International Journal of Technology (2018) 5: 925-935
ISSN 2086-9614

ASSESSING THE BOND STRENGTH OF HOT MIX ASPHALT PAVEMENT FOR WEARING AND BINDER COURSES

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(Received: July 2018 / Revised: August 2018 / Accepted: September 2018)

ABSTRACT

This study investigated the use of a shear box device to measure the bond condition between two layers of hot mix asphalt pavement: the wearing course and the binder course. The wearing course analysed was a Malaysian dense-graded asphaltic concrete mixture of nominal maximum aggregate 10 mm in size (AC10), which was applied over the binder course of another dense-graded asphaltic concrete mixture, AC28. A range of bond conditions was investigated by selecting various asphalt emulsions, application rates, and wearing course thicknesses based on the Malaysian standards of specification. Test results showed that interface shear strength increased as tack coat application rates and wearing course thicknesses increased. Among the tested asphalt emulsion types, a modified asphalt emulsion called RS2KL provided the highest shear resistance. Findings also show that a binder's complex shear modulus elastic portion ($G^*/\sin\delta$) can affect interface shear strength for thin mixes at low rates of tack coat application.

Keywords: Asphalt pavement; Asphalt emulsion; Bituminous layer; Bond strength; Tack coat

1. INTRODUCTION

Modern asphalt pavements are engineering structures normally constructed in several layers to withstand traffic loadings. As a layered structure, the performance of the hot mix asphalt overlay relies considerably on the bond strength between the contact interfaces of adjacent layers. Tack coat is typically applied between the interfaces of the surfacing layers to provide the necessary adhesion and enable the overall structure to behave monolithically. A tack coat can either be straight or cutback asphalt; however, it usually is in the form of emulsified asphalt because of environmental concerns. Emulsified asphalt is considered to be 'greener' because it can be applied at ambient temperatures with no heating required. However, pavement failures related to bond strength, such as slippage, delamination, and the formation of shallow potholes, have been reported (Muench & Moomaw, 2008; Alhaji & Alhassan, 2018). This study focused on the laboratory assessment of shear bond strength between two layers of Malaysian dense-graded hot mix asphalt: the wearing and binder courses. The interface shear strength was also

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Permalink/DOI: https://dx.doi.org/10.14716/ijtech.v9i5.2193

correlated to the rheological properties of the asphalt emulsion residue to determine their possible relationship. Testing was carried out using a shear box to measure the interface properties. Over the years, the number of commercialized vehicles has gradually grown. This phenomenon has also increased the standard equivalent axle loads, which are harmful to existing pavements. The consequence is a series of reported road deteriorations and distresses that affects overall driving quality (Lee et al., 2013). Numerous studies on material properties have been conducted to increase the performance of the overall mix; however, the performance of the bonding between pavement layers has often been overlooked (Puri, 2017). In Malaysia, road deteriorations due to interface shear strength remain high and alarming. Hence, interface bonding must be given due attention because it can be equally important in the performance of a constructed pavement.

Research in the area of pavement's interface bond strength developed rapidly as early as the late 1970s when Uzan et al. (1978) and Leutner (1979) first worked on the shear mechanism and studied the shear bond strength of a two-jointed interface. Uzan et al. (1978) examined the effects of the tack coat application rate, test temperature, and magnitude of confinement pressure on interlayer properties using a shear box. They identified a relationship between interface shear strength, which is parallel to the decreasing test temperature and increasing confinement pressure, a finding verified further by different researchers (Canestrari et al., 2005; West et al., 2005; Chen & Huang, 2010). Their testing indicated that an optimum application rate of tack coat would produce maximum shear resistance. The optimum tack coat application rate identified (from the total of the emulsion weight) was 0.49 L/m^2 at 25°C and 0.97 l/m^2 at 55°C for dense-graded and open-graded types of mixture, respectively. A review of the literature shows that different factors were identified as contributing to pavement bond strength. The identified factors are worth studying so that pavement bond strength can progress further, particularly the strength of local, Malaysian materials that comply with local designs and specifications. Therefore, this study investigated behaviours at the pavement interface using the Malaysian asphalt mixture design and locally available tack coats. The study also attempted to correlate interface bond strength with rheological properties of the tack coat using laboratory-prepared specimens.

