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Evaluation of shear bond for double-layer asphalt based on shear test

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Abstract: Asphalt concrete pavement often appears damaged such as rutting, fatigue crack, potholes, etc. at high air temperature, heavy rain in long time, or at locations with high traffic, large horizontal force, and poor-quality construction sites. This causes a deterioration in the service quality, leading to a lot of maintenance costs. These failures are often related to bond between layers of asphalt concrete. Therefore, this paper shows the evaluation results of shear bond of double-layer asphalt (with tack coat rate of 0, 0.2, 0.5, 0.8 l/m^2) based on shear test at the experimental temperatures (25, 40, 60^{o}C), normal pressure (0, 0.14, 0.2, 0.4, 0.6 MPa). The results show that, when the temperature increases from 25^{o}C to 60^{o}C, the shear bond between the asphalt layers decreases sharply. At 25^{o}C, the average shear bond that tested with normal pressure of 0.6 MPa increases by 52.19% compared to that tested at pressure of 0 MPa. When the temperature reaches 60^{o}C, the average shear bond that tested with normal pressure 0.6 MPa increases by 94.87% compared to that tested at 0 MPa pressure. At 25°C, non-tack coat samples have lowest shear bond. However, at 40^{o}C and 60^{o}C, the shear bond of 0.8 l/m^2 tack coat-based samples reach the lowest value. At the same time, a regression equation between shear bond and input variables proposed by Minitab V17 software provides high reliability results.

Keywords: Shear bond, double-layer, asphalt, shear test, tack coat.

1. Introduction

Currently, the flexible pavement structure is designed in multiple layers by different materials. Good bond between different layers of asphalt concrete (AC) for the purpose of ensuring the unity features of the pavement structure [1]. The design and construction standards of asphalt concrete pavements in Vietnam do not pay much attention to the degree of bond between AC layers. Some structural design assumptions still assume that the layers are completely bonded [2]. Moreover, the construction process of AC layers only specifies about the bond between two layers that is evaluated by qualitative observation of the field coring [3]. It can be seen that there has not been quantified in terms of experimental method. Thus, the bond quality related to the shear resistance of the flexible pavement structure is completely evaluated qualitatively. Studies to provide a quantitative method as well as the required shear bond strength value of double-layer AC sample have been carried out in the US and some European countries from the 90s to the present [4-7].

Obviously, the factors affecting the shear bond properties between AC layers play an important role, determining the bond strength for AC pavement in general [8]. Some factors affecting the shear bond between asphalt concrete layers have been studied including factors of tack coat material (type, ratio, and curing time) [6,7,9], surface properties of the interface [5,7,10,11], characteristics of the concrete sample and mixture [5,12], and in-process parameters [13-16]. Some factors that greatly affects the shear bond of double-layer AC sample are the tack coat application rate, the test normal pressure and temperature. According to Mohammad et al. [7], Canestrari et al. [6], Romanoschi and Metcalf [5], too little tack coat will not ensure the bonding, however too much tack coat will lead to slippage between layers. Shear bond usually reaches its highest value when tack coat rate is optimal. The studied tack coat rates are usually in range of 0-1.0 l/m^2. According to Canestrari et al. [4], West et al. [11], Hachiya et al. [9], temperature is the most influential factor on shear bond because the properties of bituminous material depend much on temperature. When the temperature increases from 15-60°C, the shear bond of the tack coat-based interface will decrease sharply. In addition, Chen and Huang [13], Uzan [16], Canestrari [4], West [11], evaluated the shear bond by shear test under some normal pressure levels (0 - 0.6 MPa). The results show that growth of normal pressure increases the shear bond of the interface layer. At high temperatures, the shear bond is strongly dependent on the normal pressure. In Vietnam, some authors have also studied a number of factors affecting the shear bond resistance between AC layers such as type and rate tack coat, temperature [17-20]. The experiments were carried out on modified Leutner device (shear device without normal pressure) [18], inclined shear device [19]. However, there is no study to evaluate the regression relationship between shear bond and influencing factors such as normal load, temperature, and tack coat rate.

