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EVALUATION OF ASPHALT PAVEMENT LAYER BONDING STRESS

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Abstract. This study is to evaluate the bonding shear stress between asphalt pavement layered structures with emulsion and cutback asphalt as tack coat materials. A simple direct shear test device is set up for testing the shear force of the pavement composite interface. The test results show that the shear force decreases with an increase in temperature. It had a maximum value at optimum application rate and the emulsion asphalt used exhibited higher shear force than that of cutback asphalt. The shear stress model represented by exponential equations between shear stress and temperature is reasonable and is not significantly different to the shear stress from experimental field test, in accordance with the statistic of analysis of variance test. The shear stress modeling developed in this paper provides a valuable method to simulate the shear stress of a different nominal aggregate gradation and tack coat material.

Keywords: tack coat materials, emulsion asphalt, shear stress model, ANOVA.

Introduction

Emulsion and cutback asphalt as adhesion materials, called asphalt tack coat, is a light application of liquid asphalt materials that are used to improve the bonding strength between the surface being paved and overlying course. According to ASTM D3628 (2008), asphalt tack coat is defined as: an application of bituminous material applied to an existing, relatively nonabsorbent surface to provide a thorough bond between old and new surfacing. Simply, asphalt tack coat is used to be a bond of the pavement composite interface between two layers of hot mix asphalt (HMA). Adequate bonding between two layers of HMA is critical in order for the completed pavement composite structure to behave as a single unit and to provide an adequate strength. If adjacent layers do not bond to each other, they essentially behave as multiple independent thin layers which result in a significant reduction in the shear strength of the pavement composite structure, thus, making it more susceptible to a variety of distresses such as cracking, rutting, and potholes (West *et al.* 2005; Hachiya, Sato 1997; NAPA 2000). In the recent years, interface shear performance has been widely investigated, especially given that the behavior of in-service pavements has on occasion revealed several types of premature distresses, due to an inadequate selection of interface boundary conditions during the pavement design stage (Raab, Partl 2009; Collop *et al.* 2009; Romanoschi, Metcalf 2001; Romanoschi 1999; Canestrari *et al.* 2005; Mohammad *et al.* 2005; Miro-Recasens *et al.* 2005; Partl *et al.* 2006; Diakhaté *et al.* 2006; Chaignon, Roffe 2001; Al-Hakim *et al.* 2000; Raab *et al.* 2009; Ascher, Wellner 2007). The photograph of typical slippage failure of the pavement composite layer occurring at locations where traffic accelerates, decelerates, or turns is the most commonly observed problem as shown in Figure 1.

Previous studies that focused primarily on the interface characteristics between pavement layers had shown the importance of good bonding between layers for the overall pavement composite performance and had found that shear resistance at the interface increased significantly with an increase in vertical load and decreased with an increase in temperature (Shahin *et al.* 1986; Ishai, Livneh 1984).

Fig. 1. A typical sample of slippage failure

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Some researchers conducted a number of studies with the aim to find optimum application rates, further described: Uzan *et al.* evaluated that the direct shear resistance of an asphalt binder tack coat by a constant shearing rate of 2.5 mm/min were achieved at 25 °C and 55 °C, and optimum tack coat application rates were found to be 0.49 and 0.97 l/m^2 at 55 °C and 25 °C, respectively (Uzan *et al.* 1978). Mrawira and Damude reported that non-tacked overlays exhibited slightly higher maximum shear strengths than tack coated overlays at the shear testing of an emulsion grade SS-1 tack coat between freshly paved asphalt layers by a constant rate of 1 mm/min at 22 °C (Mrawira, Damude 1999). Mohammad *et al.* investigated on the influence of the different emulsions and two asphalt binders as asphalt tack coat materials, and five different tack coat application rates ranging from 0.0 l/m^2 to 0.9 l/m^2 at test temperatures of 25 °C and 55 °C on the shear strength of interfaces between asphalt pavement composite layers (Sivilevičius 2011; Vaitkus *et al.* 2011; Mohammad *et al.* 2002). The Superior Performing Asphalt Pavement (Superpave) shear tester was used for applying a shearing load at a constant rate of 218.27 N/min; and the results indicated that the CRS-2P emulsion was the best tack coat type; and 0.09 l/m^2, was the optimum application rate at which the maximum interface shear strength was measured for both test temperatures. Lavin (2003) recommended that application rates ranging from 0.2 l/m^2 to 1.0 l/m^2 were used for tack coat materials which were diluted to a final asphalt binder content of 30% to improve uniformity of spray, and suggested that milled pavements may require the application rates of 1.0 l/m^2, or more for the larger surface area caused by grooving. Sholar *et al.* (2004) developed a shear testing device to evaluate shear strength of HMA overlays. Their study also involved the construction of three field projects and the evaluation of several variables included the application rate, surface condition, surface texture, and mixture type that could affect the bonding strength between HMA layers. The residual application rates examined were 0.00 l/m^2, 0.091 l/m^2, 0.226 l/m^2, and 0.362 l/m^2. Their test result showed that there was a slight effect of the application rates on the shear strength, and a residual application rate of 0.091 l/m^2, and 0.266 l/m^2, as a minimum required and optimum rate, respectively.

