

OPTIMIZATION OF TACK COAT APPLICATION RATES AND CURING TIMES FOR ENHANCED INTERLAYER SHEAR STRENGTH IN MULTILAYER PAVEMENT

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INTISARI

Penelitian ini mengkaji dosis penerapan takaran *tack coat* dan waktu curing untuk meningkatkan kekuatan geser antar lapisan pada perkerasan beraspal. Dua jenis *tack coat* yang digunakan, yaitu CRS-1 dan CRS-1P, diaplikasikan di antara lapisan AC-WC dan AC-BC dengan bahan pengikat PG 76 dan Pen 60/70. Kadar Aspal Optimum (KAO) ditentukan menggunakan metode Marshall, kemudian dilakukan pengujian geser langsung pada variasi dosis *tack coat* 0,25; 0,35; dan 0,45 liter/m² serta waktu curing 15–75 menit. Hasil menunjukkan bahwa kekuatan geser maksimum dicapai pada dosis 0,35 liter/m² dan waktu curing 45 menit. CRS-1P menghasilkan kekuatan geser tertinggi sebesar 1,61 MPa, lebih tinggi dibandingkan CRS-1 sebesar 1,39 MPa. Peningkatan dosis dan waktu curing di luar kondisi optimum menurunkan kekuatan geser akibat efek pelumasan. Analisis mekanistik menggunakan BISAR 3.0 mendukung hasil eksperimental. Temuan ini menegaskan pentingnya pengendalian penerapan *tack coat* untuk meningkatkan kinerja ikatan antar lapisan perkerasan beraspal.

ABSTRACT

This study investigates the optimization of tack coat application rate and curing times to enhance interlayer shear strength in asphalt pavement structures. Two types of tack coat, CRS-1 and CRS-1P, were applied between the Asphalt Concrete–Wearing Course (AC-WC) and Asphalt Concrete–Binder Course (AC-BC) using PG 76 and Pen 60/70 binders. The Optimum Asphalt Content (OAC) was determined using the Marshall mix design method, followed by direct shear testing under tack coat application rates of 0.25, 0.35, and 0.45 L/m² and curing times ranging from 15 to 75 minutes. The results indicate that the maximum interlayer shear strength was achieved at an application rate of 0.35 L/m² and a curing time of 45 minutes. CRS-1P produced a higher peak shear strength (1.61 MPa) compared to CRS-1 (1.39 MPa). Excessive application rates and prolonged curing times reduced shear strength due to lubrication effects. Mechanistic analysis using BISAR 3.0 supported the experimental findings. These results highlight the importance of proper tack coat application to improve interlayer bonding performance in asphalt pavements.

Keyword:

Asphalt Pavements

Tack Coat

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1. INTRODUCTION

The increasing volume and weight of the vehicle lead to a lack of road ability to withstand traffic loads. The load of a vehicle passing through a road pavement will result in shear forces and bending moments on the pavement layer [1]. The shear strength of each working layer is highly dependent on traffic load, vehicle speed, layer thickness, and construction type. Bonding between layers is critical to the performance of a multilayer pavement system, which provides optimal road service [2]. Non-ideal bonding between layers will result in various road damages such as slippage, cracking, premature fatigue cracking, top-down cracking, delamination, and potholes [3]. Bonding inability or failure causes a slip between the pavement layers, resulting in a significant reduction in the shear strength of the pavement structure, thus making the pavement more susceptible to various distresses, such as cracking, rutting, and potholes [4], [5].