This paper presents an evaluation of shear bond strength of double-layer asphalt samples fabricated by shear test device with normal pressure. The parameters of temperature (25, 40, 60°C), normal pressure (0, 0.14, 0.2, 0.4, 0.6 MPa) and tack coat rate (0, 0.2, 0.5, 0.8 l/m^2) were considered as input variables. Also, a regression equation between shear bond and three factors initially was proposed.

2. Shear test

2.1. Sampling

Table 1. Mixing ratio

Type	AC19	AC12.5
Crushed stone 25	7	-
Crushed stone 19	20	15
Crushed stone 12.5	32	31
Crushed stone 4.75	36	49
Filler	5	5
Bitumen	4.6	4.9

AC12.5 and AC19 are asphalt concrete mixtures with nominal maximum particle sizes of 12.5 and 19 mm, respectively.

Table 2. Technical parameters of mixture

Parameters	AC 19	AC 12.5	Requirement [3]
Marshall stability, kN	11.22	14.67	Min 8
Marshall flow, mm	2.71	2.92	1.5-4
Air Voids, %	5.57	4.82	4-6
Voids in Mineral Aggregate, %	13.95	13.47	Min 12
Void Filled of Asphalt, %	68.56	71.26	65-75

The experiment was conducted on a double-layer dense AC sample with diameter of 10 cm and height of 12 cm. The upper layer of AC12.5 is 5 cm thick, and the lower layer of AC19 is 7 cm thick. The dense-graded AC mixtures were designed in accordance with TCVN 13567-1:2022 [3]. Crushed stone of D25, D19, D12.5, and D4.75 was obtained from Dong Ao quarry, Thanh Thuy, Thanh Liem district, Ha Nam province. Filler is stone powder taken from Phu Ly, Ha Nam. The above aggregate components were checked and guaranteed according to the technical requirements of TCVN 13567-1:2022 [3]. Bitumen grade 60/70 supplied by Petrolimex Asphalt Co., Ltd. ensures the requirements of TCVN 7493:2005 [21] and TCVN 13567-1: 2022 [3]. CRS-1 emulsion was used as a tack coat material between two layers to ensure the requirements according to TCVN 8817: 2011 [22].

The process of manufacturing and testing the AC samples was strictly adhered to the standards of TCVN 13567-1: 2022 [3] and AASHTO T245 [23]. The mixing ratio and obtained basic technical results were shown in Table 1 and 2.

2.2. Testing

The mixture is mixed and compacted at the specified temperature according to TCVN 13567-1: 2022 [3]. After compacting the lower layer, CRS-1 emulsion with different ratios (0, 0.2, 0.5, 0.8 l/m^2) was applied on it surface. Depending on the applied rate of CRS-1 emulsion, the temperature and humidity of the laboratory, the curing time of the tack coat often ranged from 4 to 6 hours. Samples before testing were capped by gypsum (Figure 1a) and curing in a water tank at the test temperature for at least 2 hours.

The shear test was performed in accordance with the AASHTO TP 114-15 [24] (Figure 1b). The concentrated shear force was provided with a constant speed of 2.54 mm/min and chosen normal pressure until the specimen failed. The value of shear bond is calculated according to the following formula:

$$\tau_{max} = \frac{P_u}{(\frac{\pi . D^2}{4})}$$

where:

τ_{max} : Shear bond, MPa;

P_u : Maximum force acting on the sample, N;

D: Sample diameter, mm;

Figure 1. (a) Samples, (b) Shear test

3. Results and discussion

The experiment results are shown in Figures 2; Figure 3; Figure 4. It shows that the shear bond between the concrete layers decreases sharply as temperature rises. The shear bond is in the range of 0.23-0.70 MPa, 0.1-0.54 MPa and 0.02-0.47 MPa in 25, 40 and 60°C respectively. Moreover, with the temperature growth, the displacement results are also more dispersed. The displacement is in range from 1.3-2.3 mm, 1.4 to 3.4 mm, and 1.7 to 3.9 mm in 25, 40 and 60°C respectively.

