Interface Bonding Strength Between Asphalt Pavement Layers Under Mixed Shear-Tensile Mode: Laboratory Evaluation and Modelling Predictions

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Abstract: Highway traffic loads and environmental conditions, including temperature and moisture at the layer interface, could cause debonding or delamination between adjacent asphalt pavement layers in tensile, shear, or mixed mode failures. Thus, studying the tensile and shear strengths of interface bonding is crucial to maintaining durable and functional pavement structures. The main objective of this research is to evaluate and estimate the interface bonding strength (IBS) between asphalt pavement layers under the mixed shear-tension loading mode. To this end, an experimental, statistical, and machine learning (ML) approach was adopted. A total of 164 double-layered hot mix asphalt specimens consisting of hot mix asphalt AC-13 in the upper layer and AC-20 in the lower layer were tested via a direct tensile device with a supplementary shear fixture. The effects of test temperature, shear stress, and tack coat application rate on the IBS were considered. The results revealed that with increasing tack coat dosage, the IBS peaked at 0.8 kg/m^2 and was subsequently decreased. It was also found that the IBS was very sensitive to temperature changes and heavily dependent on shear stress at elevated temperatures. On the other hand, with increasing shear stress from 0 to 0.20 MPa, the IBS at temperatures of 5, 20, and 35°C declined by 10.96%, 61.85%, and 83.16%, respectively. Two prediction models for the IBS based on the conventional statistical models of multiple linear regression (MLR) and nonlinear regression were successfully developed. However, the nonlinear model outperformed with a better prediction accuracy of 24.2% than the linear regression (R^2=71.8%). Finally, a highly accurate feed-forward backpropagation (FFBP)- artificial neural network (ANN) model was developed to predict and form a relationship between the IBS and independent variables with an extremely low margin of error. It was revealed that the developed FFBP-ANN model could capture 99% of the measured data. Finally, a comparative analysis demonstrated that the developed FFBP-ANN model was superior to regression modeling in terms of predicting the IBS.

Keywords: asphalt pavement; interlayer bonding strength; direct tension test; shear load; evaluation; prediction; linear regression; nonlinear regression; ANN.

1. Introduction

Nowadays, flexible pavements are the most widely constructed pavement type worldwide due to their acceptable serviceability and low construction costs. However, with the rapid growth of highway traffic, vehicles' axle loads coupled with environmental conditions, including temperature and moisture, can lead to different potential distresses in the pavement structure and, therefore, shorten its service life and increase the maintenance costs (Kubo et al. 2015; Woo and Yeo 2016). Asphalt pavement is a multi-layered structure typically comprised of a wearing course, a base layer, and a subbase layer that lays on the subgrade and is designed to perform as a single unit and endure traffic and environmental loads. Consequently, the bonding between adjacent pavement lifts is crucial in allowing the asphalt pavement to act as a monolithic system. In other words, sufficient bonding between pavement layers (i.e., no stress/strain discontinuity at the layer interface) is critical for achieving a durable and functional pavement structure. In contrast, insufficient or missing bonding between successive pavement layers may result in various forms of damage, such as slippage cracking, top-down cracking, premature fatigue cracking, and delamination, thereby activating distress mechanisms that end in total failure of the pavement structure (Alae et al. 2020; Buttlar et al. 2018; Cho et al. 2019; Hossain et al. 2019; Jaskula and Rys 2017; Le et al. 2020; Nguyen et al. 2016; Romanoschi and Metcalf 2001; Tschegg et al. 1995; Wu et al. 2017; Xu et al. 2021), (see Figure 1(a)).

In real field conditions, bond failure at the layer interface could be categorized into four groups: pure shear (Mode I), pure tension (Mode II), shear-compression (mode III), and shear-tension (modes I+II) (Petit et al. 2018; Sutanto 2010) as is shown in Figure 1b. Modes I and III could occur in the transverse or longitudinal directions and are generated mainly by shear stresses induced by temperature and/or traffic loading at interfaces without joints. Mode II could occur at pavement interfaces consisting of a joint. Tensile failure can happen due to the tensile stress as a result of suction of the tire, or blistering. A mixed shear-tension mode (mode I+II) could occur at the interface below the thin surfacing layer, where the interface shear strength is relatively weak, resulting in a limited capability to transfer horizontal loads. Thus, the horizontal loads are concentrated in the surfacing layer and may cause buckling of the thin surfacing layer at the front of the tire. The buckling could generate vertical tensile stress while shear stress at the layer interface is induced by horizontal loading (Figure 1.c). Therefore, evaluation and prediction of the interface bonding strength are of great significance in designing and maintaining pavement structures. In this regard, many testing methods have been developed in the lab and the field to assess the bonding condition at the layer interface. Rahman et al. (Rahman et al. 2017) mentioned that testing methods for evaluating bond strength could be divided into eleven test methods. Interface shear testing is a widely used method because of its straightforward operation. Researchers (Ai et al. 2017; Diakhaté et al. 2011; Raab et al. 2009; Song et al. 2015; Sutanto 2010; Wang et al. 2018; West et al. 2005) have adopted this method (i.e., modes I and III) for evaluating interface bonding and corresponding influential factors.

Fig.1. (a) Scheme of a pavement system subjected to traffic and environmental loadings; (b) Failure modes at layer interface; and (c) Shear-tensile separation associated with buckling.

