Influence of Different Interface Properties on the Interlayer Bond Shear Stiffness

Borislav Hristov

University of Applied Sciences Berlin, Germany

E-mail: Borislav.Hristov@HTW-Berlin.de

Abstract. A good and durable interlayer bond is crucial for the long service life of asphalt pavements. In order to determine the shear stiffness at the interface between two asphalt layers, a new apparatus for cyclic testing of the interlayer bond (CTIB) in double-layered asphalt specimens has been developed. An extensive testing procedure has been created to take into account all the parameters that influence the interlayer bond, namely the interactions of repeated traffic loading, acceleration and braking processes as well as temperature. Numerous experimental tests have been carried out under sinusoidal repeated shear loading conditions at varying frequencies and temperatures under different normal stresses. A comparison between the average shear stiffness values at 200 g/m^2, 300 g/m^2 and 400 g/m^2 of C60BP1-S bitumen emulsion applied on the underlying layer's surface with different degrees of contamination has been made. Furthermore, in order to examine only the effect of adhesion, without having aggregate interlocking and friction at the interface, both layer's surfaces have been finely polished before applying the tack coat at the interface.

1. Introduction

The construction of asphalt concrete pavements in Germany usually consists of a surface course, a binder course and a base course. The individual asphalt layers are connected with each other through a tack coat (e.g. bitumen emulsion). This full-surface and rigid connection at the interfaces between the asphalt layers is called interlayer bond. The durability of the whole multilayer structure depends largely on the good quality of the bond between the asphalt layers.

Despite the availability of numerous studies on this subject, the combined influence of temperature, normal stress and shearing frequency on the bonding properties is still insufficiently researched. Therefore, work has been undertaken using a newly developed test apparatus for CTIB and a very detailed automatic testing procedure for determination of the shear stiffness of the interlayer bond.

The main objective of this study is to determine and evaluate the functional dependency between shear stiffness, temperature, shearing frequency and normal stress.

2. Background

The interlayer bond is achieved through the interlocking of the aggregate particles at the interface, the friction between the surfaces of the two asphalt layers and the adhesion between the asphalt binder of the two layers and the applied tack coat. The procedure to create a good bond between the asphalt layers is to clean the top surface of the underlying layer before spraying it with a bitumen emulsion and before placing the next layer.

The asphalt concrete pavement is loaded permanently in both a vertical direction by vehicle's wheel loads and a horizontal direction by braking and acceleration processes. If a poor interlayer bond

is present, the three-dimensional stress state in the entire pavement structure may fully be changed and horizontal displacements of the layers may appear. Additional stresses are also caused by temperature variation, which can compromise the functionality of the pavement.

The assessment of the interlayer bond in asphalt pavements in Germany is currently carried out with a static test according to Leutner by determining the shearing-off force as a criterion for the evaluation of the achieved bond strength, which is regulated in FGSV (2007). The main disadvantage of all static tests, which exist worldwide, is that they cannot simulate the real loading state in the pavement due to repeated loads, and therefore they are inapplicable for the accurate description of the bond behavior.

In order to simulate as accurately as possible the real load conditions, which exist on in-service asphalt pavements, a new improved apparatus for CTIB has been designed at the Department of Pavement Engineering at TU Dresden. Combined with the created extensive testing procedure it has been possible to take into account the interactions of repeated traffic loading, acceleration and braking processes as well as weather-related effects.

3. Experimental program

3.1. Preparation of double-layered asphalt specimens

All possible layer combinations were produced in the laboratory, but only some of them are shown in this work. Two-layered asphalt slabs (320 mm x 260 mm) were prepared in the roller sector compactor using a compression program with position-controlled pre-compression and force-controlled main compression (figure 1). The slabs of the underlying course were produced and stored at room temperature (RT) for 24 hours. The slabs surfaces were cleaned with a brush, or, alternatively, they were contaminated with the two amounts of silt described below. The bitumen emulsion was then applied uniformly using a flexible foam roller. The coated slabs were left at RT for at least two hours until the complete breaking of the bitumen emulsion (AL Sp-Asphalt 09). The hot bituminous mixture of the upper course was then laid and compacted. Four cylindrical specimens (Ø 100 mm) were drilled from one double-layered asphalt slab (figure 1).

Figure 1. Roller sector compactor (a), two-layered asphalt slab (b) and specimen (c)

The polymer modified cationic bitumen emulsion C60BP1-S was used in order to produce the interlayer bond. The bond was tested using respective amounts of 200 g/m^2, 300 g/m^2 and 400 g/m^2 at two roughness combinations of layer surfaces, namely finely polished and normal.