There is no standardized method to assess tack coat application for pavement layer and the proper application rate for each tack materials is often unclear (West *et al.* 2006). The optimum application rates depended on the characteristics of tack coat materials are based on empirical determination at local area. Although a variety of asphalt materials are used as tack coats, the emulsion and cutback asphalt are the most frequently used them in Taiwan. Thus, the objective of a simple direct shear test (SDST) study is to find the optimum application rates of emulsion and cutback asphalt for the adhesion required to improve the structural integrity of the composite pavement. In addition, the study derives shear stress model equations to stimulate the behavior of shear stress in field test.

1. Experimental methods

1.1. Application tack coat materials

The materials included three tack coat materials, one asphalt emulsion (CRS-1) and two cutback asphalts (RC-70 and MC-70), were used for laboratory specimens prepared to determine the effects of tack coat material types. CRS-1 which is a cationic rapid set emulsion made with asphalt cement, water and an emulsifying agent is met the specification requirement of ASTM D2397 (2013). RC-70 (rapid curing) and MC-70 (medium curing) based on the relative rate of evaporation of the solvent are manufactured by blending asphalt cement with a petroleum solvent in accordance with ASTM D2028 (21015) and D2027 (2013), respectively.

The tack coat materials with three level rates of 0.1 l/m^2, 0.2 l/m^2 and 0.3 l/m^2 were used for finding a maximum shear stress as optimum application rates by SDST at the same curing time and room temperature. Once the optimum application rates had been determined, the performance of the tack coat was evaluated by SDST at three different temperatures of 20 °C, 40 °C and 60 °C. In general, the application method is in accordance with ASTM D2995-99 (2009) and laboratory test uses hand sprayer instead. The application rates can be set up in the computer of asphalt distributor car during field construction.

1.2. Laboratory specimen preparation

One coarse graded, 19 mm nominal aggregate size, as shown in Table 1, was used for specimen mixture in accordance with ASTM D3515 and ASTM D6925. The aggregate graded is following the Superpave criteria which consist of: (1) an asphalt binder specification; (2) an HMA mix design method; and (3) HMA tests and performance prediction models. Each one of these components is referred to by the term "Superpave" which is an overarching term for the results of the asphalt research portion of the 1987–1993 Strategic Highway Research Program (SHRP). The properties of aggregate are shown in Table 2. AC-20 and hydrated lime were used as asphalt binder and mineral filler, respectively.