As previously mentioned, due to traffic or environmental factors, tensile failure may occur at the layer interface. The direct tension (pull-off) test is a standard test method for evaluating IBS under tensile force. Test set ups such as Louisiana Tack Coat Quality Tester (LTCQT) (Mohammad et al. 2009), field tack coat evaluator (A tacker) (Buchanan and Woods 2004), interface bond test (IBT) (Hakimzadeh et al. 2012a), UTEP pull-off device (UPOD) (Eedula 2006) or wedge splitting test (WST) (Tschegg et al. 1995) allow performing the tension tests (i.e., mode II). Furthermore, the relationship between interface shear strength and tensile (pull-off) adhesion was discussed based on the outcomes of the pull-off and shear tests (Hakimzadeh et al. 2012b).

The findings of previous studies revealed that selecting the suitable type and optimum content of tack coat material and ensuring that the interface surface is rough and clean are primary conditions for achieving sufficient interlayer bonding, which results in a durable pavement system during its service life. Moreover, several numerical analyses were conducted to characterize and analyze the pavement interlayer behavior. (Chun et al. 2015; Mattos et al. 2017; Romanoschi and Metcalf 2001). For instance, under different loading scenarios acting on the pavement surface during vehicle maneuvering and temperature conditions, Rahman et al. (Rahman et al. 2021) developed a 3-dimensional (3D) pavement model using the ABAQUS software. They demonstrated that the interface debonding or failure could be caused by the combined effect of loading and environmental circumstances. Similarly, Cho et al.(Cho et al. 2019) employed the FlexPAVE™ simulation software to study the impact of the debonding phenomenon on the fatigue cracking performance in asphalt pavements. They discovered that debonded surface layers in asphalt can reduce the fatigue performance life of the pavement structure by about 90%. Furthermore, based on the finite element analysis, a 2D simulation of the indirect tensile test of asphalt pavement interlayers was carried out, and the associated calculation formula was derived by Zhang et al. (Zhang et al. 2021).

On the other hand, other researchers (Ai et al. 2017; Das et al. 2018) employed statistical techniques to develop models (mathematical models) for predicting interface bonding between pavement layers. In addition, artificial neural networks (ANNs) have recently been utilized to develop relationships and recognize behavioral patterns of pavement interface since not only could they save time and cost but assist practitioners and researchers in dedicating resources for other necessary operations (Nian et al. 2022; Raab et al. 2009). For instance, Raab et al. (Raab et al. 2015) applied three artificial neural networks to analyze and predict changes in interlayer bonding properties over time. Taking everything into consideration, one can conclude that most previous studies evaluated the interlayer bonding of asphalt pavement exclusively under shear mode (mode I) or tension mode (mode II). Therefore, further research is necessary to acquire a deeper understanding of the interlayer bonding behavior under mixed shear-tension loading mode (modes I and II). This study aims to efficiently address the issue by adopting an experimental, statistical, and machine learning (ML) approach to interface bonding strength between asphalt pavement layers. The major objectives of this study are as follows:

- To evaluate the changes in the interface bonding strength (IBS) affected by testing temperature, tack coat application rate, and horizontal shear stress under mixed tensile-shear loading mode (modes I+II) through laboratory experiments.
- To develop new prediction models using different statistical analysis techniques to estimate the relationship between the IBS and different factors.
- To construct a novel FFBP-ANN for accurately predicting and analyzing the IBS from input-determined parameters.
- To conduct a comparative analysis of the accuracy of developed models.

The outcomes of this study are expected to provide some new insights into the evaluation and prediction of the mechanical response of the layer interface. This study employed linear and nonlinear regression techniques to build accurate predictive models using the statistical package for the social sciences (SPSS) software. At the same time, the ANN model was developed using MATLAB software. Figure 2 illustrates an overview of the methodology introduced in this study.

Fig. 2. An overview of the proposed approach in this study

2. Experimental program

2.1. Materials

Interlayer bonding assessment was conducted through direct tensile testing with a supplementary fixture that can apply a horizontal shear load. The tests were carried out with a total number of 164 double-layered asphalt specimens manufactured from two different dense-graded hot mix asphalts, in which AC-13 and AC-20 were chosen for the top and bottom layers. Table 1 illustrates the aggregate gradation design of the two mixtures as per the Chinese standard of JTGF40-2004.

Table 1. Aggregate gradation of mixtures (%).

For preparing asphalt mixtures, basalt was used for both coarse and fine aggregates, which were clean, dry, free of weathered particles, and pure. Limestone mineral powder was utilized as the filler material. Properties of mineral materials met Chinese Technical Specifications for the Construction of Highway Asphalt Pavements (JTG F40-2004). The properties of coarse and fine aggregates are shown in Tables 2 and 3. Styrene-butadiene-styrene (SBS) modified asphalt was used as the binder in two asphalt mixtures with the properties presented in Table 4. The optimal asphalt content of the mixtures was 4.9% by weight of the total mixture. The tack coat material was cationic emulsified asphalt with 38% bitumen, which was applied at different application rates. The properties of tack coat material are summarized in Table 5.

Table 2. Properties of coarse aggregate.

Table 3. Properties of fine aggregate.

Table 4. Properties of the SBS modified asphalt.