The experimental program also included an interlayer bond at three degrees of contamination of the surface of the underlying layer with silt:

- clean   0 g/m^2 silt,
- medium contamination   180 g/m^2 (15 g per slab),
- high contamination   360 g/m^2 (30 g per slab).

The layer combination was surface course on base course. Before applying the bitumen emulsion, the amount of fine dry silt per asphalt slab was applied homogeneously on the surface of the

underlying asphalt base layer (figure 2) and was then moistened using a spray bottle containing approx. 10 g of water. The bitumen emulsion was applied in the desired amount (figure 3). It is obvious, that the worst coverage was achieved when using 200 g/m^2 bitumen emulsion.
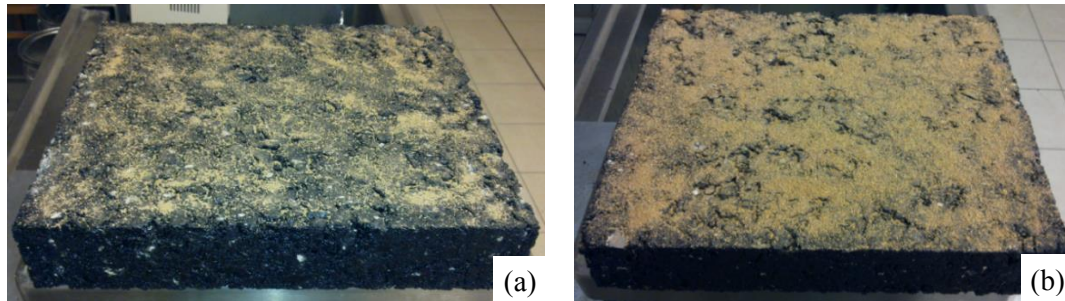

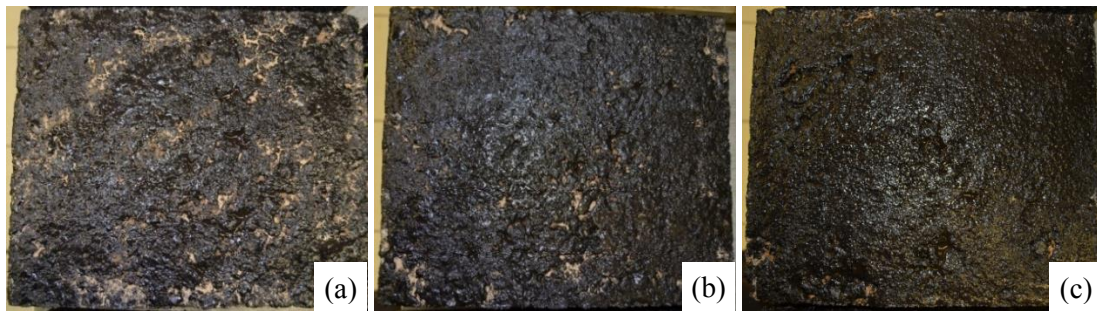**Figure 2.** Medium (a) and highly contaminated surface (b) with silt

Figure 3. Highly contaminated surface (30 g per slab) with applied bitumen emulsion
(a) 200 g/m^2, (b) 300 g/m^2, (c) 400 g/m^2

In order to examine only the effect of adhesion, without having aggregate interlocking and friction at the interface, both layer's surfaces were given a fine polish before applying the tack coat on the underlying layer (figure 4). The layer combination was surface course on base course. After a four-hour tempering of the surface course specimen at 55°C (temperature ring and ball), it was pressed onto the base course specimen in the compaction device shown in Figure 4 using a static press. The compressive force was applied at a speed of 0.5 KN/s until a maximum force of 19.5 KN was reached.

Figure 4. Finely polished base course surfaces with applied bitumen emulsion (a), opened compaction device (b) and closed compaction device (c)

