ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ СОФИЯ

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EXPERIMENTAL DETERMINATION OF INTERLAYER BOND SHEAR STIFFNESS AT DIFFERENT CONDITIONS

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Keywords: *shear stiffness, temperature dependence, normal pressure dependence, frequency dependence, interlayer bond, cyclic test, master function, gradients, clean surfaces, finely polished course surfaces, three-dimensional representation*

ABSTRACT

A durable and well-performing interlayer bond is essential to ensuring the long-term service life of asphalt pavements. To evaluate the shear stiffness at the interface between asphalt layers, a new Cyclic Testing of Interlayer Bond apparatus (CTIB) has been used to test double-layer asphalt specimens. An extensive testing methodology was designed to investigate the combined effects of repeated traffic loading, acceleration, braking actions, and temperature, while considering all relevant factors that influence interlayer bonding. Experimental tests were conducted under sinusoidal cyclic shear loading at various frequencies, temperatures, and normal stress levels to investigate the combined effects of these conditions. The gradients of the average interlayer shear stiffness were calculated for a C60BP1-S bitumen emulsion applied at rates of 200 g/m², 300 g/m² and 400 g/m² on clean surfaces of both asphalt layers. A sigmoidal master function was used to determine the optimal amount of bitumen emulsion. A comparison of the shear stiffness of finely polished coarse surfaces at three bitumen emulsion rates was conducted. For the conventionally produced interlayer bond, shear stiffness values were significantly higher at all three tack coat application rates than at finely polished interfaces. Complete loss of adhesion and frictional resistance was observed for both conventionally prepared interfaces and polished surface specimens at +50 °C under the lowest loading frequency and in the absence of normal stress, indicating severe deterioration and inadequate interlayer bonding under these conditions.

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1. Introduction and Research Objectives

In Germany, asphalt pavements are generally designed as multilayer systems consisting of a surface course, a binder course, and a base course. The adhesion between adjacent asphalt layers is achieved through the application of a tack coat, typically composed of a bitumen emulsion. The mechanical performance of the entire pavement structure is determined not only by the material characteristics of the individual layers but also by the quality of the interlayer bonding. Inadequate bonding at the interfaces may significantly increase the likelihood of pavement failure, even when the constituent asphalt layers possess optimal material properties. Consequently, the long-term performance and durability of asphalt pavements are strongly dependent on the effectiveness of the bond between layers.

Despite extensive research efforts in this field, the combined effects of multiple influencing parameters on interlayer bonding behavior remain insufficiently understood. To address this knowledge gap, the authors are employing a newly developed testing apparatus together with a comprehensive experimental procedure to evaluate the shear stiffness of interlayer bonds.

The principal objective of this study is to investigate the effect of temperature, normal pressure and frequency on the quality of the interlayer bond. Accordingly, variations in interlayer shear stiffness under different surface conditions were examined, and both qualitative and quantitative analyses were conducted to assess the effects of temperature, normal stress, and shearing frequency on experimentally determined bonding behavior. In addition, this work seeks to develop a regression-based analytical approach for predicting shear stiffness as a function of these three governing parameters. The resulting model is intended for implementation in the SAFEM (Semi-Analytical Finite Element Method) program to enable detailed analysis of the influence of interlayer bonding on the structural performance of asphalt pavement systems.

2. Theoretical Background

The structural integrity of multilayer asphalt pavements is highly dependent on the effectiveness of bonding between adjacent layers. Interlayer bond is generated through several mechanisms, including the cohesive interaction between asphalt binders and tack coat material, mechanical interlock of aggregate particles across the interface, and frictional resistance between contacting surfaces. Achieving a durable bond, therefore, requires adequate surface preparation, particularly the thorough cleaning of the underlying layer prior to the application of bitumen emulsion and subsequent paving operations.

Asphalt pavements are continuously exposed to complex loading conditions arising from traffic and environmental influences. Vehicle wheel loads induce vertical compressive stresses, while braking and acceleration generate significant horizontal forces. These combined actions create a three-dimensional stress state within the pavement system. Where interlayer bonding is inadequate, relative movements between layers may occur, resulting in increased horizontal displacement and stress concentrations. Environmental factors, especially fluctuations in temperature and moisture infiltration, further intensify these stresses and may adversely affect pavement functionality.

The deterioration associated with insufficient interlayer bonding can manifest in multiple forms. Reduced structural capacity, accelerated fatigue damage, pothole development, layer separation, slippage cracking, permanent deformation, and delamination of the wearing course

are among the most common consequences. Such damage not only shortens pavement service life but also negatively affects ride quality and traffic safety.