Table 5. Properties of tack coat material.

2.2.Specimen preparation

Under the Marshall compactor, the specimens were manufactured using cylindrical molds with an inner diameter of 101.6mm and a height of 76.2mm. The blows were applied only to each layer's top surface until the bulk density reached 98% to 100% of Marshall density. The process began by compacting the bottom half of the AC-20 mixture using 125 blows to reach a height of 32mm. After allowing the mixture to cool down to room temperature for 24 hours, tack coat material was spread uniformly using a paintbrush on the cleaned surface at the specified rate. The coated surface was then left to cure at room temperature. Next, the top half of the AC-13 loose mixture was poured into the mold and compacted with 100 blows to a height of 32mm. Before conducting the experiment, the prepared specimens were allowed to cool at room temperature for 24 hours.

It is noteworthy that cores drilled from the roller compactor or field may provide a more accurate representation of the in-situ compaction. However, due to existing limitations in the laboratory's facilities, the Marshall compactor was utilized for manufacturing the specimens in this study.

2.3.Direct tension test (pull-off) with a shear load

In this study, a customized pull-off test device supplemented with a shear fixture was developed, as shown in Figure 3.

Fig. 3. Schematic diagram of interlayer bond testing configuration.

The set up applies a tensile force (*P*) and a horizontal shear force (*F*) at the interface between double-layered cylindrical specimens. As can be seen, the interface is in the middle of both layers. The testing procedure is as follows:

(1) A double-layered asphalt specimen was prepared and conditioned in the climatic chamber at the target temperature. Then, the epoxy resin was applied to firmly attach the prepared specimen vertically with the top plate and bottom support of the pull-off test device.
(2) According to the test needs, the appropriate horizontal shear load (*F*) was set and applied to the side of the specimen via a sequence of components: the jack, the load cell, the circular plate, the spring, and the circular shutter. A load reader records the applied load while a hydraulic jack regulates it.
(3) The vertical tensile loading (*P*) was applied with a displacement rate of 10mm/min by the actuator of the universal testing machine (UTM) (CJJ 139-2010, JTG E20-2019)(Code of China 2010; Code of China. 2019) to carry out the pull-off test and measure the interlayer bond strength of the specimen (Figure 4).

Fig. 4. Procedure of interlayer bonding strength: (a) specimen preparation, (b) installation of the set up, (c) shear load application, and (d) failed specimen at the interface.

2.4.Experimental parameters and test plan

It is well known that factors such as temperature, tack coat material and application rate, tack coat curing time, and surface condition and preparation, among other factors, affect interface bonding performance. In general, the tack coat material is applied as a bonding agent to create sufficient adhesion between successive layers of the pavement. The bond's strength depends on the type and dosage of tack coat material being applied. Temperature can also greatly affect the viscosity and adhesion properties of the tack coat. The influence of temperature on interface bond strength would be greatest when the adhesion component plays a key role in the measured bond strength. Shear loading can cause pavement adjacent layers to slip or shear against each other as a result of poor bonding, affecting its performance. Owing to their significant influence on the IBS, factors of tack coat application rate, temperature, and shear loading were considered in this research to evaluate the IBS under mixed shear-tensile loading mode (modes I+II). Tack coat rate affects the bonding effectiveness between layers. Insufficient tack coat content at the layer interface leads to debonding between layers, whereas excessive tack coat leads to slippage cracking. In this study, first, residual tack coat application rates ranging from 0.40 to 1.60 kg/m^2 were selected to evaluate the effects of tack coat dosage on the measured IBS. The tests were conducted at a single temperature of 20°C and four shear stress levels of null confinement (0 MPa), 0.10MPa, 0.15MPa, and 0.20MPa. Subsequently, the optimal value of the tack coat rate was identified. In the next step, different temperature levels of 5°C, 20°C, 35°C, and 50°C were selected, and tests were carried out under the determined optimal tack coat rate and similar shear stress levels applied in the previous step to evaluate the effect of temperature on the IBS. Finally, under the testing temperatures of 5°C, 20°C, and 35°C, different shear stress levels of 0MPa, 0.05MPa, 0.1MPa, 0.15MPa, and 0.20MPa were applied to simulate the shear loading generated by the vehicle when driving on the road surface. Consequently, the influence of shear stress on the pull-off strength between asphalt pavement layers was investigated.

Under the BZZ-100 standard axle load, the tire-pavement contact pressure is 0.70 MPa. The existing literature results indicate that the common emulsified asphalt bonding layer at room temperature has an interlayer shear strength of about 0.50 MPa (Cheng Meng et al. 2011). In order to ensure that the applied shear load would not directly damage the interlayer bonding, the selected range of shear stress was less than 50% of the interlayer shear strength, ranging from 0 to 0.2 MPa. The experimental parameters and their levels are summarized in Figure 5. Parameters and their ranges were carefully chosen to simulate field circumstances.