To prepare the double-layered asphalt specimens for the dynamic test, every asphalt specimen was fixed inside two steel adapters with the aid of a two-component epoxy adhesive. The gap between the two steel adapters was set to 1.0 mm and the interface of the specimen was precisely adjusted to fit in this gap. The four half-shells were fastened together with eight screws (figure 5).
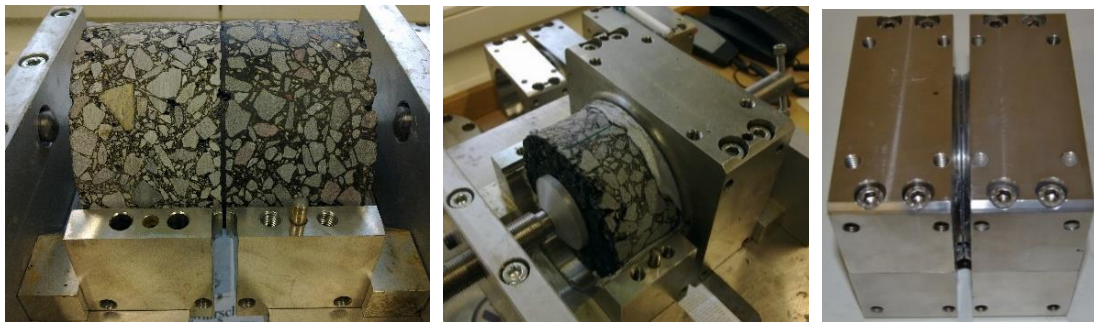
Figure 5. Specimen preparation for CTIB

3.2. New apparatus for cyclic testing of the interlayer bond

The new test apparatus was designed to apply cyclic shear force in the vertical direction and static normal force in the horizontal direction and was mounted in the temperature chamber of a servo-hydraulic testing machine (figure 6). The test sample was inserted and fixed in the jowls A and B, so that half of the sample was in A and the other half was in B. The gap between the jowls was the same as it was between the steel adapters of the sample (1.0 mm). The steel adapters were fastened in the jowls with 24 screws to avoid any possible movement of the sample in the test device. The sinusoidal shear cyclic loading was applied to one layer of the specimen (jowl B) by the hydraulic cylinder of the servo-hydraulic testing machine and was position-controlled. The second half of the specimen was held unmovable in vertical direction by jowl A. The normal pressure was applied on the back of the asphalt specimen (jowl A) by a piston rod through a steel plate. To counteract the normal pressure, the specimen was blocked at the front surface through a second steel plate held by a socket which was fastened to jowl B. The vertical shear displacement of jowl B and the horizontal motion of jowl A was measured by four sensors.
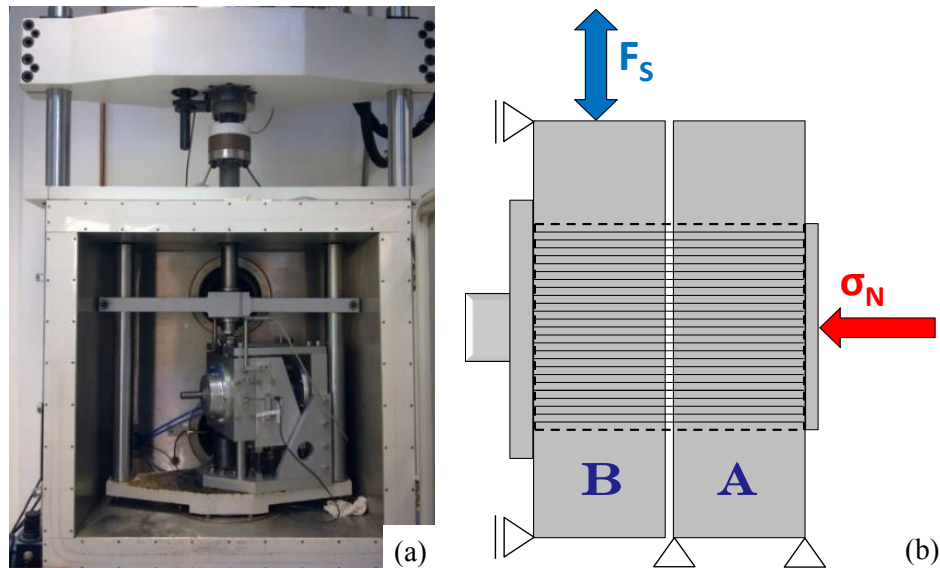

Figure 6. Newly developed test apparatus for CTIB (a) and mechanical model (b)

3.3. Testing procedure

The test procedure started always at a temperature of T = -10°C, normal stress σ_N = 0.9 MPa, shearing frequency f = 10 Hz and a maximal shear displacement $s_{w,max}$ = 0.03 mm. For each specimen it ended

at T = 50°C, σ_N = 0.9 MPa, f = 10 Hz and $s_{w,max}$ = 0.15 mm. The whole experiment was conducted at four different temperatures. At each temperature the specimen was loaded with five normal stresses. Six frequencies at the corresponding number of load cycles changed successively during each normal pressure. The whole procedure of simultaneous and consecutive process runs was fully automated and no manual interference was required. The duration of the whole procedure for one specimen lasted 11h 43min.