The use of Tack Coat is essential to support the performance of pavement to improve the road's ability to withstand vertical and horizontal loads from vehicles when maneuvering. The adhesive properties of the Tack Coat between asphalt pavement layers are critical for the structural behavior of the pavement, showing that the partial fixed bond condition, even on aged (10 years) and unloaded pavements, does not affect the Leutner test results, causing specimen failure in the tangential force direction [6]. The use of too little Tack Coat or the spread of Tack Coat that is too thin will result in easy release of bonds between pavement layers, while if the provision of tack coat is too excessive, it is feared that it will form a slip plane between the layers. A previous study reported that a 30% tack coat content in Stone Matrix Asphalt (SMA) provided optimum interlayer performance, although the drying process still affected adhesion [7]. Pavement durability and maintenance depend on several factors. One of the most influential is the bond between layers. Several studies have concluded that the most influential variables are tack coat type, dosage, mix type, surface characteristics, temperature, and emulsion evaporation time. To achieve the highest bond strength values, the following factors should be considered: high surface macro-texture values, low temperature, use of hot-adhesive emulsion, dosage of 0.30 to 0.45 liters/m² of residual asphalt, and compaction after the emulsion has evaporated [8]. Appropriate application of Tack Coat will greatly improve the performance of the pavement between layers. The time during which these thinners begin to evaporate (depending on weather conditions) is known as the setting time or curing time. The shear resistance produced by the Tack Coat against the paved layer will increase in line with the length of curing time up to a certain time limit. Shear strength increases to a certain extent in line with the length of curing time. The curing time for each temperature variation is different; the curing time at 60°C is optimum at a curing time of 90 minutes [9]. The optimum shear strength for the use of Pen 60/70 asphalt with a tack coat variation of 0.2 l/m² to 0.6 l/m² on CSS-1 type emulsified asphalt spread of 0.4 l/m² is 1.214 MPa [10]. The trackless layer treated with tack coat effectively improved the adhesion performance between pavement layers. The coating showed an adhesion performance of 1.05 MPa in a direct tensile strength of 0.45 liters/m², higher than the fast-hardening tack coat [11].

Previous studies have shown that tack coat type, application rate, and curing time significantly influence interlayer bond performance. However, limited information is available on the combined effect of these variables for CRS-1 and polymer-modified CRS-1P under Indonesian material conditions, particularly for the interface between AC-WC using PG 76 and AC-BC using Pen 60/70. Therefore, this study aims to determine the optimum tack coat application rate and curing time required to maximize interlayer shear strength. The experimental results are further interpreted using BISAR 3.0 to provide mechanistic support for the observed interlayer behavior.

2. MATERIALS

2.1. Asphalt Concrete

Asphalt concrete is a type of pavement that consists of aggregate and asphalt, with or without additives, mixed at a specific temperature. Asphalt concrete mixtures have the properties of stability, durability, flexibility, resistance to shear, resistance to fatigue, impermeability, and ease of implementation. Pavement is a mixture of aggregates and binders used to serve traffic loads [12]. Flexural pavement is a type of pavement that is widely used [13]. Statistics show that 95% of the world's roads are made of flexible pavement. The type of binder distinguishes the two most significant types of pavements, namely flexible pavements and rigid pavements. In rigid pavements, Portland cement is used as the binder, and asphalt is used as the binder for flexible pavements. Asphalt concrete is a mixture of aggregate and asphalt. Asphalt concrete mixtures can be classified into three main categories based on their aggregate gradation: Hot Mix Asphalt (HMA), Hot Rolled Sheet (HRS), and Stone Mastic Asphalt (SMA) [14].

2.2. Tack Coat Type

The Tack coat is a thin layer of asphalt-based adhesive (such as emulsified or liquid asphalt) applied between pavement layers to ensure a strong bond [15]. An adequate interface bond between the HMA overlay and the underlying pavement layers is essential for optimal pavement performance [16]. The use of tack coat to provide the necessary adhesive bond between overlapping pavement layers ensures that the entire pavement layer behaves as a monolithic system capable of withstanding traffic [17]. In general, tack coat is a thin adhesive layer spread between the old asphalt pavement layer and the new asphalt pavement, or between the composite pavement in other words, tack coat is a thin layer of asphalt that provides adhesion while providing strength between the old pavement layer and the new pavement layer [18]. The amount of tack coat distribution depends on the condition of the old road construction surface (existing), ranging from 0.15 - 0.50 kg / m² with a temperature of 110 ± 10°C [19]. The tack coat layer requires the use of emulsified bitumen (SS, CSS, or micro surfacing grade). Emulsified asphalt is diluted and sprayed at a rate of 0.23 - 0.45 Liters / m², and then the tack coat is allowed to dry for a certain time [20].