Fig. 5. Experimental parameters and their levels of the test plan

3. Results and discussion

3.1. Effect of tack coat application rate

Figure 6 depicts the changing trend of the IBS against tack coat application rate at 20 °C under different shear stress levels. It can be seen that under the combined influence of shear and tension loads, the interlayer bonding strength first increased as the amount of tack coat increased, reaching its highest point at a rate of 0.80 kg/m^2 before declining with further increases in tack coat content. Thus, an application rate of 0.80 kg/m^2 was determined to be the optimum content for the tack coat. Moreover, when the tack coat rate was 0.8 kg/m^2 and the shear stress increased from 0 to 0.2 MPa, the resulting bonding strength decreased by 38% of the original strength. In addition, corresponding slopes (k1 to k4) of the curves decreased with increasing shear stress, indicating that the bond strength improvement resulted from tack coat application suppresses with shear stress application. In other words, after applying shear stress, the interlayer is subjected to the superposition of shear and tensile loads, which weakens the overall performance of interlayer bonding and gradually reduces the contribution of adhesion to the IBS. That clarifies why tack coat dosage becomes less significant.

Fig. 6. Effect of tack coat rate on the IBS under the mixed shear-tension load mode

3.2.Effect of temperature

Figure 7 illustrates the temperature effect on the IBS under different shear stress levels. It is evident that the temperature significantly affected the degree of bonding strength under mixed shear-tension loading mode. As the temperature increased, there was a notable reduction in the IBS of asphalt pavement. For instance, when the temperature raised from 5 to 20°C, the interface bonding strength associated with shear stresses of 0, 0.1, 0.15, and 0.2 MPa reduced by 55.5%, 72.1%, 76.6%, and 80.9%, respectively, with an average of 73.3%. With further temperature increase from 5 to 35°C, the resulting interface bonding strength corresponded to shear stress of 0, 0.1, 0.15, and 0.2 MPa declined by 83.1%, 87.1%, 93.3%, and 96.8%, respectively, with an average of 90.1%. Finally, under conditions where the temperature reached the peak from 5 to 50 °C, the resulting interface bonding strength under shear stress levels of 0, 0.1, 0.15, and 0.2 MPa fell substantially by 96.3%, 100%, 100%, and 100%, respectively, having an average reduction of 99.1%. These results demonstrate that a considerable strength reduction is expected for larger shear stresses practically at elevated temperatures. It can be concluded that at low temperatures (i.e., within the range of 5 to 20°C), interface bonding strength dropped moderately, at normal temperatures (i.e., within the range of 20 to 35°C), it declined significantly, and at high temperatures (i.e., within the range of 35°C to 50°C), it fell dramatically, indicating that decreasing trend of interlayer bond strength under different temperature ranges is dissimilar.

Fig.7. Effect of test temperature on the IBS under the mixed shear-tension load mode

3.3.Effect of shear loading

The results of the shear stress effect on the IBS under different temperatures are displayed in Figure 8. It can be observed that the IBS at different temperatures declined with the increase of the shear stress, denoting that horizontal shear stress reduces interlayer bonding performance.

Increasing shear stress from 0 to 0.20MPa at temperatures of 5, 20, and 35°C resulted in an average reduction of interlayer bonding strength by 10.96%, 61.85%, and 83.16%, respectively. It leads one to conclude that the consequence of the shear stress application for the interlayer bonding strength was the smallest at low temperatures. In other words, the analysis indicates that at low temperature (5°C), the tack coat material has a higher viscosity, resulting in better adhesion. In this regard, the applied shear stress can hardly cause damage to interface bonding, so the application of shear stress at low temperatures cannot significantly affect the tensile strength of the interlayer. However, at normal temperature (20°C), the tack coat material is in a viscoelastic state, and its viscosity and strength are lower than at a low temperature. Therefore, the increase of shear stress leads to interlayer damage, thus affecting the bond strength and reducing the overall performance of the interlayer bonding.

Fig.8. Effect of shear stress on the IBS under mixed shear-tension loading mode.

To further analyze the influence of shear stress on the IBS, bonding strength under no confinement (F = 0 MPa) at each temperature was taken as a reference point. Afterward, the ratio of the IBS under various shear stresses to nil confinement was computed, as presented in Table 6. It can be observed that the decrease rate in bonding strength is different under varying temperature conditions. Take, for instance, the case of 0.20 MPa shear stress. The decreased ratio of bonding strength at 5 °C, 20°C, and 35°C was 1.12, 2.62, and 5.90, respectively, denoting that as temperature increases, the expected impact of shear stress on the IBS becomes greater. Based on these results, one can deduce that the viscosity and adhesion properties of emulsified asphalt materials weaken with increasing temperature. Shear stress reduces interlayer friction resistance, and temperature negatively affects bonding strength. Therefore, under mixed shear-tension loading mode, the reduction of interlayer bonding strength is significant. That is also why the interlayer debonding failure is more likely to occur in summer and in road sections where the vehicles accelerate, decelerate, brake, or turn, generating excessive shear stresses at the layer interface.

Table 6. Interface bonding strength ratios under different horizontal loads

3.4.Statistical analysis

3.4.1. Descriptive statistical and ANOVA analysis

A descriptive statistical analysis was performed to summarize and/or describe the statistical characteristics of the main parameters considered in this study. That is an important initial step in the data modeling process, which measures indicators of central tendency (such as the mean) and dispersion (such as standard deviation). Table 7 provides the descriptive statistical analysis of input and output parameters.