4. Experimental results

In order to exclude the initial deviations at the beginning of each shearing frequency, only the data from the last five cycles at its end were used for the calculation of the shear stiffness. Because of the long tempering duration between the different test temperatures, it was not reasonable to show the variation of the shear stiffness with time. Therefore, a sequential numbering was chosen on the x-axis. The shear strain is calculated as follows:

$$\tan \gamma_s = \frac{\tau_s}{G_s} \tag{1}$$

For small shear angles $\tan\gamma_s \approx \gamma_s$.

$$\tan \gamma_s = \gamma_s = \frac{s_w}{d_s} \tag{2}$$

The shear stiffness is therefore

$$G_s = \frac{\tau_s}{\gamma_s} = \frac{\tau_s}{\left(\dfrac{s_w}{d_s}\right)} \tag{3}$$

with

$$\tau_s = \frac{F_s}{A} \tag{4}$$

where F_s is the shear force amplitude (N), γ_s is the shear strain (-), τ_s is the shear stress (MPa), A is the cross section at the interface (mm^2), s_w is the shear displacement amplitude (mm), d_s is the gap between steel adapters (mm), and G_s is the shear stiffness (MPa/mm).

4.1. Normally produced interlayer bond on clean surface

A comparison between the average shear stiffness values at 200 g/m^2, 300 g/m^2 and 400 g/m^2 of C60BP1-S bitumen emulsion applied on clean surfaces as well as the temperature, normal stress and frequency gradients from the tests are shown in figure 7. The layer combination was binder course on base course and three asphalt specimens were tested for each amount of bitumen emulsion. It was observed that the normal stress and the shearing frequency influences the shear stiffness to various degrees at different temperatures. The shear stiffness of the interlayer bond decreased rapidly with increasing temperature and grew with increasing normal stress, as it occurs under traffic load. The impact of the normal stress on the shear stiffness was considerably smaller at low temperatures compared to the higher temperatures irrespective of the tack coat amount used. As can be seen in the diagram, the shearing frequency has a significant impact on the shear stiffness. The latter increased with increasing frequency, whereby the smallest increment was observed at the temperature extremes. The highest shear stiffness was observed for 300 g/m^2 while the lowest was measured for 200 g/m^2 tack coat at all temperatures. The shear stiffness values of the interlayer bond with 400 g/m^2 bitumen emulsion was always between the stiffness values of the other two amounts. It is assumed that because of the high roughness of the base course's surface the smaller amount of 200 g/m^2 penetrates into the pores and therefore strong adhesion cannot be achieved. Obviously 300 g/m^2 bitumen emulsion is the optimal amount to produce a stronger bond for clean surfaces. The interlayer bond does not get better

when increasing the amount of tack coat above 300 g/m^2, because the bitumen emulsion starts acting as a "lubricating film" between the layers, thereby reducing the interlocking at the interface.