Tack coats sprayed on top of the coating can fill voids in the underlying pavement and increase the contact area, thereby improving adhesion between layers. The use of tack coat in improving shear strength can be affected by several factors, such as tack coat material, test conditions, pavement surface conditions, and moisture [21]. It functions as an adhesive layer between the old pavement layer and the new pavement layer to provide strong adhesion. The tack coat is applied using an asphalt distributor or sprayer by adjusting the position of the nozzle and the height of the nozzle stick in such a way that the tack coat will be evenly distributed according to the specified distribution rate. The tack coat layer should be allowed to set for a while to allow time for the diluent (oil or water) contained in the asphalt cutback or asphalt emulsion to evaporate. The length of time that these thinners begin to disappear (depending on weather conditions) is known as setting time or sometimes curing time [22].

2.3. Tack Coat Rate

Emulsified asphalt is a nonflammable liquid substance produced by combining asphalt cement with water using emulsifying agents or surfactants, such as soap, dust, and more. Emulsified asphalt has advantages over hot asphalt and cutback asphalt, as it can be used with cold or hot aggregates and with dry or damp aggregates. In addition, emulsified asphalt does not need to be at high temperatures for proper application, and thus, the fire hazard is eliminated, and installation is much faster than cutback asphalt [23]. Asphalt sprayed on top of the underlayment can fill the voids under the pavement and increase the contact area, and consequently, improve interlayer adhesion. In comparison, if the asphalt layer is placed too thick, the slip will occur in the interlayer, reducing interlocking adhesion and resistance. Therefore, the use of the right level of tack coat is important to obtain a high interlayer shear strength between pavement layers.

From these references, this research will use a rapid type of asphalt emulsion, where this type of tack coat is not only fast reacting but provides strong adhesion, so that pavement repairs in the field can be done quickly, considering these conditions are appropriate or good to be applied in Indonesia. The types of tack coat used are CRS-1 and CRS-1P. There are still a few studies on this type of tack coat in Indonesia. The types of tack coats and doses available in Indonesia can be seen in the following table:

Table 1. Type and measurement of tack coat

Tack Coat of Types	Measurement (liters/m ²)		
	Slippery New or Old Asphalt or Concrete Surfaces	Porous and Weather-Exposed Surfaces	Cementitious Binder Surface
Liquid Asphalt	0.15	0.15 – 0.35	0.2 – 1.0
Asphalt Emulsion	0.20	0.20 – 0.50	0.2 – 1.0
Polymer Modified Asphalt Emulsion	0.20	0.20 – 0.50	0.2 – 1.0
	Residual Content (liters/m ²)		
All	0.12	0.12 – 0.21	0.12 – 0.60

2.4. Software BISAR 3.0

Bitumen Stress Analysis in Roads (BISAR) is a program that adopts the concept of multi-layered elastic theory analysis that can be used to calculate stress, strain, and displacement in elastic layered systems subjected to one or more uniform circular vertical loads on the surface of the pavement system. In addition to stress and strain calculations, BISAR 3.0 can calculate deflections and can handle horizontal forces and slip between pavement layers [24].