From a mechanical perspective, an ideal interlayer condition corresponds to full bonding, where a continuous and rigid interface ensures monolithic behavior of the pavement system. Under these circumstances, traffic-induced loads are effectively distributed and no relative displacement develops between adjacent layers. Conversely, weak or absent bonding permits interfacial slippage and localized deformation, significantly compromising structural performance. Accordingly, reliable interlayer bonding is regarded as a prerequisite for durable pavements with satisfactory operational and safety characteristics.

In Germany, interlayer bond performance is presently evaluated using the static shear test according to Leutner, in which bond quality is assessed through the measured shearing-off force as specified in [1]. Comparable testing approaches have been established internationally, although they differ with respect to loading configurations and testing conditions [3, 4, 13]. Several researchers have enhanced conventional methods by incorporating the application of normal stresses during testing [5 – 9] and some added cyclic loads with or without interaction of normal loads [10, 11, 15 – 17]. Despite these developments, static procedures remain limited in their ability to reproduce realistic pavement loading scenarios characterized by repeated traffic actions. Consequently, their capability to accurately represent actual bond behavior under service conditions is restricted.

To overcome these limitations, numerous experimental devices have been developed to investigate interlayer performance under cyclic loading conditions, with or without simultaneous normal stress application. These systems differ substantially in loading principles, control modes, testing temperatures, and stress regimes. At TU Dresden, earlier investigations by Wellner and Ascher [12] employed a cyclic shear apparatus operating under static normal loading. Their experimental program covered temperatures from −10 °C to +50 °C, frequencies between 1 and 15 Hz, and normal stresses up to 1,1 MPa, with the objective of establishing a bonding indicator capable of distinguishing between adequate and inadequate interface conditions.

Building upon this foundation, the ongoing research project entitled “Cyclic Shear Stiffness and Shear Fatigue Test for Evaluation and Optimization of the Interlayer Bond in Asphalt Pavements” has led to the development of an advanced CTIB testing device at the Institute of Urban and Pavement Engineering at TU Dresden. The newly designed apparatus aims to reproduce field loading conditions with greater realism and precision than previously available systems. In conjunction with this development, an extensive testing protocol has been established to capture the combined effects of cyclic traffic loading, braking and acceleration processes, and environmental influences on interlayer behavior [14].

Within this framework, interlayer shear stiffness has been defined as the ratio of shear stress amplitude to the normalized shear displacement measured between the steel adapters holding the double-layer asphalt specimen. Experimental determination of this parameter was performed under systematically varied temperatures, shearing frequencies, and normal stress levels. To enable analytical prediction of shear stiffness for arbitrary combinations of these variables, a sigmoid-based regression model was formulated by [2] and validated against experimental observations. The developed model provides a basis for implementation within German pavement design procedures and offers the potential for integration into numerical analysis frameworks to evaluate the influence of interlayer bonding on pavement response and long-term service life.

3. Experimental methodology

3.1. Specimen Preparation Procedure

Two types of bitumen emulsion were employed to establish the interlayer bond: polymer-modified cationic C60BP1-S emulsions supplied by two different manufacturers and a solvent-containing cationic C40BF1-S emulsion. The experimental program investigated the influence of tack coat application rates of 200, 300, and 400 g/m² in combination with three interface surface textures, namely finely polished, standard roughness corresponding to a surface course placed on a base course, and a rough texture representing base course on base course contact.

Two-layer asphalt slabs measuring 320 mm × 260 mm were manufactured in a roller sector compactor using a compaction sequence consisting of position-controlled pre-compaction followed by force-controlled primary compaction. Initially, slabs representing the lower pavement layer were produced and conditioned at room temperature for 24 h. Prior to tack coat application, the slab surfaces were either cleaned using a brush or deliberately contaminated with predetermined amounts of silt.

The bitumen emulsion was subsequently applied in a uniform layer using a flexible foam roller at the specified application rates. Following application, the coated slabs were conditioned at room temperature for a minimum of two hours to ensure complete emulsion breaking. Thereafter, the hot asphalt mixture corresponding to the upper layer was placed and compacted. From each double-layer slab, four cylindrical specimens with a diameter of 100 mm were cored for subsequent testing.

For mechanical testing, each specimen was mounted within two steel adapters composed of four half-shell elements and bonded using a two-component epoxy adhesive (Fig. 1).