2. MATERIALS AND METHODS

2.1. Test Matrix

In this study, a dense-graded hot mix asphaltic concrete mixture with a nominal maximum aggregate size of 10 mm (AC10) was selected as the wearing course material for interface shear testing because of the prevalent use of this mixture in Malaysia. The binder course specimen was also a dense-graded hot mix asphaltic concrete mixture that had a nominal maximum aggregate size of 28 mm (AC28). The respective aggregate gradations are presented in Figure 1.

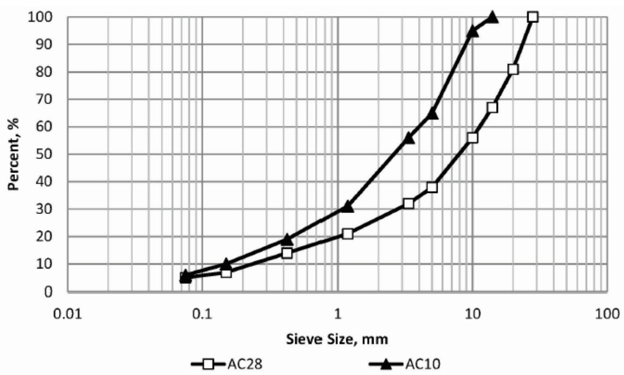

Figure 1 Aggregate gradations of wearing course and binder course

A test matrix, presented in Table 1, was designed to test the effects that tack coat types, tack coat application rates, and wearing course thicknesses have on interface shear bond strength. Each test combination included three tack coat types, three tack coat application rates, and three layer thicknesses on top of five replicates. The tack coat application rates used were based on the total emulsion rate as specified in the Standard Specification for Road Works on Flexible Pavement in Malaysia (Public Works Department of Malaysia, 2008). Three types of emulsified asphalt tack coat were used in this study, namely the conventional RS1K, RS2K, and latex-modified emulsified asphalt tack coat known as RS2KL. RS represents the 'rapid set' type of emulsion. The asphalt emulsion is graded by introducing a numerical value, normally in a range from 1 to 2, to represent the viscosity of the particular emulsion. The suffix K stands for kationik, which means 'cationic' in the official Malaysian language of Malay. Generally, all the asphalt emulsions used were positively charged (i.e. cationic) and possessed at least 50% bitumen content. A total of 135 double-layered specimens were used for the interface shear testing.

Table 1 Test matrix in this study

Variable	Content	Level
Mixture types	AC10	1
Tack coat types	RS1K, RS2K, RS2KL	3
Application rates	0.25 *l*/m^2, 0.40 *l*/m^2, 0.55 *l*/m^2	3
Layer thickness	35 mm, 50 mm, 65 mm	3
Replicates	5 replicates	5
Total number of specimens		135

The Public Works Department of Malaysia has specified that the tack coat application rate must be within the range of 0.25 to 0.55 l/m^2 for dense- and gap-graded mixtures (Public Works Department of Malaysia, 2008). Therefore, three tack coat application rates were selected for this study: 0.25, 0.40, and 0.55 l/m^2. Three wearing course thicknesses (35, 50, and 65 mm) were selected to investigate the effect of layer thickness on the interface strength. However, a constant thickness of 50 mm was maintained for the binder course. The material properties of each emulsified tack coat with respective residual bitumen are presented in Table 2. The residual bitumen was recovered by using the distillation process specified in the international standard ASTM D6997 (2012). The complex shear modulus, G*, and phase angle, δ, for each type of residual bitumen were also measured at 31°C using a dynamic shear rheometer. A higher value of the complex shear modulus elastic portion (G*/sinδ) for a residual bitumen indicated that it had a larger elastic component of stiffness compared to the remaining residual bitumen. At the same time, the higher G*/sinδ also proved that there were changes of elasticity within the residual asphalt with the addition of polymers.