The shear bond of asphalt samples value decreased significantly (about 87.3%) as the experimental temperature increased from 25°C to 60°C at all the tack coat rate. In contrast, the shear bond value increased significantly as the normal test pressure rises from 0 to 0.6 MPa (about 0.35 MPa). Furthermore, when the normal pressure increased by 76.67% (from 0.14 to 0.6 MPa), the mean shear bond increased by 54.74%. On the other hand, at high temperature the effect of normal pressure on shear bond is much more obvious and significant than at low temperature. At 25ºC, the average shear bond tested with normal pressure of 0.6 MPa increased by 52.19% compared to that tested at pressure of 0 MPa. When the temperature reached 60ºC, the average shear bond tested with normal pressure 0.6 MPa increased by 94.87% compared to that tested at 0 MPa pressure.

Moreover, the result show that the applied tack coat rate of 0.2 l/m^2 gives the highest value of shear bond at all experimental temperature. At 25°C, non-tack coat samples have the lowest shear bond. However, at 40ºC and 60ºC, the shear bond of samples applied 0.8 l/m^2 tack coat reached the lowest value. The tendency of the shear bond decrease with the rising of tack coat rate can be explained by the bond behavior model of Goodman's model [16,25,26]. It states that interlayer shear stress is proportional to the strain and shear modulus at interface. In this case, a high rate of tack coat leads to an increase in the thickness of the bond film, which leads to a decrease in the ability to hook aggregate particles together. Hence, the shear bond is reduced.

Regression analysis

The results of checking the conditions for applying the statistical method are shown in Figure 5. The Normal Probability Plot compares the probability distributions of residuals (shown as points) with a normal distribution (shown as solid lines). The graph shows that the residuals are distributed very close to the normal distribution. Histogram shows how often residuals occur. The graph of Versus Fit, evaluation of the covariance, shows the relationship between the residuals and the corresponding values of the regression model. The randomly distributed points have no rules, proving that the shear bond data is not affected by any other regular control factors. The Versus Order graph, randomness assessment, shows the relationship between the residual and the order of the data points. The points are not randomly distributed, do not follow any rules, showing that the shear bond data is not affected by time factors (for example, the larger the later). The more randomly the Versus Fit and Versus Order distribute around the 0.0 line and without any rules, the better data is.

Multivariate regression, a statistical technique, is used to determine the relationship between input variables (factors) and the outcome (objective function). Due to the small number of experimental variables (3 variables), to evaluate the influence of the factors, the full two-level experimental plan (2^k) was chosen. Set of experiments with k variables, each variable receiving two levels of values (high and low value).

The experiments were carried out based on changing the conditions of tack coat rate, temperature and normal pressure. Since then, the study uses a regression model at the three-factor interaction level including one constant coefficient b_o, three coefficients corresponding to b_{xx} with three experimental variables (main influence coefficients), three coefficients b_{xxx} of two-level interaction effects, and a coefficients of three-level interaction effects. Therefore, the general regression equation has the following form:

$$Y = b_o + b_1.X_1 + b_2.X_2 + b_3.X_3 + b_{12}.X_1.X_2 + b_{13}.X_1.X_3 + b_{23}.X_2.X_3 + b_{123}.X_1.X_2.X_3$$

where:

b_o, b_x, b_{xx}, b_{xxx} are coefficients listed by MINITAB.

Y is the value of shear bond (MPa).

X_1, X_2, X_3 are the variables summarized in Table 3.

Table 3. Parameters of regression model

Variables	Lowest value	Highest value
Tack coat rate (X_1)	0	0.8
Normal pressure (X_2)	0	0.6
Temperature (X_3)	25	60

The result of regression model parameters is showed in Table 4. Column T represents the t-distribution value of the quantity under consideration. Column P shows the probability p value when checking the statistical hypothesis about the possibility that the coefficients are zero. P value greater than the significance level α indicates that the existence of the corresponding coefficient is not statistically significant. In other words, when p > α, it can be trusted to (1- α)% to get that coefficient equal to 0. The effect of the corresponding component is negligible on the objective function.

The model results also show that the regression model evaluation parameters including R-Sq and R-Sq(adj) are greater than 90%, proving that the found regression model matches the analyzed data. On the other words, the suggested regression model has high reliability.