Table 7. Descriptive statistical analysis

Moreover, based on the above findings, tack coat application rate (TAR), test temperature (T), and horizontal load (HF) exert an influence on the IBS under mixed shear-tensile loading mode. However, the level of significance of each factor is uncertain. For this reason, the statistical analysis of variance (ANOVA) was performed to determine each factor's significance level on the IBS statistically. The analysis was carried out using data obtained from the testing program. ANOVA is a set of statistical processes that measure how independent (single) variables and their combinations affect particular responses, such as IBS. In this study, a P-value of 0.05, corresponding to a confidence level of 95%, was considered. Table 8 presents the results of the ANOVA for the IBS.

The results indicate that the P-values of all factors are less than the significance level of 0.05, indicating that all factors have a significant effect on the IBS statistically. In order of importance, the resulting F-values, which exhibit the significant level of each factor on the IBS, rank as test temperature, horizontal load (shear stress), and tack coat rate. Moreover, the interactions between tack coat and horizontal load, tack coat and test temperature, and horizontal load and test temperature on the IBS were statistically significant. Overall, the most significant factor affecting the IBS for a given tack coat was the temperature, followed by shear stress. While tack coat application rate was not the most influential parameter under mixed shear-tension loading mode, its optimal application rate contributes to the IBS to some extent, as previously mentioned.

Table 8. ANOVA results for the single and interaction factor's effect on IBS of pavement.

3.4.2. Multiple linear regression (MLR)

For the purpose of predicting and analyzing the potential change in the IBS of the pavement, the MLR was performed using SPSS software (IBM, 2009). MLR is a statistical technique that describes the relationships between several independent variables (categorical and numerical) and a single dependent variable. However, MLR implementation may cause overfitting and multicollinearity. Overfitting happens when too many independent variables are included in the model, which can cause insignificant contributions to the model. Multicollinearity occurs when some or all independent variables are associated. Thus, it is crucial to consider these factors, along with other important test diagnostics and assumptions.

The general form of the MLR model is illustrated in Equation (1).

$$Y = \beta_o + \sum \beta_i X_i \quad (1)$$

where Y is the dependent variable; X_i is the independent variable; β_o is the intercept; and β_i is the regression coefficient.

Each coefficient in multiple regression represents the dependent variable's expected change for a one–unit change in an independent variable while keeping all other interdependent variables constant. Thus, the measured IBS represents the dependent variable, whereas T, HF, and TAR were designated as independent variables.

Several MLR models were developed for the IBS of asphalt pavement in this work. However, a model with the minimum mean square error (MSE) and highest coefficient of determination (R^2) was selected as the best one. The MSE can be calculated as shown in Equation (2).

$$MSE = \frac{1}{n}\sum_{i=1}^{n} \left(y_{(act)i} - y_{(\text{pred})i}\right)^2 \quad (2)$$

where $y_{(act)}$ is the actual value; $y_{(\text{pred})}$ is the predicted value; and n is the total amount of data samples.

As mentioned above, certain test assumptions and diagnostics should be carefully considered to carry out the linear regression analysis appropriately. These assumptions for regression include linearity, normality of error distribution, homoscedasticity, and independence. Test diagnostics, such as checking multicollinearity and influential points, are also required to enhance the model's robustness.

Following analysis conduction, results were produced and summarized after checking and verifying all assumptions of regression and test diagnoses. Table 9 summarizes the ANOVA, normality test, coefficients, and multicollinearity diagnostics of the developed linear regression model. This study employed a stepwise MLR approach to formulate desired prediction models that included or excluded predictors based on strict criteria at a 95% confidence level. It is evident that the model is acceptable and statistically significant, as demonstrated by the high *F*-value (135.51) and very low (below 0.05) *P*-value. Furthermore, according to normality test results, Kolmogorov-Smirnov and Shapiro-Wilk tests indicated that errors are normally distributed (values always greater than 0.05). Although the Kolmogorov-Smirnov test is more suitable for a larger dataset, it was also appropriate for the dataset in this study. In addition, the statistical analysis of the regression standardized residuals was presented in two forms: a frequency histogram and a normalized P-P plot. The frequency histogram illustrates the distribution of the residuals, while the normalized P-P plot provides a visualization of the probability distribution of the residues. Figures 9a and 9b display a normality-based histogram and normal P-P plot. Hence, the results confirm the null hypothesis that the residues are normally distributed.

The model's coefficients and their relative significance are shown in Table 9 as well. All three predictors (T, HF, and TAR) were statistically significant, as demonstrated by significance values of less than 0.05. Moreover, this analysis used indicators such as tolerance, variation inflation factor (VIF), and condition index to measure collinearity. To ensure that the predictors are not inter-correlated, the VIF, the condition index, and the tolerance should be less than 10, 30, and larger than 0.1, respectively (Kim 2019), which is the case for the developed IBS model. Figure 10 shows the good fitness of the developed model. Along the line of best fit, the estimated values of IBS are plotted against the observed values.

Table 9. Model summary, test of normality, ANOVA, coefficients, and multicollinearity diagnostics of the proposed MLR model.

Fig. 9. Regression standardized residuals: (a) Frequency histogram; (b) Normalized P-P plot

Fig. 10. Measured vs. expected IBS values (in MPa) using the developed linear model.