Table 2 Material properties of the emulsified tack coat and the respective residual bitumen

Test	Method	RS1K	RS2K	RS2KL
Test on Emulsion				
Saybolt Furol Viscosity, s (25 ºC)	ASTM D7496	39	42	40
Particle Charge	ASTM D7402	Positive	Positive	Positive
Distillation residue, %	ASTM D6997	50	60	63
Test on Residue				
Penetration, PEN	ASTM D5	62.6	66.1	49.9
Softening Point, ºC	ASTM D36	39.8	41.4	55.5
Viscosity @ 90 ºC, Pa.s	ASTM D4402	2.9	6.0	21.6
G*/sinδ @ 31 ºC, kPa	ASTM D7175	327.3	409.6	788.3

2.2. Specimen Preparation

Both mixture AC10 and AC28 were designed according to Malaysian specifications (Public Works Department of Malaysia, 2008). The specimens were prepared in the laboratory using the Marshall Mix design method. The optimum binder content for mixture AC10 and AC28 was 6.1% and 4.3%, respectively. When preparing the double-layered specimens, binder course specimens were first mixed and compacted with 75 blows in a standard Marshall mould according to ASTM D6926. Emulsified tack coats were applied onto the binder course interface according to the proposed application rates. The application rates, which were initially expressed in terms of litre per square metre, were converted into grams (refer to Table 3) and applied using a brush to ensure targeted application rates.

Table 3 Emulsified tack coat application in grams

Application rate, *l*/m²		0.25	0.40	0.55
Application rate, g	RS1K	2.04	3.27	4.49
	RS2K	2.04	3.27	4.50
	RS2KL	2.04	3.26	4.48

The tack coat was applied to the specimen and weighed at the same time to ensure that the weight measured was the weight of the tack coat that stuck to the specimen. The emulsified tack coats were left outdoors to cure sufficiently based on Table 4, which shows the results of a previous experiment published elsewhere (Yaacob et al., 2014).

Table 4 Minimum curing time of asphalt emulsions

Emulsions	Rates (l/m²)	Curing time (min)
RS1K	0.25	15
	0.40	25
	0.55	35
RS2K	0.25	15
	0.40	20
	0.55	30
RS2KL	0.25	20
	0.40	30
	0.55	35

After preparing the interface, the material for the wearing course was mixed properly and compacted on top of the binder course, which remained unextruded in the mould. Compaction work was conducted to compress the double-layered specimen to the desired thickness. For specimens with wearing course thicknesses of 35, 50, and 65 mm, single face compacting efforts of 85, 140, and 185 compaction blows, respectively, were applied in a single lift as explained in Yaacob et al. (2014). As also discussed in Yaacob et al. (2014), the targeted degree of compaction for specimens compacted in single face was 98%, which is equivalent to 2.264 g/cm^3. At single face compaction of 85, 140, and 185 blows, it was found that the AC10 mixture managed to achieve the desired 98% degree of compaction for specimens with 35, 50, and 65 mm thicknesses, respectively. These laboratory-fabricated double-layered specimens were extruded for direct shear testing to determine interface shear bond strength.

2.3. Test Procedure

The direct shear test was carried out using a shear box tester. A diagram of the direct shear device is shown in Figure 2. The direct shear test was executed at room temperature, approximately ±30°C. A shearing rate of 2.64 mm/min was applied based on the Ancona Shear

Testing Research and Analysis (ASTRA) shear box used by Canestrari et al. (2005). During the shear test, ultimate shearing force and relative shear displacement were recorded with a data acquisition system. A specimen's interface shear strength was calculated using Equation 1.

$$\text{Interface shear stress, ISS} = F_{peak} / A \quad (1)$$

where F_{peak} is the peak load applied to the specimen, as recorded, and A is the cross-sectional area of the specimen.