The temperature dependence is a characteristic feature of the bituminous binder, which makes the adhesion temperature dependent too. At the lowest temperature the adhesion at the interface was strong. The friction was insignificant because the displacements were smaller than 30 μm and therefore it could be neglected. The effects of adhesion, aggregate interlocking and friction took place concurrently at temperatures of 10°C and 30°C. Adhesion strength decreased with increasing temperature, which in turn led to continuous reduction in shear stiffness indicating a successive deterioration of the interlayer bond. At 50°C there was no adhesion at all, and the shear stiffness at the interface was achieved only through the aggregate interlocking and the friction between the surfaces of the two asphalt layers. The results show that at 50°C all three shear stiffness gradients are nearly the same at any normal stress and frequency. The shear stiffness values are approximately zero MPa/mm for all three tack coat amounts at the lowest frequency when no normal stress is applied. This means that there is a complete loss of friction at the interface indicating an inadequate interlayer bond. Once normal pressures and higher shearing frequencies were applied, the friction was activated again and the shear stiffness increased.
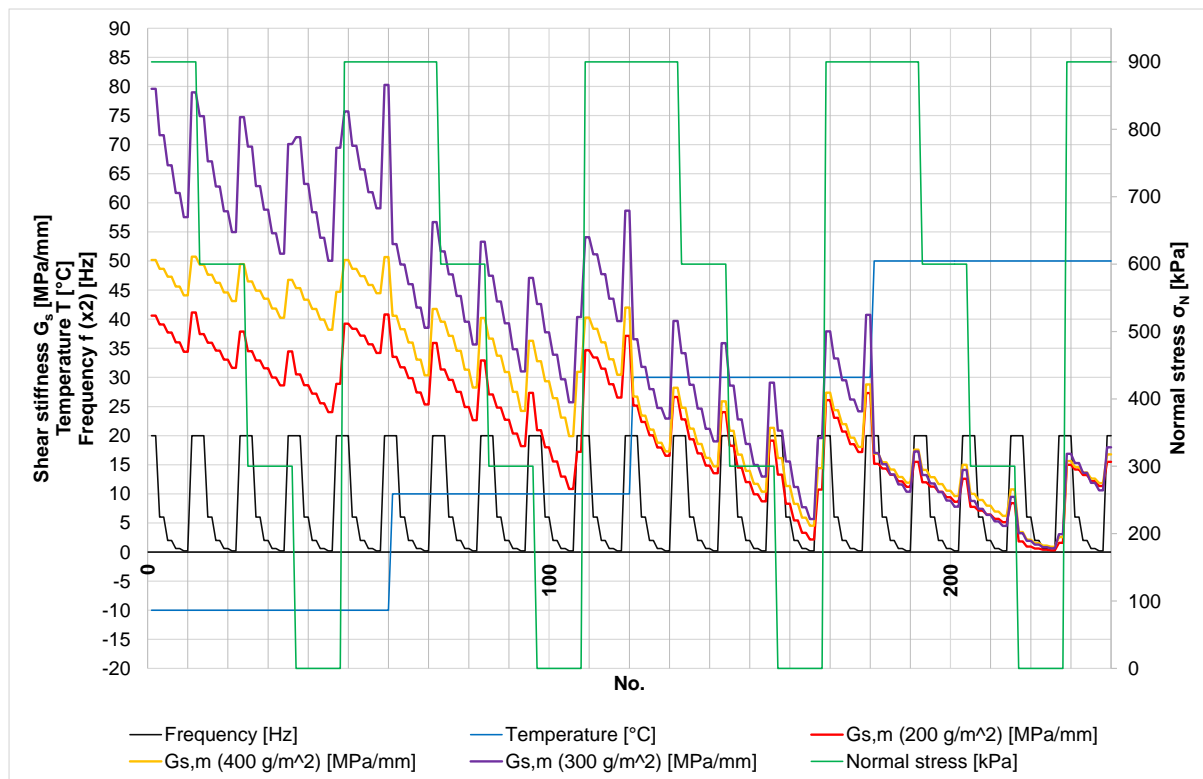

Figure 7. Gradients of the average shear stiffness for 200 g/m^2, 300 g/m^2 and 400 g/m^2 bitumen emulsion C60BP1-S applied on clean surface

4.2. Interlayer bond produced on contaminated surfaces

The strongest interlayer bond was produced when using 300 g/m^2 bitumen emulsion C60BP1-S at both clean and medium contaminated surface. The shear stiffness are in the same range and reach almost the same values at all temperatures (up to 97 MPa/mm at -10°C), whereat the bond at medium contamination shows even slightly better results at the lower frequencies. For highly contaminated surfaces, the shear stiffness values decrease dramatically at all temperatures, normal pressures and shearing frequencies. The highest values are around 40 MPa/mm at the lowest temperature (figure 8) and the difference between the average values at -10°C and 30°C are marginal.