3.4.3. Nonlinear regression

A nonlinear regression analysis was conducted further to enhance the predictive capability of the developed linear model. Developing a suitable nonlinear regression between a dependent and independent variable requires identifying the individual nonlinear relationships and conducting overall nonlinear modeling. Individual nonlinear relationships could be found by scouring through mathematical space with software tools like Curve Fitter, which was utilized in this study to find the most suitable formula. The resulting formula is then entered into the SPSS nonlinear regression tab for iteratively determining the best-fitting parameters. Table 10 summarizes the nonlinear model for predicting IBS values of the asphalt pavement.

The developed nonlinear model is represented graphically in Figure 11. It is important to point out that the predictive capabilities of the model significantly improved by 24.2% through nonlinear regression compared to the linear regression model. The significant increase in prediction accuracy indicates that the relationship between the IBS with temperature, shear loading, and tack coat is nonlinear. For this reason, a nonlinear model for predicting the IBS is preferred to a linear one.

Table 10. Results of the developed nonlinear regression model.

Fig. 11. Measured vs. predicted IBS values (in MPa) using nonlinear regression modeling.

3.5. Artificial neural networks (ANNs)

Supervised machine learning techniques such as ANNs are highly flexible and well suited for handling nonlinear relationships. Moreover, when correctly implemented, ANNs can be relatively robust regarding overfitting, noise, and outliers in the data, which can be problematic for conventional nonlinear models. In this context, a multilayer feed-forward backpropagation (FFBP-ANN) algorithm was utilized in this study to improve or enhance the nonlinear model. Within the framework of this algorithm, inputs are multiplied by the weight values of the connections linking the inputs to the hidden neurons. The sum of the results is processed through an activation function that produces a value that serves as input for the next layer. The output of any given layer would become the input of the next layer; this process is called feedforward. The error is determined by comparing the desired outcome (the target) to the output of the network. To enhance the precision of predictions in the subsequent cycles, the network weights are tuned through backpropagation, which involves propagating the error backwards through the network to minimize it. This procedure will continue until the error is optimized. Each iteration is called an epoch. A training Levenberg–Marquardt backpropagation algorithm was employed in this study. Accordingly, the entire input network training model was randomly arranged in this study to predict the IBS. Specifically, 70% of the data was utilized for training the network, 15% for network validation, and the remaining 15% for network testing, all of which were divided randomly (Gholamy et al. 2018). The training set was used for learning, i.e., fitting the weights and biases for the desired output, validation data was used to tune the network parameters, and the testing dataset was used to provide an independent measure of the network performance. Moreover, to evaluate the performance of the ANN model, a 10-fold cross-validation technique was employed. This procedure reduces the chance of overfitting and bias and avoids data leakage.

The FFBP-ANN model for the IBS is shown in Figure 12. The design of the chosen FFBP-ANN model includes three layers, an input layer with three neurons for the three parameters, a hidden layer with ten neurons between the input and output layers, and an output layer representing the IBS. This figure shows a representation of the final FFBP-ANN model, which has been designed through an extensive process of experimentation that involved adjusting the number of hidden neurons, the activation function associated with each layer, and the bias connections among the layers. The activation functions used here were the tangent sigmoid and purelin in hidden and output layers, respectively.

Figure 13 illustrates the performance of the proposed FFBP-ANN for predicting the IBS. It is evident that extremely few errors occurred during the network system's performance, and the best validation performance was achieved at epoch 35, reaching a value of 0.00019542 MPa. Nonetheless, the average MSE on the test set that resulted from performing a 10-fold validation was 0.00011667 MPa.

Furthermore, Figure 14 displays the regression of the designed FFBP-ANN model (the relationship between the network outputs and the targets). This figure demonstrates that the developed FFBP-ANN model corresponds well with the experimental results. It was also verified through a high correlation between FFBP-ANN input and target variables during training, validation, and testing, as indicated by the high R^2 and low MSE values in Table 11. These results suggest that the developed FFBP-ANN model is well-trained, can explain over 99% of the experimental data, and is accurate enough to predict the IBS of asphalt pavement.

Fig. 12. The proposed feed-forward backpropagation FFBP-ANN model for interlayer bonding strength (IBS)

Fig. 13. FFBP-ANN Performance (MSE vs. the number of epochs)

Fig.14. Regression scheme of actual versus predicted values by FFBP-ANN model for training data, validation data, testing data, and all data

Table 11. Performance of interlayer bonding strength of asphalt pavement FFBP-ANN model.

3.6.Comparative analysis

The performance of three studied models, namely multiple linear regression, nonlinear regression, and feed-forward back-propagation (FFBP-ANN), was compared to identify the best predictive model for accurately predicting the IBS of asphalt pavement. The comparison between data obtained from the laboratory experiment and output data from three proposed models is illustrated in Figures 15a, 15b, and 15c. The X-axis represents the number of samples, while the Y- axis represents the IBS of asphalt pavement. The findings indicate that the output values from the developed models are highly close to the experimental data and follow a similar procedure, particularly nonlinear and ANN models. It demonstrates that the models learned and predicted the empirical data with an acceptable degree of accuracy. However, as can be seen, the FFBP-ANN model had the best performance, followed by the nonlinear and linear models, respectively. Another indicator of the effectiveness of the models was associated with the R-squared value, in which the FFBP-ANN model exhibited the best correlation (R^2=0.99), followed by the nonlinear model (R^2=0.96) and linear model (R^2=0.72). Consequently, the FFBP-ANN model is more precise in forecasting the IBS of asphalt pavement owing to the ANN technique's ability to uniformly and accurately represent the training data.