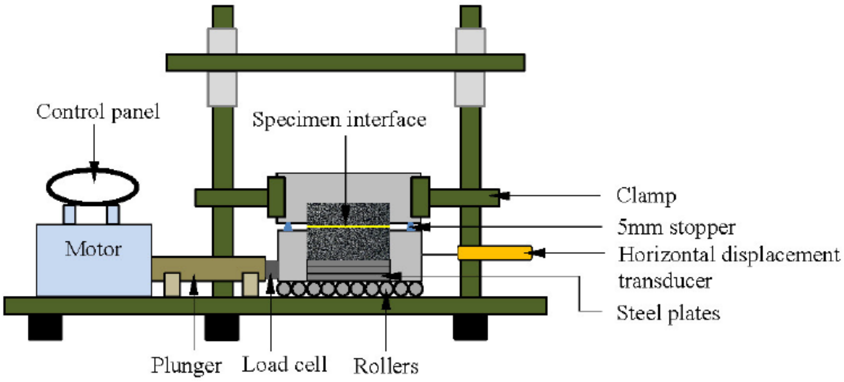

Figure 2 Illustration of shear box used to perform shear testing

3. RESULTS AND DISCUSSION

3.1. Interface Shear Strength

Table 5 summarizes the test results concerning the interface shear strength of the tested mixture combination AC10/AC28. The coefficient of variation (COV) was generally less than 15%, except for specimens at 35 mm with RS1K applied at 0.40 L/m^2, which can be considered as a good estimate for bonding properties at the interface. The test results indicate that interface shear strength generally increased as tack coat application rates increased, and as the layer thickness increased for two of the three tack coats studied: RS1K and RS2K. Some exceptions were observed. One exception involved RS2KL. In terms of application rates, a reduction of interface shear strength was observed in each specimen with a 35 or 50 mm thickness when RS2KL application rates increased from 0.40 l/m^2 to 0.55 l/m^2. As the thickness increased from 50 to 65 mm, a reduction of interface shear strength could be observed regardless of the tack coat application rates. The overall trend of the RS2KL interface shear strength somehow contradicted the trends recorded for RS1K and RS2K, which showed a steady, incremental increase in interface shear strength with respect to tack coat application rates and layer thicknesses when either RS1K or RS2K was applied.

Increasing application rates caused an increase in the residual bitumen content, which may explain how the higher application rates provided higher shear strength. Similar to the case of layer thickness, but with the absence of confinement pressure, interface shear strength increased with increasing thickness because of the unit weight of the specimens. During the shearing process, the application of a constant horizontal load caused the appearance of a distortion in the wearing course specimen, which appeared as an edge of the specimen that had become lifted and slanted. However, no bending movement was observed at the interface. The distortion of the wearing course during the shear test could have been due to some aggregates that were stripped off but remained at the interface of the specimen. This issue was addressed by adding a dead load of 20 kg on top of the wearing course for all types of specimens. The dead load behaved similarly to miniature confinement imposed on the specimen. The effect of the dead load became more concentrated at the interface of the thinner specimen, resulting in lower shear bond strength. Despite being very minimal, the added dead load, along with material self-weight (which increased with layer thickness), enhanced the interface shear bond strength through the formation of friction characteristics. In a comparison of the performance of each type of binder used, RS2KL proved to be a better binder because it could provide higher shear bond strength. This result was anticipated because the residual bitumen content of the modified emulsified tack coat was the highest among the remaining emulsified tack coats used. In addition, RS2KL had the highest viscosity and higher values of G*/sinδ.

Table 5 Summary of interface shear strength test results

Tack coat types	Application rates		Average Interface Shear Strength (MPa)		
			35mm	50mm	65mm
RS1K	0.25	Mean	0.177	0.325	0.382
		COV: %	9.9	10.5	11.6
	0.40	Mean	0.207	0.365	0.415
		COV: %	15.8	8.3	4.9
	0.55	Mean	0.277	0.408	0.367
		COV: %	7.5	9.1	6.3
RS2K	0.25	Mean	0.196	0.358	0.373
		COV: %	8.9	8.5	6.1
	0.40	Mean	0.245	0.363	0.376
		COV: %	8.5	7.4	9.2
	0.55	Mean	0.246	0.379	0.443
		COV: %	9.5	7.9	9.7
RS2KL	0.25	Mean	0.237	0.404	0.388
		COV: %	13.7	9.1	4.8
	0.40	Mean	0.285	0.471	0.404
		COV: %	7.0	6.8	8.7
	0.55	Mean	0.282	0.448	0.439
		COV: %	6.1	9.5	7.2