Cylindrical HMA specimens, 63.5 mm height by 100 mm diameter and total weight of 1200 g, were separately two layers compacted by Superpave gyratory compactor (SGC) at 5.4% optimum asphalt contents to simulate field construction for heavy traffic design less than 30,000,000 *ESALS* (Equivalent Single Axial Loads) and the maximum compaction gyrations, N_{max}, were equal to 195 at average pavement temperature of 40 °C in accordance with Superpave criteria as shown in Table 3. The half specimen represented first layer as bottom layer had been compacted and extruded. After 24 hours curing, tack coat material was applied to the designed

Table 1. Aggregate gradation for HMA

Sieve size (mm)	Percent passing			
	ASTM D3515	Superpave		As process
		Control	Restricted zone	
25.4	100	100	–	100
19.0	90~100	90~100	–	97.6
2.5	–	<90	–	89.5
9.50	56~80	–	–	77.7
4.75	35~65	–	–	44.3
2.36	23~49	23~49	34.6	31.9
1.18	–	–	22.3~28.3	22.2
0.60	–	–	16.7~20.7	14.5
0.30	5~19	–	13.7	7.9
0.15	–	–	–	4.1
0.075	2~8	2~8	–	3.5

Table 2. Properties of aggregate

Properties	Specification	Crush stone
Bulk specific gravity, coarse	–	2.655
Bulk specific gravity, fine	–	2.516
Absorption (%)	–	0.6
Unit weight (kg/cm^3)	–	2012
L.A. abrasion (%)	<40	20.2
Sodium soundness (5 cycles) (%)	<12	9.22
Elongated (%)	>0.67	0.69
Flat (%)	>0.67	0.68
Rounded index	–	0.52
Shape factor (%)	–	0.53

Table 3. Superpave mix design results

Asphalt contents (%)	4.4	4.9	5.4	5.9	Specification
VTM@N_d	6.241	4.851	3.993	2.671	4
G_{mm}	2.475	2.454	2.442	2.41	–
VMA	15.79	15.78	15.85	16.31	>13
VFA	74.61	74.66	74.76	75.47	65–75
%G_{mm}@N_i	85.7	87.2	88.5	89	<89
%G_{mm}@N_m	95.8	97.1	97.5	98.3	<98

VTM = Air voids; N_d = Design compaction gyrations; G_{mm} = Maximum specific gravity; VMA = Voids in the mineral aggregate; VFA = Voids filled with asphalt; N_i = Initial compaction gyrations; N_m = Maximum compaction gyrations.

application rates on the top surface of the bottom layer and allowed two hours for curing. The second layer of HMA was placed and compacted over the tacked surface on the bottom layer in a SGC mould, as shown in Figure 2a. During compaction a vertical force of 600 kPa is applied, and the mould is tilted to an angle of 1.25º. The SGC forces the tilt of the mould to rotate at a rate of 30 rpm. This was conducted to simulate HMA overlay of an in-place HMA pavement.

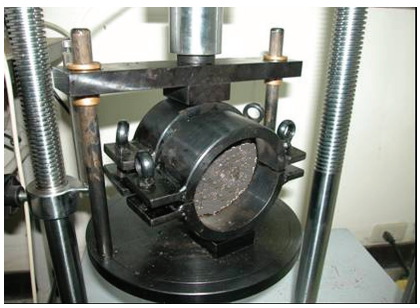
1.3. Shear test

After 24 hours curing at test temperatures of 20 °C, 40 °C and 60 °C, specimens were placed in the SDST device with the specimen interface carefully aligned with the gap of the device frame interface. After that, the shear device with specimen was placed into a Marshall loading device for testing, as shown in Figure 2b. A strain displacement gauge was used to determine specimen displacement during loading. Both the displacement gauge and load cell were connected to a computer for test data retrieved. The Marshall device operated at a constant displacement rate of 5.08 cm/min. During testing, specimens were loaded parallel to the interface plane with no normal pressure. The data recorded measurements for displacement and load every 0.1 seconds until specimen failure. When the specimen failure, the maximum shear stress is then calculated using equation below:

$$\tau_{max} = \frac{4P_{max}}{\pi D^2}, \quad (1)$$

where: τ_{max} is the maximum shear stress (Kg/cm^2); P_{max} is the maximum load applied to specimen (Kg); and D is specimen diameter (cm).

a)



b)

Fig. 2. Two-layer test specimen (a) and (b) SDST

2. Material shear stress model

2.1. Optimum application rates

The shear strength of specimens with different application tack coat materials were tested in the same condition by SDST for determining the optimum application rates. The results shown in Table 4 indicate that the optimum application rates may occur in the highest values of the shear strength. However, it better uses the equation of regression analysis to precisely approach the optimum values. The equations are shown in Figure 3 indicating the maximum shear strength of the 1292 kg, 735 kg and 524 kg for the tack coat materials of CRS-1, RC-70 and MC-70 have the optimum application rates of 0.18 l/m^2, 0.17 l/m^2 and 0.09 l/m^2, respectively, as shown in Table 4.