Fig.15. Performance and validation of (a) MLR model, (b) Nonlinear model, and (a) ANN model

4. Conclusions

This study analyzed the interlayer bonding strength (IBS) of pavement under mixed tension-shear loading mode (modes I+II) using a direct tension (pull-off) test with a supplementary shear fixture. The effects of temperature, shear stress, and tack coat application rate on the IBS were investigated. Furthermore, this study is a pioneer work that developed prediction models of the

IBS using conventional statistical models and feed-forward backpropagation ANN techniques under mixed-mode loading conditions. The following conclusions can be drawn:

- When subjected to mixed shear-tension load (modes I+II), the IBS initially increased as the tack coat application rate increased, followed by a decline as the content of the tack coat was further increased. The optimal application rate of the tack coat was found to be 0.8 kg/m^2.
- Simultaneous increase of the shear stress and the tack coat content slightly affected the IBS. However, increasing the shear stress from 0 to 0.2 MPa at the optimal tack coat application rate decreased bonding strength by 38% of the original strength.
- The IBS of asphalt pavement was greatly affected by temperature, leading to its noticeable decrease as the temperature rose. The reduction degree in bonding strength was dissimilar in different temperature ranges. In this regard, the increase of the shear stress from 0 to 0.20 MPa led to an average decline of 10.96%, 61.85%, and 83.16% in interlayer bonding strength at 5, 20, and 35°C, respectively.
- An ANOVA analysis showed the relative significance of each parameter for the IBS. The test temperature had the greatest impact, followed by shear stress and tack coat application rate.
- The developed MLR model was significant at the 0.05 significance level, indicating that testing temperature, shear stress, and tack coat application rate significantly affected the IBS. In addition, the MLR model could explain more than 71% of the measured data of the IBS. Nonlinear regression improved the modeling power by 24.2% compared to linear regression, explaining about 96% of the measured data of the IBS.

- The feed-forward backpropagation ANN model achieved excellent prediction results with an accuracy of 99.0%, 99.8%, and 98.6% for training, validation, and testing data. The model achieved the best validation performance in epoch 35 with an MSE of 0.000195 MPa, and the average MSE on the testing set that came from performing a 10-fold validation was 0.00011667 MPa, indicating high accuracy in predicting the IBS. Moreover, the FFBP-ANN technique exhibited a practical advantage that allows the IBS of asphalt pavement to be estimated in the shortest time with high accuracy without conducting a large number of laboratory experiments, which could save time and cost. That makes the application of the ANN technically justifiable.

The findings of this research can provide experimental support and a basis for more scientific evaluation and accurate prediction of interfacial bonding conditions in the design and construction of asphalt pavement. Nevertheless, further laboratory testing should be carried out to verify these findings. This research utilized only one type of tack coat and a single tensile loading rate. It is recommended that for future studies effects of different types of tack coat and loading rates, along with other factors, such as interlayer surface characteristics and loading conditions, on the interface behavior under mixed shear-tension loading mode, are taken into consideration.

Data Availability Statement

The data supporting the models in this paper, as well as other findings of this study, are available from the corresponding author upon reasonable request.

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Figure Captions

Fig. 1. (a) Scheme of a pavement system subjected to traffic and environmental loadings; (b) Failure modes at layer interface; and (c) Shear-tensile separation associated with buckling.

Fig. 2. An overview of the proposed approach in this study.

Fig. 3. Schematic diagram of interlayer bond testing configuration.

Fig. 4. Procedure of interlayer bonding strength: (a) specimen preparation, (b) installation of the set up, (c) shear load application, and (d) failed specimen at the interface.

Fig. 5. Experimental parameters and their levels of the test plan.

Fig. 6. Effect of tack coat rate on the IBS under the mixed shear-tension load mode.

Fig.7. Effect of test temperature on the IBS under the mixed shear-tension load mode.

Fig. 8. Effect of shear stress on the IBS under mixed shear-tension loading mode.

Fig. 9. Regression standardized residuals: (a) Frequency histogram; (b) Normalized P-P plot.

Fig. 10. Measured vs. expected IBS values (in MPa) using the developed linear model.

Fig. 11. Measured vs. predicted IBS values (in MPa) using nonlinear regression modeling.

Fig. 12. The proposed feed-forward backpropagation FFBP-ANN model for interlayer bonding strength (IBS).

Fig. 13. FFBP-ANN Performance (MSE vs. the number of epochs).

Fig. 14. Regression scheme of actual versus predicted values by FFBP-ANN model for training data, validation data, testing data, and all data.

Fig. 15. Performance and validation of (a) MLR model, (b) Nonlinear model, and (a) ANN model.

Table 1. Aggregate gradation of mixtures (%).

Mixture	Sieve size (mm)											
Type	26.5	19	16	13.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
	Passing percentage (%)											
AC-13	-	-	100	95	76.5	53	37	26.5	19	13.5	10	6
AC-20	100	95	85	71	61	41	30	22.5	16	11	8.5	5

Table 2. Properties of coarse aggregate.