When applying the highest bitumen emulsion amount of 400 g/m^2, the shear stiffness values show that the bond is heavily weakened for both clean and medium contaminated surface (figure 9). The highest shear stiffness values reach only approximately 62 MPa/mm at -10°C. The lowest shear stiffness values at all temperatures, normal pressures and shearing frequencies were calculated for the highly contaminated surface. Increasing the bitumen emulsion quantity does not lead to a better interlayer bond. Highly contaminated surfaces have, as expected, a negative effect on the quality of the interlayer bond.
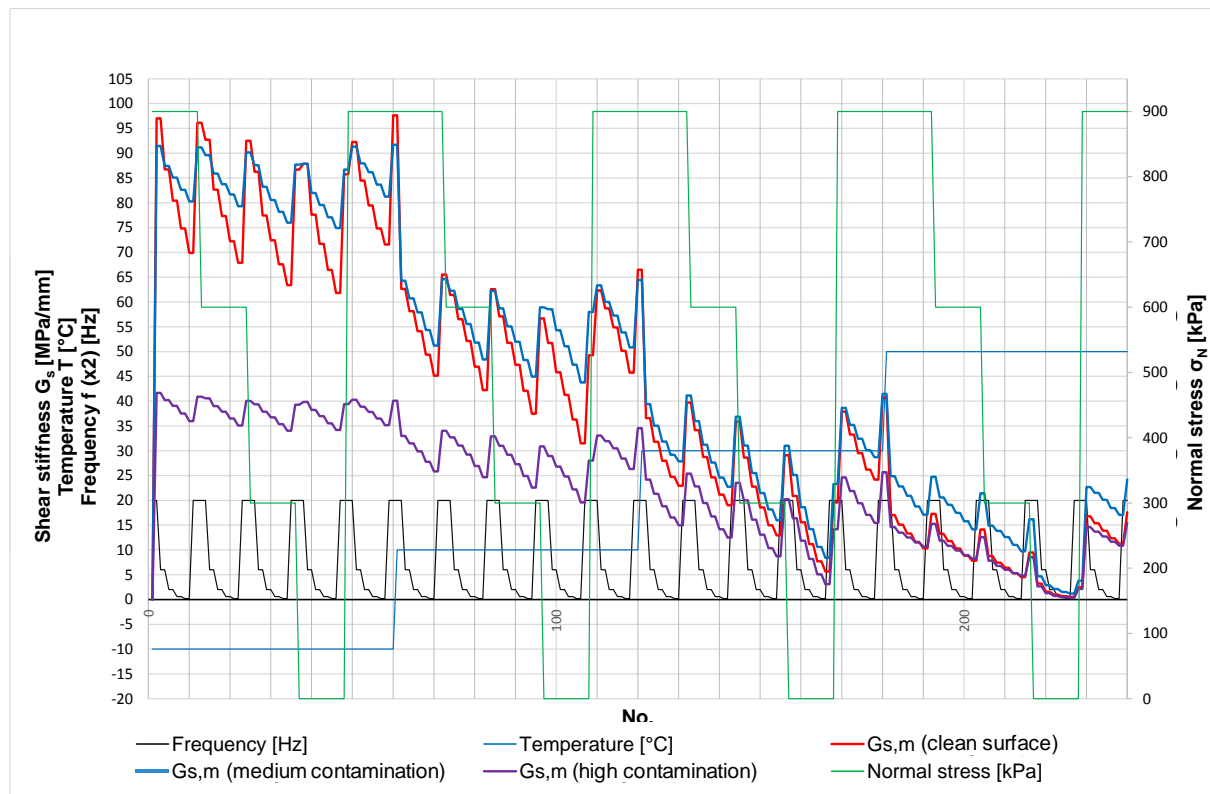

Figure 8. Gradients of the average shear stiffness for clean, medium and highly contaminated surface using 300 g/m^2 bitumen emulsion C60BP1-S
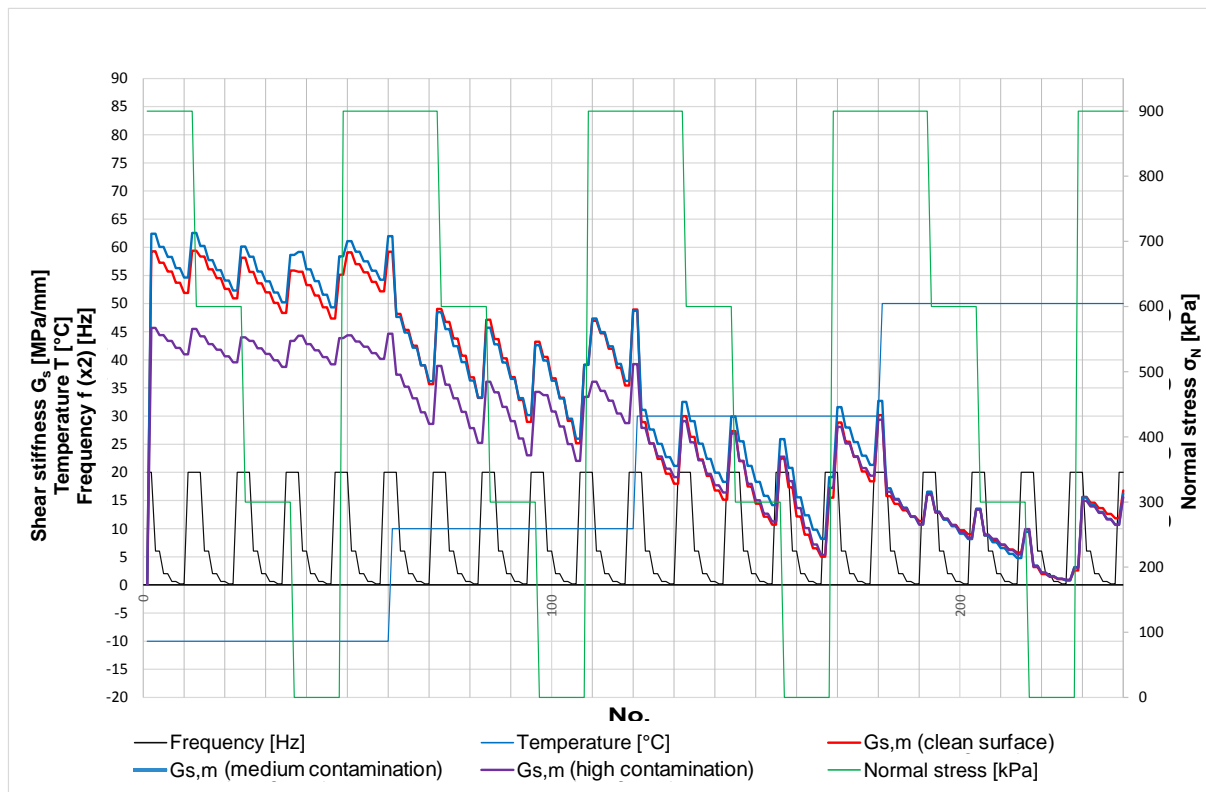
Figure 9. Gradients of the average shear stiffness for clean, medium and highly contaminated surface using 400 g/m^2 bitumen emulsion C60BP1-S