One of the uses of BISAR 3.0 is to calculate slip (full or partial slip). This type of calculation is made with the help of the sliding tool, a parameter that should not be confused with the coefficient of friction. BISAR 3.0 assumes the coefficient of friction is not possible, as its value is different for static and dynamic conditions [25]. The BISAR 3.0 program can solve the problem, but the BISAR 3.0 model assumes a continuous relationship for all parameters. The shear stress in the surface layer causes a relative horizontal force displacement of the two layers, proportional to the stress acting on the interlayer. Flexural pavement is a multilayer system with full slip and full bonding conditions in the pavement structure and mix design. The coefficient of friction between the wheel and the pavement surface is assumed to range from 0 to 0.5; the horizontal load is defined by multiplying this coefficient by the vertical load value [26]. The horizontal load is found in the range between 0 - 12.5 KN for standard dual wheel loading and in the range of up to 50 KN for overload conditions. The vehicle load is assumed to be horizontally loaded by friction due to the vehicle starting to maneuver or coming to a stop, which forms a linkage [27]. The vehicle is assumed to use a combination of vertical load and horizontal load with a tandem axle dual wheel configuration, which is 176.52 kN or 18 Tons, while the tire contact pressure is 0.7 MPa, the contact radius is taken to be 0.105m. BISAR 3.0 is used to calculate the forces and displacements that occur in the pavement structure.

3. METHODS

This study employed an experimental laboratory approach to evaluate the effect of tack coat type, application rate, and curing time on the interlayer shear strength between Asphalt Concrete–Wearing Course (AC-WC) and Asphalt Concrete–Binder Course (AC-BC). The research consisted of five main stages: (i) material selection and characterization, (ii) Marshall mix design to determine the Optimum Asphalt Content (OAC) of the AC-WC and AC-BC mixtures, (iii) preparation of composite specimens and direct interlayer shear testing, (iv) mechanistic modeling using BISAR 3.0, and (v) data analysis and interpretation. The Marshall method was selected because it remains a standard and practical mix design approach for asphalt concrete and provides the volumetric and mechanical parameters required to obtain representative AC-WC and AC-BC mixtures. The Leutner Shear Test configuration was adopted because it directly measures interlayer shear resistance under controlled loading. BISAR 3.0 was used to complement the laboratory findings through multilayer elastic analysis so that the experimentally observed bond behavior could be interpreted in relation to the mechanistic response of the pavement structure.

3.1. Material selection

The constituent materials comprised coarse aggregate, fine aggregate, mineral filler, Pen 60/70 asphalt, PG 76 asphalt, and two tack coat emulsions, namely CRS-1 and CRS-1P. The aggregates were obtained from the Clereng quarry area, Kulon Progo, D.I. Yogyakarta. Pen 60/70 and PG 76 binders were supplied by Shell Indonesia, while the CRS-1 and CRS-1P tack coats were supplied by PT Buntara Megah Inti. All materials were tested prior to use and were selected only after satisfying the applicable technical specification requirements. The AC-WC mixture used PG 76 as the binder, whereas the AC-BC mixture used Pen 60/70.

3.2. Marshall mix design and determination of OAC

Marshall mix design was conducted separately for the AC-WC and AC-BC mixtures before preparing the composite specimens for the interlayer shear test. The mixtures were designed in accordance with the 2018 Bina Marga specifications using dense-graded aggregate gradations. Five asphalt-content levels were evaluated for each mixture. For each asphalt-content level, three Marshall specimens were prepared and tested. Therefore, a total of 15 Marshall specimens were used for the AC-WC mixture and 15 Marshall specimens for the AC-BC mixture, giving 30 Marshall specimens in total.

The selected aggregates were first dried, sieved, and weighed according to the target gradation. The aggregates and asphalt binder were then heated to the required mixing temperatures before being mixed thoroughly until a homogeneous mixture was obtained. The mixture was compacted in Marshall moulds using the specified compaction effort. After cooling, the cylindrical specimens were removed from the moulds and measured for height and diameter, and then weighed in dry, submerged, and saturated surface-dry conditions.

The volumetric characteristics of the mixtures, including density, voids in mineral aggregate (VMA), voids in the total mix (VITM), and voids filled with asphalt (VFWA), were determined from the Marshall specimens. Mechanical testing was then carried out to obtain Marshall stability and flow, from which the Marshall Quotient (MQ) was calculated. The Optimum Asphalt Content (OAC) for each mixture was determined using the narrow-range method based on the compliance of the volumetric and mechanical

parameters with specification requirements. The OAC values obtained from this stage were then used to prepare the AC-WC and AC-BC layers for the interlayer shear test.