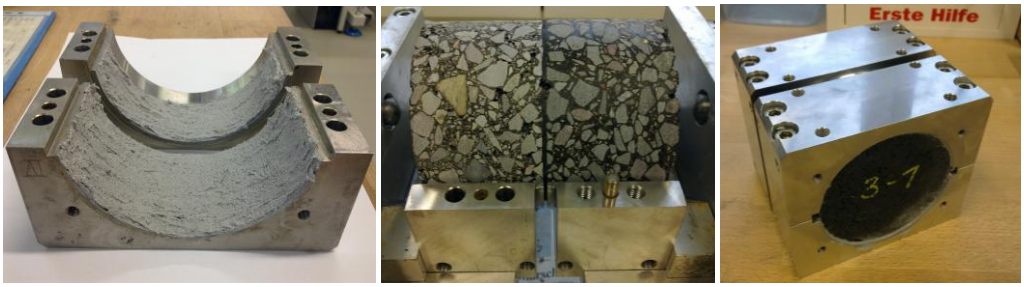


Figure 1. Specimen preparation for the test

3.2. Testing Device for Cyclic Assessment of Interlayer Bond Behaviour

The testing apparatus was designed to simultaneously apply cyclic shear loading and static normal loading to investigate the interlayer bond behavior under controlled laboratory conditions (Fig. 2). The system was installed within the temperature chamber of a servo-hydraulic testing machine to enable testing under predefined thermal conditions.

During testing, the specimen was mounted between two clamping jowls, designated A and B, with each half of the double-layer specimen secured within one jowl. A constant gap of 1,0 mm was maintained both between the jowls and between the steel adapters attached to the specimen. To prevent unintended specimen movement during loading, the steel adapters were rigidly fixed to the clamping system.

Cyclic shear loading with a sinusoidal waveform was applied in a position-controlled mode through the hydraulic actuator of the servo-hydraulic machine. This loading acted on the specimen half secured in jowl B, while the opposite half remained restrained in jowl A. Jowl A was supported by specially designed double-T stainless-steel bearings that restricted vertical displacement while permitting horizontal movement when induced by loading conditions.

The static normal load was introduced horizontally through a piston rod acting on the rear face of the specimen via a steel loading plate. Resistance to this normal force was provided at the front face by a second steel plate connected to a socket assembly rigidly attached to jowl B, thereby establishing a stable loading configuration.

The deformation response of the specimen was monitored using a dedicated sensor arrangement. Two displacement transducers mounted on jowl B recorded vertical shear displacements, while an additional pair of horizontally positioned sensors attached to jowl A measured horizontal movements generated during testing. The corresponding mechanical representation of the testing configuration is illustrated in Fig. 2.

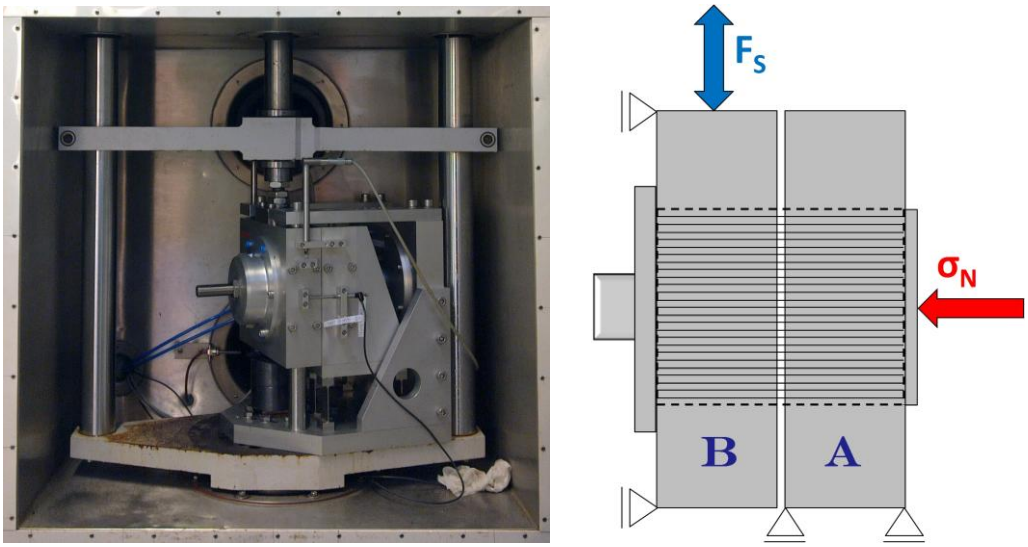


Figure 2. Test apparatus installed in the temperature chamber of a servo-hydraulic testing machine (left) and schematic representation of its mechanical configuration (right)

