optical measurements performed on two pavements with GA11 and SMA11 at 20°C showed that at maximum shear load the horizontal displacement was about four to three times smaller than the vertical displacements [2]. For the interlayer shear tests, the horizontal displacements were on the order of 0.06*mm* which was about 60% of the corresponding in-layer values. In addition, the measurements showed that after the starting phase of the shear test, the vertical displacements were distributed quite evenly over the cross section of the specimen. Note the difference of the fracture pattern in Fig. 9 between interlayer and in-layer test. The interlayer shear fracture occurred in the adhesion plane and a narrow fracture zone of about 4*mm* width was observed. For in-layer shear a dispersed fracture with a fracture zone width of about twice the maximum aggregate size (22*mm*) was observed.

In this investigation the shear stiffness value in the interlayer is also always higher than the in-layer stiffness value, a fact that had been already found for surface and binder courses in an earlier investigation [2, 9]. Unlike the findings in this earlier paper, the maximum interlayer shear forces are considerable higher than the in-layer shear forces of the upper layer.

Conclusions

From the investigation described in this paper, the following conclusions can be drawn:

1. For interlayer shear testing, the gap width between the shearing rings of the Leutner device does have an influence on the interlayer shear test results, especially in cases when the material characteristics of the two mixtures are different. Here, an increasing gap width leads to decreasing maximum shear force and shear stiffness value. If the layer material characteristics are similar, the gap width is less important.
2. By increasing the gap width, the eccentricity is also increased, resulting in a combined bending-shear stress situation. This may lead to an underestimation of the shear properties in case of big in-layer material characteristics.
3. By increasing the gap width, the shear plane becomes less defined and failure tends to occur at the weakest point rather than at the exact interface. Therefore, regarding to a standardization of interlayer shear testing, a gap width of 5*mm* may lead to results which reflect combined inlayer and interlayer properties.
4. In order to simplify and optimize the testing (more tolerance in the shear plane and less difficulty to perfectly align the interface to the shear plane, especially for specimens having irregular interfaces), a gap width slightly larger than 0*mm* would be sufficient. So far, the gap width of existing devices does not exceed 2.5*mm*.
5. As already found in earlier research, there is a qualitative difference between interlayer and in-layer shear force - shear deformation curves, suggesting that the interlayer adhesion behavior at 20°C is less ductile (and therefore stiffer) than the in-layer shear behavior of the pavements. Optical measurements showed that for the interlayer shear tests, the horizontal displacements during shear testing were about 60% of the corresponding in-layer values. Optical measurements further reveal the difference in the fracture pattern between interlayer and in-layer test. When the interlayer shear fracture occurred in the adhesion plane and a narrow fracture zone of about 4*mm* width was observed for in-layer shear, a dispersed fracture with a fracture zone width of about twice the maximum aggregate size was found.
6. Interlayer shear force and the stiffness value of two pavement layers are mostly considerably higher than the in-layer shear force and stiffness value of the upper pavement layer.

7. In the case of good interlock, the influence of the gap width appears small. On the other hand, this means that in cases of comparatively poor interlayer bond, the gap width may well influence the results and can therefore not be ignored. Standardization should therefore opt for narrow gap width tolerances.
8. Mixes with smaller maximum aggregate on mixes with bigger maximum aggregate appear to have a better interlock than mixes with bigger aggregate on mixes with smaller maximum aggregate.
9. Although the presented test results are limited, it is indispensable to perform tests on the gap width in a wider scale (different mixtures types and maximum aggregate sizes etc.) before test configurations are specified in international testing standards such as European standards.

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