2.2. Shear stress model

Specimens were fabricated with the optimum application rates of the tack coat and tested by SDST at three different temperatures of 20 °C, 40 °C and 60 °C. The relationship of shear strength versus displacement curve can be plotted as an example shown in Figure 4a. In Figure 4b, the material shear stress model can be derived by two parts of elasticity and friction. In the elastic zone, the curve is a liner behaviour with an angle interface reaction modulus, *K* the slope of the curve which is equal to tanθ. The shear displacement increasing linearly with the shear strength can be represented as below:

$$\tau = d \tan\theta , \qquad (2)$$

where *d* is a shear displacement (mm) and tanθ is a slope.

Failure of the interface occurs when the shear stress reaches τ_{max}. In the friction zone, the two bodies at the interface are completely separated. The failure condition is majorly concerned by this study. Thus, following the curve, the shear stress model equation is derived as below:

$$\tau_{max} = K d_{max} , \qquad (3)$$

where *K* is the slope of the curve called an interface reaction modulus (Kg/cm^2-mm) and d_{max} is a maximum shear displacement (mm).

Table 4. Optimum application rates with optimum shear strength

Tack coat materials	Application rate (l/m^2)	Average shear strength (Kg)	Optimum application rate (l/m^2)	Optimum shear strength (Kg)
	0.1	1241		
CRS-1	0.2	1288	0.18	1292
	0.3	1164		
	0.1	662		
RC-70	0.2	716	0.17	735
	0.3	440		
	0.1	524		
MC-70	0.2	492	0.09	524
	0.3	407		

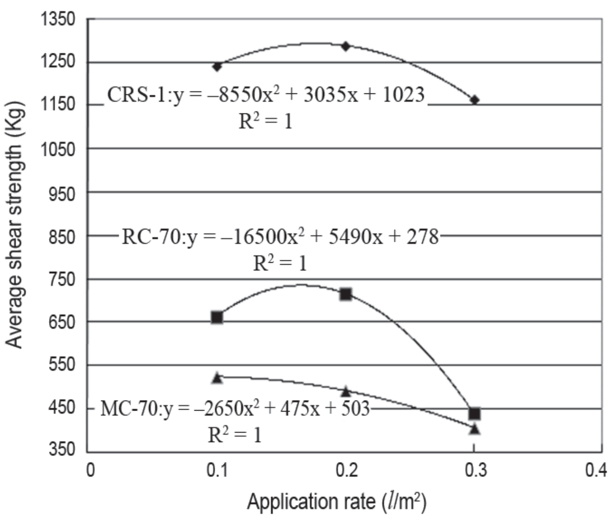


Fig. 3. Optimum application rate determination

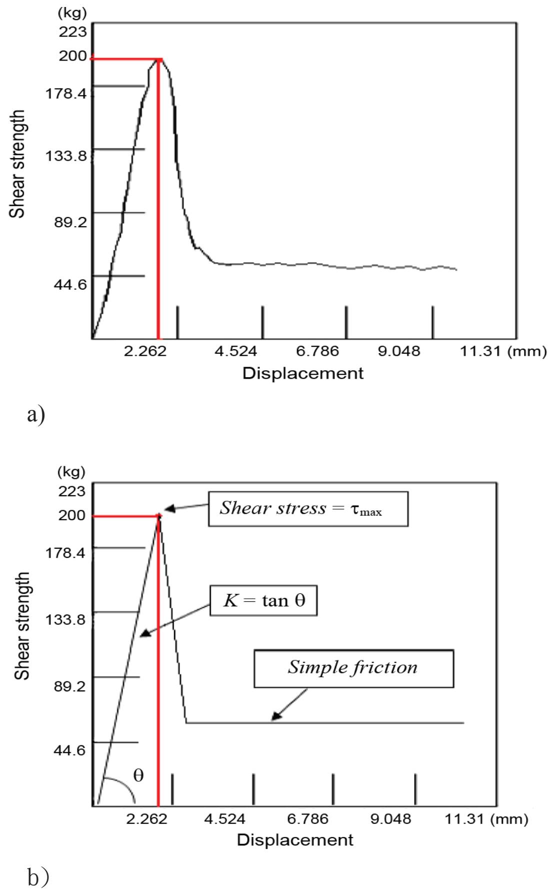


Fig. 4. a) Shear strength and displacement relationship;
b) Modelling shear strength and displacement relationship