The span between clean and medium contamination is obviously not critical for producing a good interlayer bond, which can be seen in the calculated 3D plots in figure 10. The 300 g/m^2 bitumen emulsion rate is definitely the optimal one and can be recommended for application in situ.
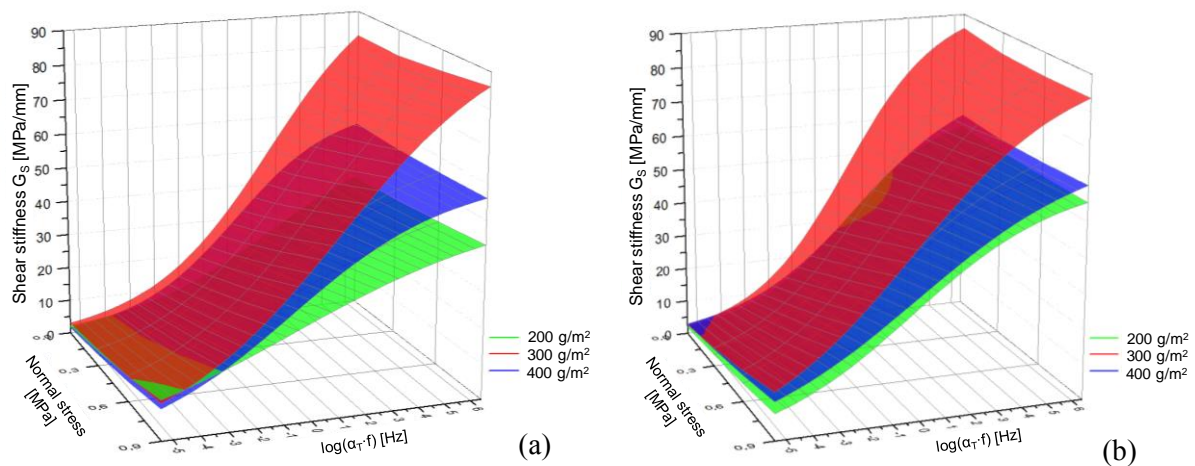

Figure 10. Comparison between the 3D plots of the calculated shear stiffness at the three bitumen emulsion rates for clean (a) and medium contaminated surface (b)

4.3. Interlayer bond produced on finely polished surfaces
It was observed that the shear stiffness gradients for 200 g/m^2 and 300 g/m^2 are superimposed at all temperatures (figure 11). The average values for all three tack coat amounts were almost the same.