Property	Unit	Particle size /mm			Test method
		9.5–16	4.75–9.5	2.36–4.75	
Crushing value	%	9.3	9.3	9.3	T0316
Los Angeles abrasion value	%	4.1	4.1	4.1	T0317
Apparent density	$g.cm^{-3}$	2.890	2.877	2.87	T0304
Soundness value	%	1.91	1.52	3.14	T0314
Elongated particle	%	5.58	7.07	-	T0312
Water absorption	%	1.467	1.858	-	T0304
Soft particle contents	%	1.80	1.13	-	T0320

Table 3. Properties of fine aggregate.

Property	Unit	Test results	Test method
Apparent density	$g.cm^{-3}$	2.926	T0328
Soundness value	%	2.28	T0340
Silt contents	%	0.62	T0333
Sand equivalent	%	90.61	T0334
Angularity	s	38.9	T0345

Table 4. Properties of the SBS modified asphalt.

Property		Unit	Test results	Test method
Penetration (100 g, 5 s, 25℃)		0.1mm	53.2	T0604
Ductility at 5℃		cm	38	T0605
Softening point (R & B)		°C	65	T0606
Flashpoint		°C	270	T0611
Solubility		%	99.5	T0607
Flexible recovery at 25°C		%	96	T0662
After RTFOT	Mass loss	%	0.8	T0610
	Penetration ratio	%	82.9	
	Ductility at 5°C	cm	32.5	

Table 5. Properties of tack coat material.

Property		Unit	Test result	Code values	Test method
Sieve residue, 1.18 mm		%	0.03	≤0.1	T0652
Particle charge		-	(+)	Cation (+)	T0653
Normal viscosity		s	13	8-20	T0621
Storage stability at 25°C	1d	%	0.6	＜1	T0655
	5d	%	3.8	＜5	T0655
Evaporation residue content not less than		%	38	＜50	T0651

Table 6. Interface bonding strength ratios under different horizontal loads

Temperature (°C)	Horizontal load (MPa)				
	0	0.05	0.1	0.15	0.2
5	1	1.04	1.07	1.09	1.12
20	1	1.67	1.71	2.07	2.62
35	1	1.23	1.41	2.76	5.90

Table 7. Descriptive statistical analysis

Parameter	Use	No. of data	Description	Unit	Mean	Standard deviation
T	Input	164	Testing temperatures (Numerical variable)	℃	19.512	9.881
HF	Input	164	Horizontal Force (Numerical variable)	MPa	0.086	0.070
TAR	Input	164	Tack coat application rate (Numerical variable)	kg/m^2	0.910	0.335
IBS	Output	164	Interlayer Bonding Strength (Numerical variable)	MPa	0.273	0.222

Table 8. ANOVA results for the single and interaction factor's effect on IBS of pavement.

Dependent variable: IBS					
Factor	Sum of squares	Degrees of freedom	Mean square	*F*-value	*P*-value
TAR	0.04	6	0.007	42.655	0.000
HF	0.104	4	0.026	168.490	0.000
T	2.485	9	0.276	1782.135	0.000
TAR*HF	0.021	17	0.001	7.994	0.000
TAR*T	0.003	4	0.001	4.186	0.003
HF*T	0.46	7	0.007	42.166	0.000
Error	0.018	113	0.000		
Total	20.259	164			

Table 9. Model summary, test of normality, ANOVA, coefficients, and multicollinearity diagnostics of the proposed MLR model.

Model summary and normality test

Model summary				Test of normality	
Dep. variable	R^2	Standard error of the estimate	Durbin-Watson	Kolmogorov-Smirnov significance	Shapiro-Wilk significance
IBS	0.7180	0.11914	1.094	0.200	0.094

ANOVA results

Model		Sum of squares	Degrees of freedom	Mean square	*F*-value	*P*-value
IBS	Regression	5.771	3	1.924	135.51	0.000
	Residual	2.271	160	0.014		
	Total	8.042	163			

Coefficients and multicollinearity diagnostics.

Dep. variable	Indep. variables	Coefficients				Collinearity statistics		
		Unstand. coefficient	Standard error	t- statistics	*P*-value	Tolerance	VIF	Condition index
IBS	Constant	0.795	0.035	22.643	0.000			1.000
	T	-0.019	0.001	-19.575	0.000	0.984	1.017	3.054
	HF	-0.715	0.135	-5.311	0.000	0.979	1.021	4.699
	TAR	-0.106	0.028	-3.799	0.000	0.995	1.005	8.448

$$\boldsymbol{Y = 0.795 - 0.01970\,T - 0.715HF - 0.106TAR}$$

Table 10. Results of the developed nonlinear regression model.

Model	$Y = [a + bT + cT^2 + dT^3 + eT^4] + [f * exp^{g*HF}] + [\mathrm{h} * exp\left(-\frac{(TRA - i)^2}{2j^2}\right)]$										
Coefficient											R^2
	a	b	c	d	e	f	g	h	i	j	0.9601
Value	0.737	-0.047	3.6E-5	20.329	-5.14E-7	0.132	-9.002	0.125	0.908	-2.084	

Table 11. Performance of interlayer bonding strength of asphalt pavement FFBP-ANN model.

FFBP-ANN model	Training		Validation		Testing	
	MSE	R^2	MSE	R^2	MSE	R^2
3-10-1	0.001011	0.9903	0.000195	0.9979	0.001470	0.9860