3.3. Loading Conditions and Testing Procedure

Dynamic testing was conducted through a comprehensive experimental program designed to account for the principal factors influencing interlayer bond behavior. Each testing sequence commenced under identical initial conditions, namely a temperature of −10 °C, a normal stress of 0,9 MPa, a loading frequency of 10 Hz, and a maximum shear displacement amplitude of 0,03 mm. The procedure concluded at a temperature of +50 °C while maintaining the same normal stress and loading frequency, with the maximum shear displacement increased to 0,15 mm.

The experimental workflow employed for determining interlayer shear stiffness is presented in Fig. 3. The complete testing program consisted of a series of temperature-controlled subtests conducted at four distinct temperature levels. Within each temperature stage, the

specimen was subjected sequentially to five different normal stress conditions. For every normal stress level, six loading frequencies were applied consecutively, each associated with a predefined number of load cycles.

The testing process was fully automated through the use of programmable control software capable of executing predefined loading sequences. This automation enabled the simultaneous and consecutive application of testing conditions without requiring manual intervention. To reduce conditioning time and improve experimental efficiency, a temperature overmodulation program was developed, allowing the target temperatures to be reached within the asphalt specimen more rapidly. As a result, two specimens could be tested within a single working day. The complete experimental procedure required approximately 11 h 43 min for each specimen.

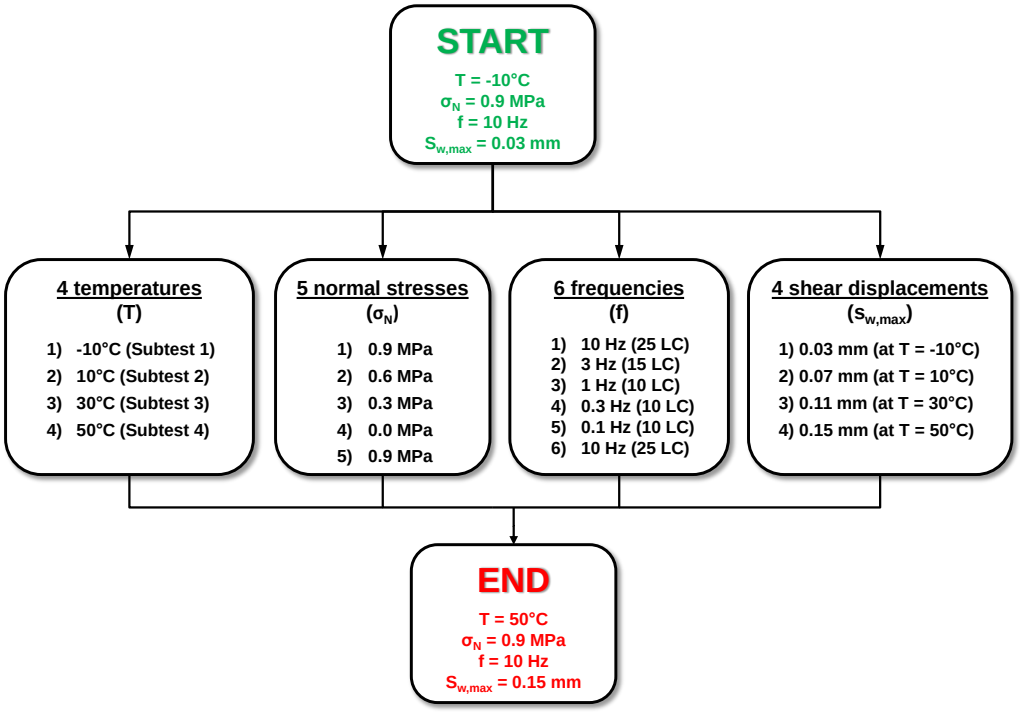


Figure 3. Overview of the experimental testing procedure

4. Results of Cyclic Interlayer Bond Testing

In this project, 400 double-layered specimens were tested under various surface conditions and with different amounts of bitumen emulsion. The variability in surface conditions, bitumen emulsion amounts, temperatures, normal stresses, and frequencies made it possible to develop a formula for analytically determining the shear stiffness of any interlayer bond. All measurements can be repeated in any laboratory that owns this testing machine, and the formula can be used for every interlayer bond between any asphalt layers.