3. Results and discussion

3.1. Shear stress model equation

The results are shown in Table 5. As can be seen, the higher temperature has the lower shear stress is and the CRS-1 has higher shear stress than that of RC-70 and MC-70 in each test temperature. The shear stress and K values are decreased with an increase in temperature. The relationship of d and K values versus temperatures are shown in Figures 5 and 6, respectively. Based on a statistical exponential regression analysis, they can be represented as below:

$$CRS-1: \tau_{max} = Kd_{max} = 57.57e^{-0.050T}; \quad (4)$$

$$RC-70: \tau_{max} = 31.58e^{-0.045T}; \quad (5)$$

$$MC-70: \tau_{max} = 18.80e^{-0.036T}, \quad (6)$$

where: τ_{max} is the maximum shear stress (Kg/cm^2); T is a temperature (°C).

Table 5. Interface reaction modulus and shear displacement

Test temperature	Materials	τ_{max} (Kg/cm^2)	d_{max} (mm)	K (Kg/cm^2-mm)
20 °C	CRS-1	22.53	3.19	7.06
	RC-70	14.49	1.81	8.01
	MC-70	8.90	1.54	5.78
40 °C	CRS-1	6.61	2.10	3.15
	RC-70	4.21	1.47	2.86
	MC-70	4.51	1.41	3.20
60 °C	CRS-1	3.01	1.55	1.94
	RC-70	2.42	1.44	1.68
	MC-70	2.07	1.35	1.53

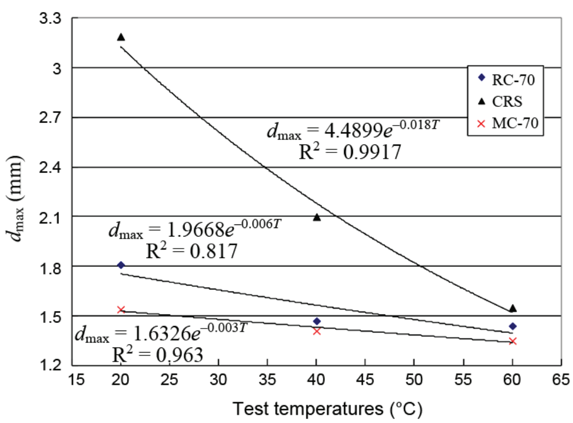


Fig. 5. Shear displacement and temperature relationships

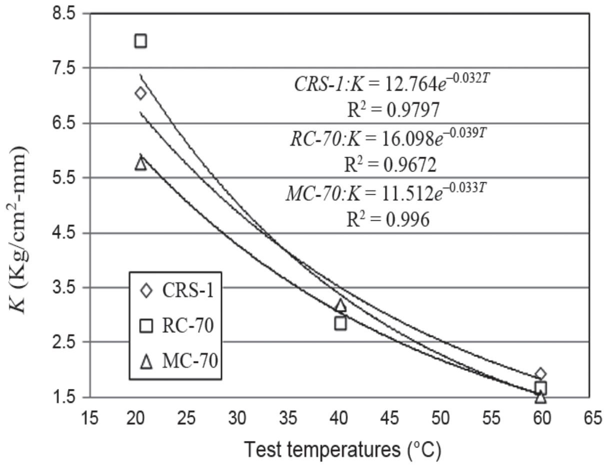


Fig. 6. Interface reaction modulus and temperature relationships

The shear stress model equations show that if temperature is limits to zero, the shear stress values will be 57.57 kg/cm^2, 31.58 kg/cm^2 and 18.80 kg/cm^2 for CRS-1, RC-70 and MC-70, respectively. If temperature is increased to a very high level, the τ_{max} will be zero for each material. Thus, the shear behaviour of the tack coat materials represented by exponential equations between and temperature is reasonable.