Whereas most studies have used residual application rates, this research used normal application rates. The practice of using normal application rates, which are based on total emulsion content, is widely accepted in Malaysia, where the Public Works Department has specified that the total emulsion content with a normal tack coat application rate must be between 0.25 and 0.55 L/m^2 for both dense- and gap-graded mixtures (Public Works Department of Malaysia, 2008). This specification has resulted in a significant reduction in residual bitumen content compared to residual application rate that could trigger any possible slippage during the shear test.

Table 6 ANOVA test results for interface shear strength

Source	df	Seq SS	Adj SS	Adj MS	F	*p*-value
Tack coat	2	0.063	0.063	0.031	34.796	0.000
Thickness	2	0.728	0.728	0.364	404.748	0.000
Rate	2	0.058	0.058	0.029	32.086	0.000
Tack coat * Thickness	4	0.017	0.017	0.004	4.653	0.002
Tack coat * Rate	4	0.004	0.004	0.001	1.001	0.410
Thickness * Rate	4	0.004	0.004	0.001	1.167	0.330
Tack coat * Thickness * Rate	8	0.035	0.035	0.004	4.855	0.000
Error	108	0.097	0.097	0.001		
Total	134	1.006	1.006			

An Analysis of Variance (ANOVA) test was conducted at a 5% significance level to investigate the effects of the tested variables on interface shear strength. Based on the analysis results presented in Table 6, all three main factors, as well as two-way and three-way interactions, were found to be significant predictors as indicated by the *p* values of less than 0.05. The F-statistic further revealed that, among the three variables, layer thickness was found to be the most significant, followed by tack coat types and application rates.

The tested independent variables exhibited significant influence on the dependent variable; hence, a post hoc test using Tukey's Honest Significant Difference method was carried out to identify the groups within the independent variables that had a significant mean. The results of the test are presented in Table 7. Several important findings were obtained from the analysis. The different types of tack coat were indicated by the *p* values when RS2KL was used. The resultant interface shear strength significantly differed when compared to using RS1K and RS2K. This finding verified the results of earlier research (Yaacob et al., 2014), which reported dominant performance by RS2KL. The performance of RS2KL differed in different groups of application rates, which can be attributed to the increase in interface shear strength with increasing application rates (i.e. no slippage occurred Similarly, the performance of RS2KL differed with varying wearing course thicknesses; a significant difference in interface shear strength was observed with the 35 mm layer thickness when compared to 50 mm and 65 mm. However, no difference was observed in the analysis of materials with 50 or 65 mm thicknesses.

Table 7 Post-hoc test results for interface shear strength

Tack coats *i*	Tack coats *j*	Mean Difference (*i*-*j*)	Standard Error	*p*-value
RS1K	RS2K	-0.006	0.006	0.580
	RS2KL	-0.049	0.006	0.000
RS2K	RS1K	0.006	0.006	0.580
	RS2KL	-0.042	0.006	0.000
RS2KL	RS1K	0.049	0.006	0.000
	RS2K	0.042	0.006	0.000
Application rates *i*	**Application rates *j***	**Mean Difference (*i*-*j*)**	**Standard Error**	***p*-value**
0.25 l/m^2	0.40 l/m^2	-0.032	0.006	0.000
	0.55 l/m^2	-0.050	0.006	0.000
0.40 l/m^2	0.25 l/m^2	0.032	0.006	0.000
	0.55 l/m^2	-0.018	0.006	0.018
0.55 l/m^2	0.25 l/m^2	0.050	0.006	0.000
	0.40 l/m^2	0.018	0.006	0.018
Thickness *i*	**Thickness *j***	**Mean Difference (*i*-*j*)**	**Standard Error**	***p*-value**
35 mm	50 mm	-0.152	0.006	0.000
	65 mm	-0.160	0.006	0.000
50 mm	35 mm	0.152	0.006	0.000
	65 mm	-0.007	0.006	0.482
65 mm	35 mm	0.160	0.006	0.000
	50 mm	0.007	0.006	0.482

3.2. Shear Reaction Modulus

Figure 3 indicates that a clear behaviour of the shear reaction modulus was not recorded. The k-value appeared to remain generally higher than 0.01 MPa/mm, a threshold value stated by Hakim (1997) and used to indicate an intermediate bond condition normally used in theoretical analysis and modelling works. Certainly, the k-value obtained in this study was remarkably lower than that obtained by previous studies, such as that by Collop et al. (2003) and Choi et al.