All measured and computed parameters generated during the experimental program were stored in log files for subsequent analysis. To minimize the influence of transient effects

occurring at the initiation of each loading frequency, the determination of shear stiffness was based exclusively on data obtained from the final five loading cycles of each frequency stage. Because extended conditioning periods between individual subtests would distort a time-dependent representation, the variation of shear stiffness was not evaluated as a function of elapsed testing time. Instead, the results were presented using a sequential numbering system along the x-axis, representing only the individual subtest measurements. For the analytical characterization of shear stiffness $\boldsymbol{G_s}$, a universal master function was developed to account for the combined effects of temperature, normal stress, and loading frequency [2].

$$G_S = G_{s,\min} + \frac{\left(G_{s,\max} - G_{s,\min}\right)}{1 + e^{(m \cdot a + b)}}, \tag{1}$$

where m is the temperature-frequency equivalence, Hz;

$G_{s,\min}$ – minimal shear stiffness, MPa/mm;

$G_{s,\max}$ – maximal shear stiffness, MPa/mm.

The dependence of the regression parameters on normal stress was examined and incorporated into the analytical formulation. Parameter $\boldsymbol{a}$ was best characterized using a logarithmic function, whereas a linear relationship proved most suitable for parameter $\boldsymbol{b}$. Incorporation of these relationships into the master function for $\boldsymbol{G_s}$ allows generalized analytical determination of interlayer shear stiffness over a broad range of thermal and loading conditions.

Figure 4 presents a comparison of the average shear stiffness values obtained for C60BP1-S bitumen emulsion applied at tack coat rates of 200, 300 and 400 g/m² on clean interfaces. The investigated layer configuration consisted of a binder course placed on a base course, with three specimens tested for each tack coat application rate. In addition to the shear stiffness values, the corresponding temperature, normal stress, and loading-frequency gradients are illustrated. The experimental results demonstrate that temperature, normal stress, and shearing frequency exert distinct and interacting effects on interlayer shear stiffness. A pronounced decrease in shear stiffness was observed with increasing temperature, whereas increasing normal stress led to higher stiffness values, reflecting the loading conditions typically experienced under traffic. The influence of normal stress was comparatively limited at low temperatures but became substantially more pronounced at elevated temperatures, regardless of the tack coat quantity applied. Loading frequency also showed a considerable effect on interlayer behavior. Shear stiffness increased with increasing shearing frequency, although the magnitude of this increase was smallest at the lowest and highest temperature levels. Among the investigated tack coat rates, the application of 300 g/m² consistently produced the highest shear stiffness values across the entire temperature range, whereas 200 g/m² resulted in the lowest stiffness. The values measured for 400 g/m² were consistently intermediate between those obtained for the other two application rates. The comparatively low stiffness observed for the 200 g/m² application rate is attributed to the high surface roughness of the base course, which likely promoted penetration of the bitumen emulsion into surface voids and thereby limited effective adhesive bonding at the interface. The results therefore suggest that 300 g/m² represents an optimum tack coat quantity for this specific layer combination. Increasing the tack coat amount beyond this level did not improve bond performance; rather, excessive emulsion appears to act as a lubricating layer that diminishes aggregate interlock and reduces overall interface resistance.

Because rough interfaces inherently involve mechanical aggregate interlocking, distinction between adhesive and frictional contributions to interlayer resistance is essential.

Under conditions without applied normal stress, it was assumed that the measured response primarily reflected adhesive mechanisms associated with the asphalt binders and the tack coat. Since bituminous materials exhibit strong temperature sensitivity, the adhesive component was likewise temperature dependent. At low temperatures, strong adhesion dominated the interface response. Frictional effects were considered negligible because measured shear displacements remained below approximately 30 µm. At intermediate temperatures of +10 °C and +30 °C, the interlayer response resulted from the combined action of adhesion, aggregate interlocking, and friction. With increasing temperature, the adhesive contribution progressively weakened, leading to a continuous reduction in shear stiffness and indicating gradual deterioration of the interlayer bond. At +50 °C, adhesive bonding was no longer considered effective, and the interface resistance was governed primarily by aggregate interlocking and friction between the adjacent asphalt layers. Under these conditions, the shear stiffness gradients for all three tack coat rates became nearly identical across the investigated normal stresses and frequencies. Furthermore, at the lowest loading frequency and in the absence of normal stress, shear stiffness approached approximately 0 MPa/mm for all tack coat quantities, indicating a nearly complete loss of frictional resistance and consequently an inadequate interlayer bond. However, once normal stress and higher shearing frequencies were introduced, frictional mechanisms became active again, resulting in a measurable increase in shear stiffness.