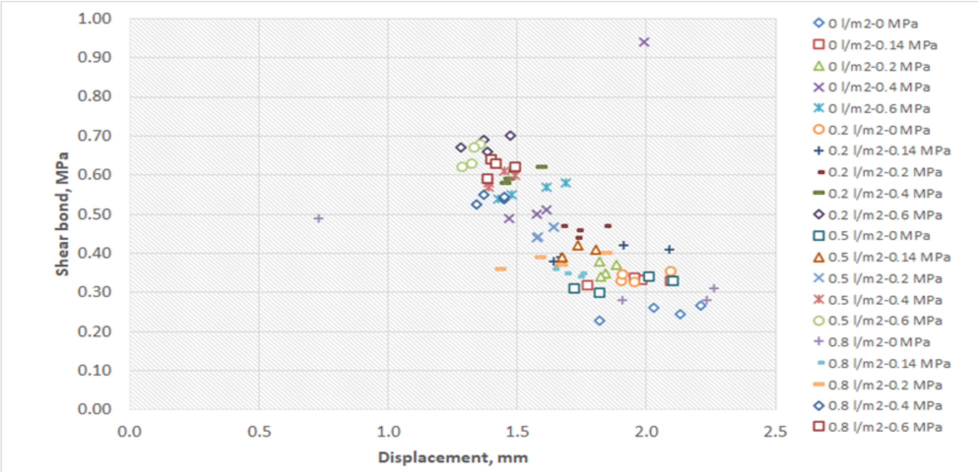

Figure 2. Result of shear bond and displacement at 25°C

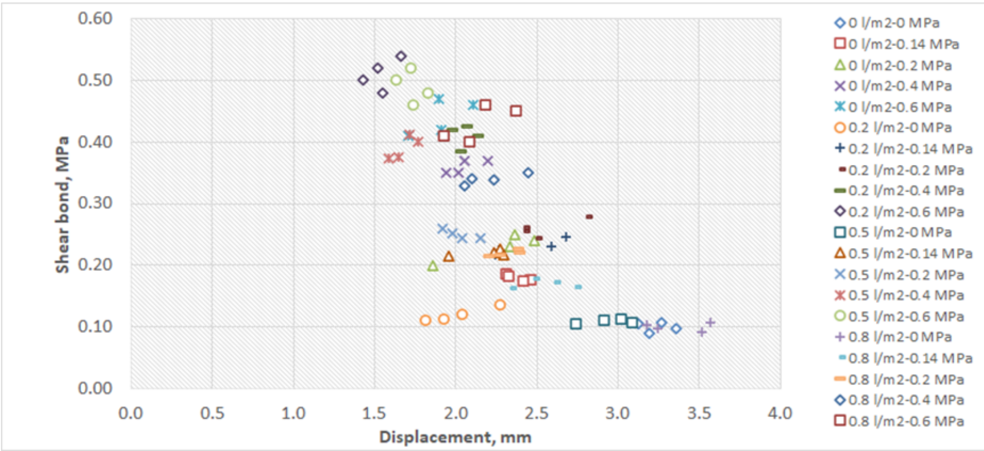

Figure 3. Result of shear bond and displacement at 40°C

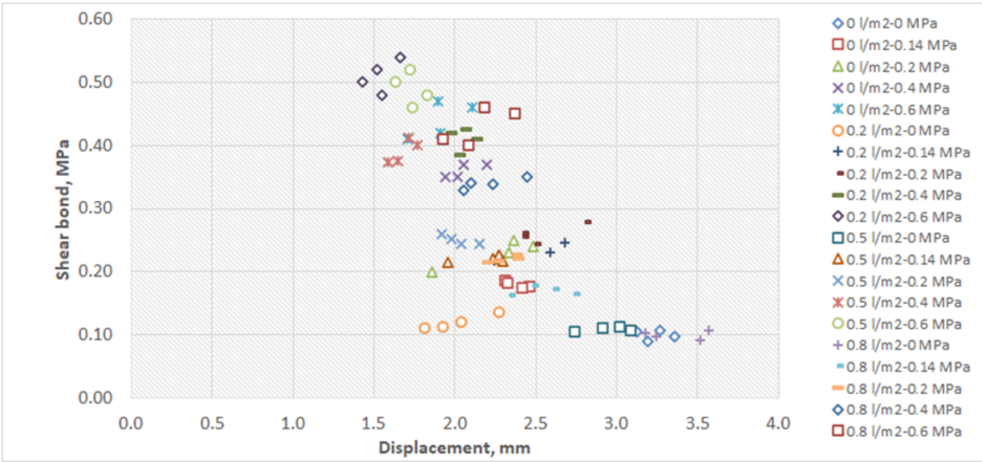

Figure 4. Result of shear bond and displacement at 60°C

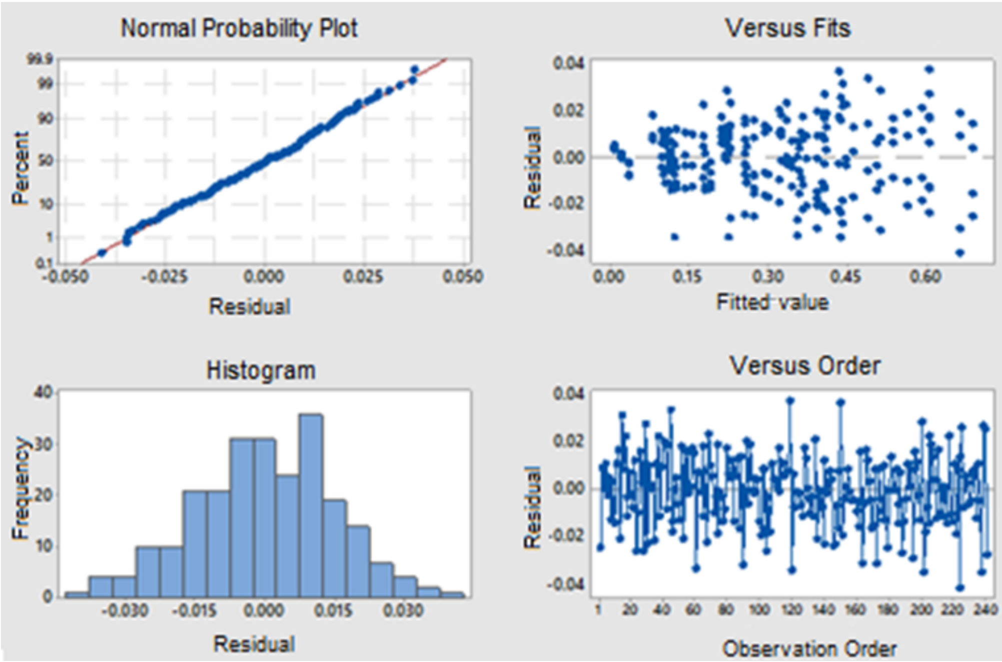

Figure 5. Residual evaluation of shear bond

Table 4. Results of regression model parameters

Coded Coefficients

Term	Effect	Coef	SE Coef	T	P	VIF
Constant		0.30750	0.00272	113.22	0.000	
X1	0.01500	0.00750	0.00272	2.76	0.011	1.00
X2	0.33000	0.16500	0.00272	60.75	0.000	1.00
X3	-0.24500	-0.12250	0.00272	-45.11	0.000	1.00
X1*X2	-0.00000	-0.00000	0.00272	-0.00	1.000	1.00
X1*X3	-0.03500	-0.01750	0.00272	-6.44	0.000	1.00
X2*X3	0.01000	0.00500	0.00272	1.84	0.078	1.00
X1*X2*X3	-0.01000	-0.00500	0.00272	-1.84	0.078	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0164032	96.47%	96.39%	96.26%

The regression equation with the bond irrigation ratios and different pressure and temperature conditions during the experiment has the following form:

Regression Equation in uncoded units:

$$\tau = 0.3900 + 0.1250\,X1 + 0.55000\,X2 - 0.006000\,X3 - 0.002500\,X1*X3$$

4. Conclusion

From the results of evaluation of shear bond for double-layer asphalt based on shear test, the following conclusions are drawn:

- The value of shear bond of double-layer AC sample is the largest at the CRS-1 rate of 0.2 l/m^2, the lowest at 0.8 l/m^2;
- When the normal pressure increases from 0 to 0.6 MPa, the value of shear bond increases 54.74%;
- When the temperature is increased from 25-60^{o}C, shear bond decreases 87.3%. Also, the effect of normal pressure on shear bond at the tack coat rates is much more

pronounced;

- The regression equation between shear bond and the input variables by Minitab V17 has high reliability (96.26%).

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