(2005), but was still comparable with results obtained by Canestrari et al. (2005). The difference is likely due to the loading rate of the shearing instrument itself. Collop et al. (2003) and Choi et al. (2005) used the Leutner shear tester, which has a displacement rate of 50 mm/min. On the other hand, the experiment by Canestrari et al. (2005) was performed on conventional types of emulsion using the ASTRA device, whereby the displacement rate was set to 2.5 mm/min, which is nearly the same as the displacement rate of this study (2.63 mm/min). As mentioned by Sholar et al. (2004), a higher displacement rate induces greater shear strength, so a higher shear reaction modulus value is to be expected. The results from the current study revealed the superior overall performance of tack coat RS2KL, except when RS1K was applied at 0.25 l/m^2 for a 65 mm specimen, a situation in which a fault is likely to occur during sample preparation, such as an inaccurate tack coat application rate. The exceptional higher viscosity and G*/sinδ of RS2KL provided greater stiffness and resistance to horizontal deformation upon shearing. Furthermore, despite marginal results, the use of RS2KL at higher test temperatures is considered to yield pronounced interface characteristics that favour the use of RS2KL over RS1K and RS2K.

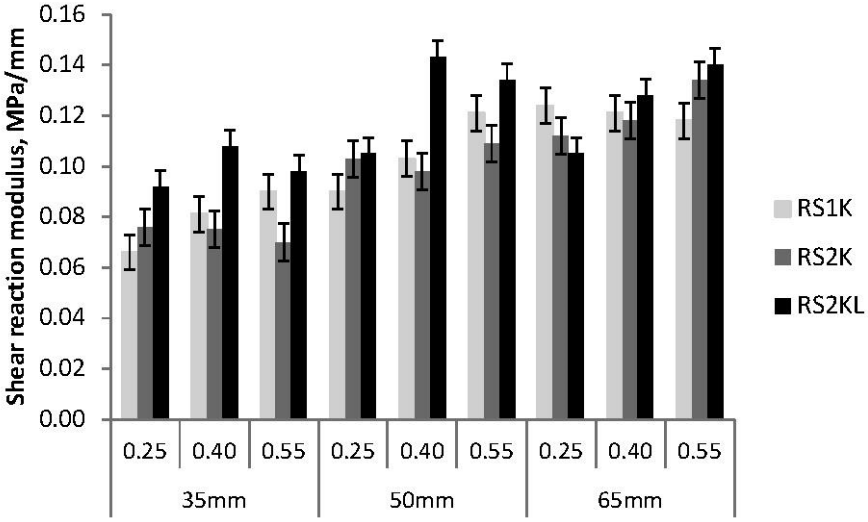

Figure 3 Shear reaction modulus of the tested specimens

3.3. Relationship between Interface Characteristics and Tack Coat Rheology

The relationship between G*/sinδ at 31°C and interface shear strength, for all types of emulsion, is presented in Figure 4a through Figure 4c. The temperature of 31°C was selected because it is a fairly accurate estimation of room temperature during the shear test to determine how the tack coat would behave. Tests showed that the specimens at low tack coat application rates (0.25 L/m^2 and 0.55 L/m^2), with 35 and 50 mm wearing course thicknesses, exhibited an incremental increase in G*/sinδ with higher interface shear strength These specimens clearly exhibited a high coefficient of determination (R^2 value) of more than 0.9. However, a much more randomized trend, with lower R^2 value, could be observed when the thickness was 65 mm, regardless of application rate. Moreover, a point where no relationship between G*/sinδ value and interface shear strength exists was recorded for the specimen at a 65 mm thickness with an application rate of 0.40 l/m^2 of tack coat. The plots in Figure 4 show that the G*/sinδ value of a binder can have a considerable effect on the interface shear strength, particularly for thin mixes with low tack coat application rates. According to Bae et al. (2010), this information can be useful in laboratory investigations, specifically in the selection of the particular tack coat material that will exhibit similar performance when applied in the field. However, further research is necessary to verify and comprehend the findings.