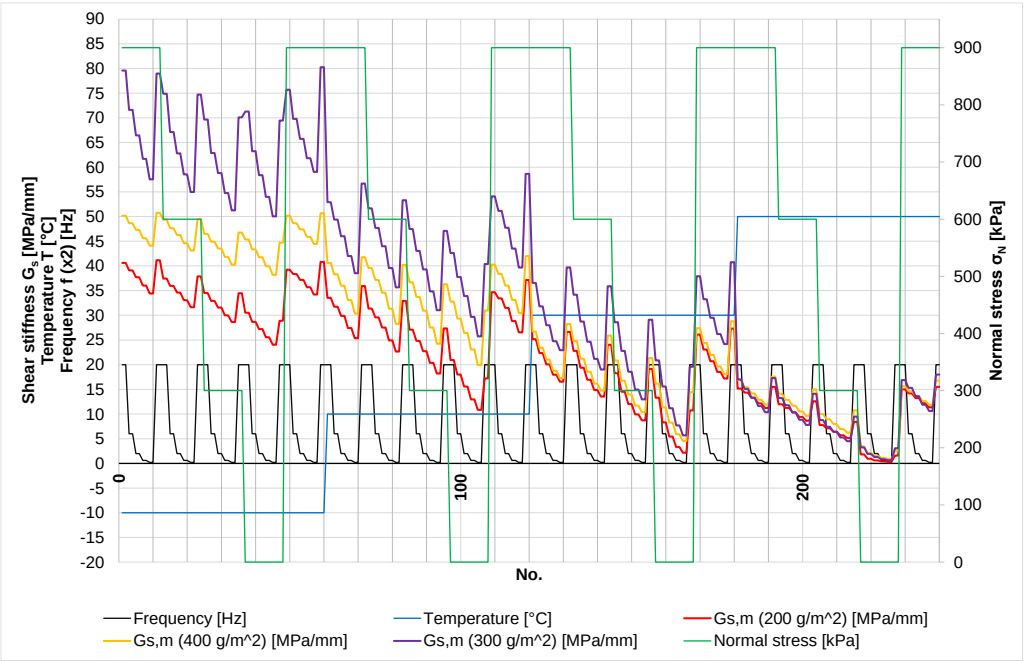


Figure 4. Gradients of the average interlayer shear stiffness for C60BP1-S bitumen emulsion applied at rates of 200 g/m^2, 300 g/m^2 and 400 g/m^2 on clean surfaces

To isolate the adhesive contribution to interlayer bonding and eliminate the effects of aggregate interlocking and friction, both asphalt layer surfaces were finely polished prior to tack coat application. Under these conditions, the measured interlayer response could be attributed predominantly to adhesion mechanisms. The results indicated that the shear stiffness gradients

obtained for tack coat application rates of 200 g/m² and 300 g/m² were nearly identical across the investigated temperature range (Fig. 5). In general, the average shear stiffness values for all three tack coat quantities exhibited only minor differences. However, the application rate of 400 g/m² produced slightly higher stiffness values at elevated normal stresses and loading frequencies, particularly at temperatures of −10 °C and +10 °C, suggesting a modest improvement in adhesive performance under these conditions. In contrast, when no normal stress was applied, the interface prepared with 400 g/m² exhibited lower adhesion compared with the other two tack coat quantities. This observation indicates that the interlayer bond formed with the highest emulsion dosage was more sensitive to the combined effects of temperature, loading frequency, and normal stress. At +50 °C, the stiffness gradients corresponding to all three tack coat rates converged to nearly identical values. Furthermore, under conditions of zero normal stress and a shearing frequency of 0,1 Hz, shear stiffness approached negligible levels, indicating a complete loss of both adhesive and frictional resistance at the interface.