3.2. Model equation evaluation

The equations evaluated by advance test were needed. The applicability assessment of the equations was performed with the data provided by field test which was constructed by the same aggregate gradation and binder contents as laboratory condition, and was applied by three types of tack coat materials of CRS-1, RC-70 and MC-70 at optimum application rates. Six specimens with each material were obtained from field and tested in laboratory at three different temperatures

The test results are shown in Table 6 indicating the values of the shear stress from field test and model equation have a little bias between 1.65 kg/cm^2 and –1.18 kg/cm^2.

Table 6. Shear stress from field test and model equation

Types	Temperatures	τ_{max} (Kg/cm^2) Field test	Model equation	Difference
CRS	20 °C	22.53	21.18	1.35
	40 °C	6.61	7.79	–1.18
	60 °C	3.01	2.87	0.14
RC-70	20 °C	14.49	12.84	1.65
	40 °C	4.21	5.22	–1.01
	60 °C	2.42	2.12	0.30
MC-70	20 °C	8.9	9.23	–0.33
	40 °C	4.51	4.49	0.02
	60 °C	2.07	2.19	–0.12

To determine the statistical significances on the effect of shear stress values from field and model equation at different temperatures, an analysis of variance (ANOVA) test was performed, which was done to determine if the treatments were significant at a certain confidence limit by the *F*-test. The *F*-test is used to determine if the regression relationship between the values obtained from field test and model equation is statistically significant. In the same manner, the *p*-value is used to test if the relationship between the values obtained from field test and model equation is linear at a level of significance of 0.05. In general, the *p*-value is less than or equal to the significance level, α, that would lead to the rejection of the null hypothesis. The null hypothesis represents that no difference exists between the control and experimental groups (for the variable being compared). Therefore, for *p*-values less than the level of significance of 0.05, the null hypothesis is rejected; thus, the relationship is significant. Table 7 shows the results of the ANOVA test; and indicates that the shear stress values from field test and model equations have no significant effect. This situation suggests that the values of the shear stress obtained from field test or from model equation are not significant difference. Thus, the model equations can be used to simulate the maximum shear stress of the tack coat materials. In Table 8, however, the take coat materials and different test temperatures have a significant effect at a confidence limit of 95% ($F > F_{0.05}$ and p-value < 0.05), which means that the use of different tack coat materials at different test temperatures can lead to different shear stress.

Table 7. ANOVA for shear stress from field test and model equation

Source of variation	*F*	*p-value*	$F_{0.05}$
20 °C shear stress	0.0454	0.8356	4.9646
40 °C shear stress	0.6359	0.4437	4.9646
60 °C shear stress	0.0861	0.7752	4.9646

Table 8. ANOVA for field test

Source of variation	*F*	*p-value*	$F_{0.05}$
Tack materials	33.4968	8.57E-07	3.5546
Temperatures	192.2115	7.17E-13	3.5546

Conclusions

Three different tack coat materials were evaluated by SDST. The results show that the CRS-1 has higher shear strength than that of RC-70 and MC-70 in each test temperature at optimum application rates determined by the SDST and regression analysis. Generally, the shear strength is influenced by temperatures and application rates. The higher temperature has, the lower shear strength is; and increasing the application rate does not significantly improve the shear strength.

The shear stress model equations represented by exponential equations depending on temperature had been conducted. Based on an ANOVA test, the equations simulating the maximum shear stresses of the tack coat materials are not significantly different the shear stress from real field test at test temperature of 20 °C, 40 °C and 60 °C. This study throughout SDST conducts the model equations of "*K*", an interface reaction modulus, and "d", a shear displacement, can be used to simulate the maximum shear stress of the tack coat materials for determination of the optimum application rates. The shear stress modelling methodology developed in this paper provides a valuable tool to simulate the shear stress of a different nominal aggregate gradation and tack coat material.

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