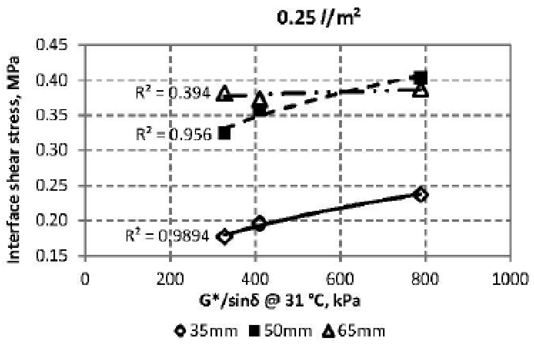

Figure 4 (a) Relationship between G*/sinδ and interface shear strength at 35 mm

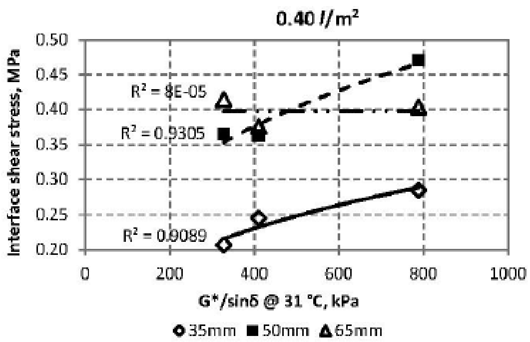

Figure 4 (b) Relationship between G*/sinδ and interface shear strength at 50 mm

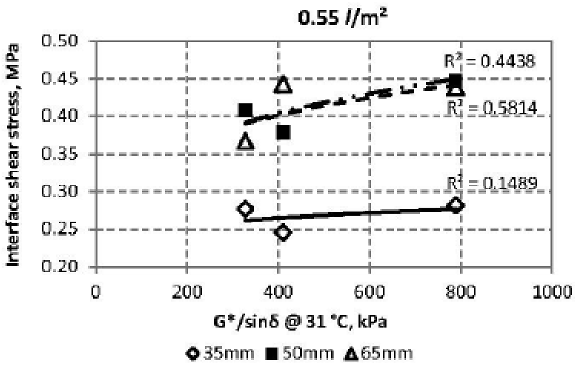

Figure 4 (c) Relationship between G*/sinδ and interface shear strength at 65 mm

4. CONCLUSION

Interface shear bond strength increased with an increase in the tack coat application rate, regardless of the type of tack coat used. In most test combinations, interface shear strength was also found to increase as the thickness of the wearing course increased. The difference in interface shear strength was especially significant when comparing the 35 mm specimen to the 50 and 65 mm specimens. However, the difference between the 50 and 65 mm specimens was marginal. Interface shear strength was observed to have a good correlation with the complex shear modulus elastic portion (G*/sinδ) of the binder for the 35 and 50 mm specimens. This observation indicates that a binder's G*/sinδ value can affect interface shear strength only for thin mixes at low tack coat application rates. Therefore, it is important to have good properties of bitumen emulsion (i.e. the right proportion of residual bitumen content with a low application rate within the specification), especially for the application of tack coat for a thin surfacing or thin asphalt layer. Future research in this area should focus on increasing the shearing speed of the tests to assess the effect of speed's consequences, particularly increased temperature, on pavement's interface bond strength.

5. ACKNOWLEDGEMENT

The authors would like to express their gratitude to associated staff members at the Malaysia Ministry of Higher Education (MOHE) and the Universiti Teknologi Malaysia for the research grants (GUP Tier 1 Vote Q.J130000.2522.17H68) that financially supported this research project.

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