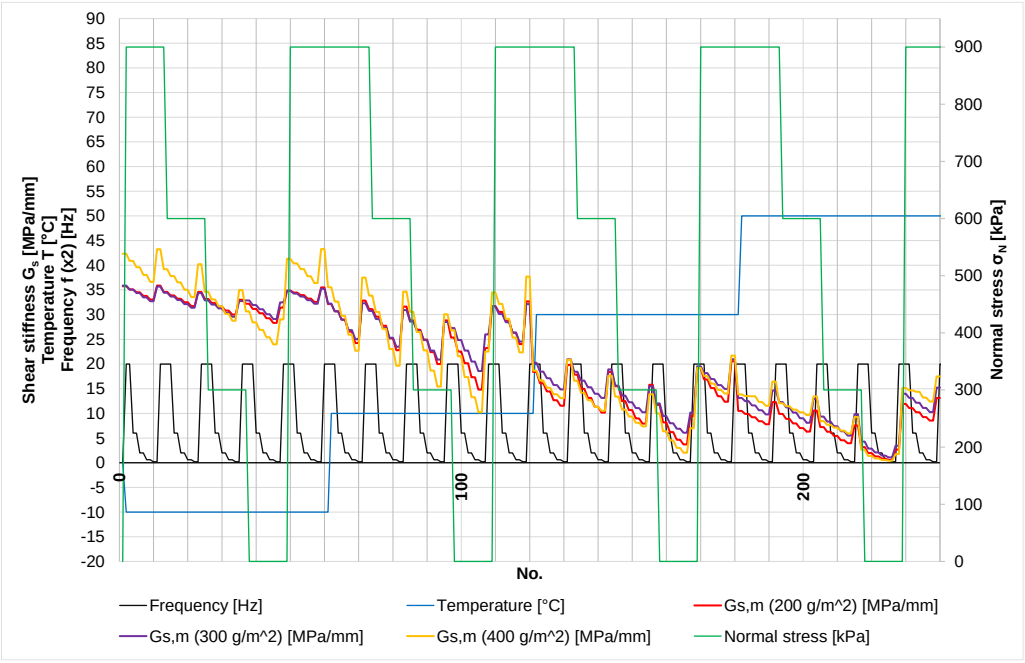


Figure 5. Comparison of average interlayer shear stiffness gradients for C60BP1-S bitumen emulsion applied at tack coat rates of 200 g/m², 300 g/m² and 400 g/m² between finely polished course surfaces

For the conventionally produced interlayer bond (Fig. 4), the additional contribution of aggregate interlocking at −10 °C and the combined effects of aggregate interlocking and friction at +10 °C and +30 °C resulted in generally much higher shear stiffness values at all three tack coat application rates compared with those observed for finely polished interfaces (Fig. 5). At +50 °C, however, the shear stiffness values for all interlayer configurations decreased to similarly low levels, indicating pronounced degradation of the interlayer bond and a substantial loss of interface resistance.

Figure 6 presents a three-dimensional representation of the dependence of shear stiffness, calculated according to Eq. (1), on normal stress, temperature, and shearing frequency. A comparison between the experimental measurements and the regression-based predictions revealed very good agreement.

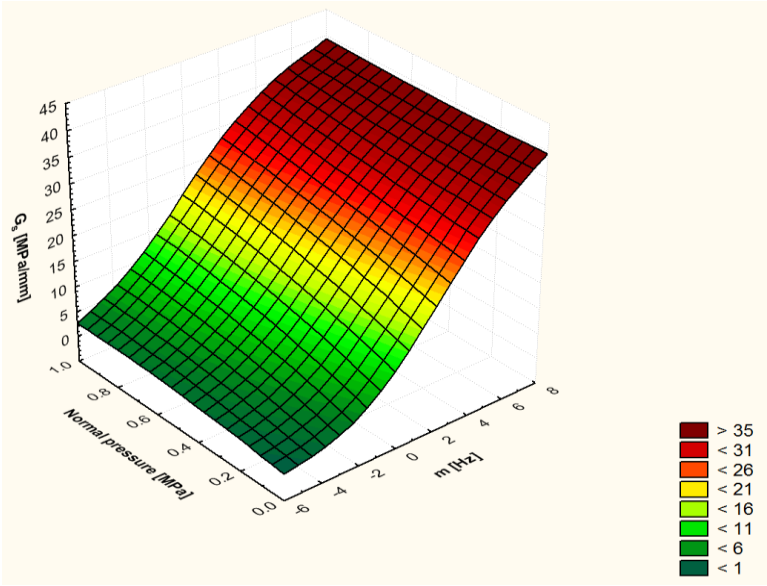


Figure 6. Three-dimensional representation of the dependence between shear stiffness calculated using Eq. (1), normal stress, temperature, and shearing frequency