Slightly better adhesion was found to exist for 400 g/m^2 at the highest normal pressure and at higher frequencies, more pronounced at -10°C and 10°C. The adhesion at 400 g/m^2 was weaker than the adhesion at the other two bitumen emulsion amounts when no normal stress was induced, which was evidence that the interlayer bond produced with the highest amount was more prone to the combined influence of all three parameters. At a temperature of 50°C all shear stiffness gradients were approximately the same and there was a complete loss of adhesion and friction at a shearing frequency of 0.1 Hz when no normal pressure was applied.
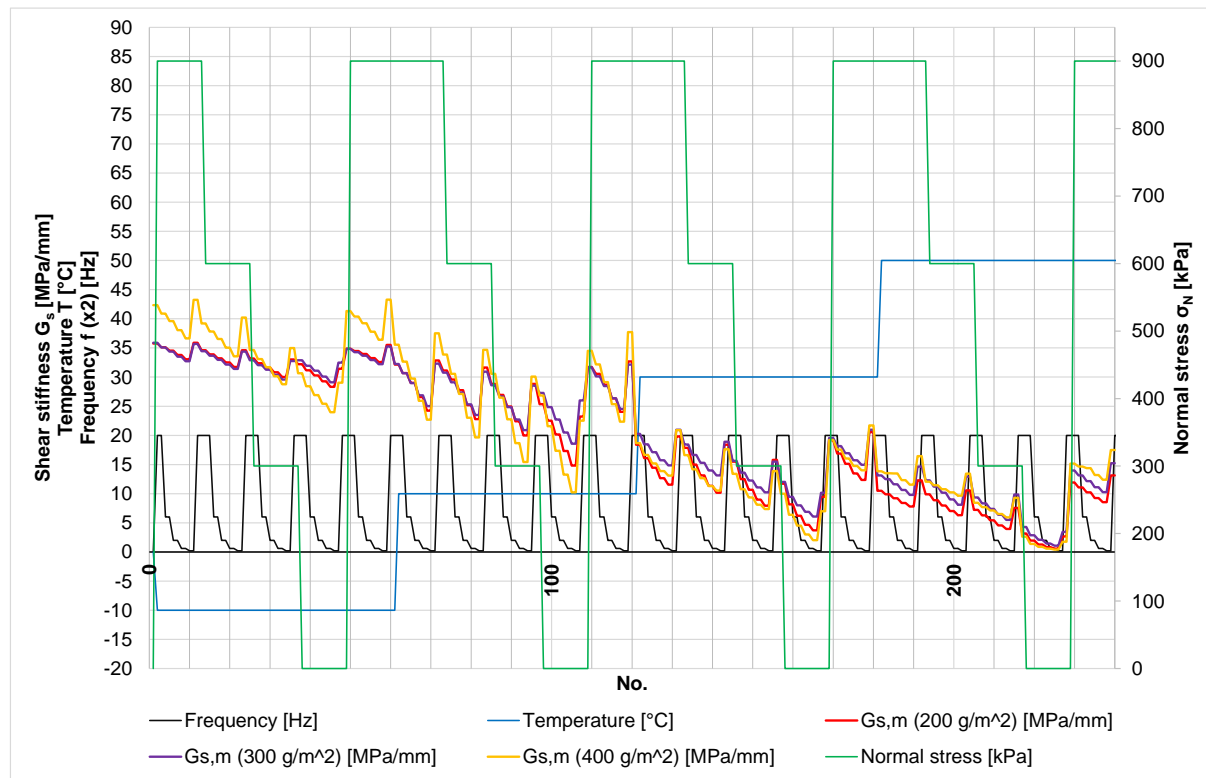

Figure 11. Gradients of the average shear stiffness for 200 g/m^2, 300 g/m^2 and 400 g/m^2 bitumen emulsion C60BP1-S between finely polished course surfaces

5. Conclusions

To determine the shear stiffness at the interface at different temperatures and normal stresses under sinusoidal repeated shear loading conditions at varying frequencies, a new test apparatus and extended automatic test procedure have been developed. The experimental results show that the shear stiffness of the interlayer bond decreases rapidly with increasing temperature. It has been observed that higher normal stresses and shearing frequencies have a positive effect on the interlayer bond shear stiffness increasing it significantly. Notwithstanding the tack coat amount, the impact of the normal stress on the shear stiffness was considerably smaller at lower temperatures compared with that at higher temperatures. The results from the tests of the bond produced normally on a clean surface with C40BP1-S bitumen emulsion show that at all temperatures the highest shear stiffness is achieved with 300 g/m^2 tack coat followed by the amount of 400 g/m^2. The lowest shear stiffness has been found to result from the use of 200 g/m^2 tack coat at all temperatures.

It has been determined, that the span between clean and medium contamination of the underlying layer is not critical for producing a good interlayer bond, but highly contaminated surfaces have a definite negative effect on the quality of the interlayer bond and must be avoided in situ.
In order to exclude the effects of aggregate interlocking and friction at the interface and to test solely the effect of the adhesion, asphalt specimens of finely polished layer surfaces have been used. It has

been observed that the shear stiffness gradients for 200 g/m^2 and 300 g/m^2 are equal at all temperatures. The interlayer bond produced with tack coat amount of 400 g/m^2 has been found to be most prone to the combined influence of temperature, shearing frequency and normal stress. Due to the additional effects of aggregate interlocking at -10°C and of the combination of both aggregate interlocking and friction at 10°C and 30°C for normally produced interlayer bond on a clean surface (figure 7) the shear stiffness values for all three tack coat amounts are generally higher than those shown in figure 11. At 50°C all shear stiffness values depreciate identically, indicating high deterioration of the interlayer bond.

Acknowledgments

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