5. Summary and Conclusions

A novel testing apparatus together with an extended experimental procedure was used to determine the interlayer shear stiffness under cyclic sinusoidal shear loading across varying temperatures, normal stresses, and loading frequencies. The experimental investigation demonstrated that temperature is a dominant factor governing interlayer behavior, with shear stiffness decreasing markedly as temperature increases. In contrast, elevated normal stresses and higher shearing frequencies were found to enhance interlayer stiffness significantly. The influence of normal stress, however, was considerably less pronounced at lower temperatures than at elevated temperatures, irrespective of tack coat application rate. A previously developed universal master function by the author [2] was employed to determine the shear stiffness G_s of the interlayer bond. The sigmoid regression model provided the most accurate representation of the experimentally measured data and successfully incorporated the coupled effects of temperature, normal stress, and shearing frequency. The strong agreement between calculated and experimentally determined stiffness values confirms the suitability of the developed model for analytical characterization of interlayer bond behavior.

For interfaces prepared with C60BP1-S bitumen emulsion, the highest shear stiffness values were consistently obtained with a tack coat application rate of 300 g/m², followed by 400 g/m², whereas 200 g/m² resulted in the lowest stiffness across all investigated temperatures. These findings indicate the existence of an optimum tack coat quantity of 300 g/m², beyond which additional emulsion does not necessarily improve bond performance.

To isolate the adhesive contribution to interlayer bonding, specimens with finely polished layer surfaces were tested to eliminate the effects of aggregate interlocking and friction. Under these conditions, the shear stiffness gradients corresponding to tack coat application rates of 200 g/m² and 300 g/m² were found to be nearly identical throughout the investigated temperature range. The interlayer bond produced with 400 g/m² tack coat exhibited the greatest sensitivity to the combined effects of temperature, loading frequency, and normal stress. For the conventionally produced interlayer bond, the shear stiffness values were significantly higher at all three tack coat application rates than those observed at finely polished interfaces.

For both conventionally prepared interfaces and polished surface specimens, a complete loss of adhesion and frictional resistance was observed at +50 °C under the lowest loading frequency and in the absence of normal stress, indicating severe deterioration and inadequate interlayer bonding under these conditions.

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ЕКСПЕРИМЕНТАЛНО ОПРЕДЕЛЯНЕ НА КОРАВИНАТА НА СРЯЗВАНЕ НА ВРЪЗКАТА МЕЖДУ АСФАЛТОВИТЕ ПЛАСТОВЕ ПРИ РАЗЛИЧНИ УСЛОВИЯ

Б. Христов[1]

Ключови думи: *коравина на срязване, температурна зависимост, зависимост от нормално налягане, честотна зависимост, междупластова връзка, циклично изпитване, основна функция, чисти повърхности, фино полирани повърхности, тримерно представяне*

РЕЗЮМЕ

Трайната и ефективна връзка между асфалтовите пластове е от съществено значение за осигуряване на дългосрочния експлоатационен живот на асфалтовите настилки. За оценка на срязващата твърдост на границата между асфалтовите пластове е използвана нова апаратура за циклично изпитване (CTIB) за изпитване на двупластови

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пробни тела. Разработена е методология за изпитване с цел проучване на комбинираното въздействие на повтарящото се натоварване от трафика, ускорението, спирачните действия и температурата, като са взети предвид всички значими фактори, влияещи върху междупластовата връзка. Експерименталните изследвания са проведени при синусоидално циклично натоварване на срязване при различни честоти, температури и нива на нормално напрежение, за да се изследват комбинираните ефекти на тези условия. Използвана е сигмоидна основна функция за изчисляване на графиките на коравината на срязване между пластовете за битумна емулсия C60BP1-S, нанесена в количества от 200 g/m^2, 300 g/m^2 и 400 g/m^2 върху чисти повърхности на двата асфалтови пласта, за да се определи оптималното количество битумна емулсия. Проведено е сравнение на коравината на срязване на фино полирани повърхности на свързаните пластове при трите количества битумна емулсия. За конвенционално произведената междупластова връзка (почистени, груби повърхности) стойностите на коравината са значително по-високи при трите количества битумна емулсия, отколкото при фино полираните повърхности. При температура от 50 °C, при най-ниската честота на срязване (0,1 Hz) и при отсъствие на нормално напрежение, се наблюдавана пълна загуба на адхезия и триене както при конвенционалните междупластовите връзки, така и при образците с полирана повърхност, което сочи за сериозно влошаване на състоянието и слаба спойка между пластовете при тези условия.