3.3. Preparation of Composite Specimens and Interlayer Shear Testing

The direct shear test was conducted on composite cylindrical specimens consisting of two asphalt layers, namely an upper AC-WC layer and a lower AC-BC layer. The layer thicknesses used in this study were 5 cm for AC-WC and 7 cm for AC-BC. All specimens were prepared using the OAC values obtained from the Marshall mix design. Two tack coat emulsions were evaluated, namely CRS-1 and CRS-1P. Each tack coat type was applied at three target application rates of 0.25, 0.35, and 0.45 L/m². For each application rate, five curing times were investigated, namely 15, 30, 45, 60, and 75 min. All test combinations were prepared in triplicate. Accordingly, each tack coat type required 90 shear specimens, and the total number of specimens used for direct shear testing was 180. The required amount of tack coat for each specimen was calculated based on the interface area of the specimen, equal to 0.008103 m², and a tack coat bulk density of 1.015 g/cm³. The resulting tack coat consumption was 2.06 g, 2.88 g, and 3.70 g per specimen for target application rates of 0.25, 0.35, and 0.45 L/m², respectively.

The composite specimen preparation consisted of three stages. First, the AC-BC bottom layer was prepared using the selected OAC, compacted in a modified mould, and allowed to cool to room temperature. Second, tack coat was uniformly applied over the AC-BC surface using the designated tack coat type and application rate. The coated surface was then left to cure for the specified period under laboratory room temperature conditions of approximately $\pm 25^{\circ}\text{C}$. Third, the AC-WC upper layer was prepared using its OAC and placed over the treated AC-BC layer in the modified mould, followed by compaction. After cooling, the composite specimens were ejected from the mould and made ready for interlayer shear testing. The interlayer shear test was performed using a Marshall testing machine modified with a hydraulic clamping mechanism in a Leutner Shear Test configuration. One part of the specimen up to the predetermined shear plane was supported and clamped, while the upper part remained free for loading. A shear load was applied to the upper part of the specimen using a semicircular shear yoke at a constant deformation rate of 50 mm/min until failure occurred along the predetermined interface. The test output consisted of shear force and displacement, from which the interlayer shear strength was calculated. The results reported for each test represent the average of three replicate specimens.

3.4. BISAR 3.0 Modeling

The mechanistic analysis was performed using BISAR 3.0 based on a multilayer elastic pavement system representing the AC-WC, AC-BC, base, and subgrade layers. BISAR 3.0 was selected because it can calculate stress, strain, and displacement in layered pavement systems under vertical and horizontal loading and can also represent interlayer conditions such as full bonding and full slip. The pavement layer properties and loading assumptions used in the simulation are presented in Table 2 and Table 3.

Table 2. Pavement layer properties used in BISAR 3.0 modeling

Layer	Thickness (cm)	Elastic Modulus (Mpa)	Poisson's Ratio
AC-WC	5	1448	0.40
AC-BC	7	1448	0.40
Base	40	212	0.40
Subgrade	Infinite	60	0.35

Table 3. Loading and contact parameters used in BISAR 3.0 modeling

Parameter	Unit	Value
Axle configuration	-	Tandem axle dual wheel
Total axle load	kN	176.52
Equivalent axle load	ton	18
Standard vertical load	kN	80
Standard horizontal load	kN	10
Overload vertical load	kN	100
Overload horizontal load	kN	12.5

Tire contact pressure	Mpa	0.70
Contact radius	m	0.105
Friction coefficient, f	-	0 – 0.5
Horizontal load relation	-	$F = w \times f$
Interface condition	-	Full bonding (FB) & full slip (FS)

The BISAR 3.0 outputs were used to evaluate the shear stress and displacement responses within the pavement structure under standard and overload conditions. These results were then compared with the laboratory interlayer shear strength to support the interpretation of the optimum tack coat condition.

3.5. Data Analysis and Interpretation

The data analysis in this study consisted of two main components. First, the Marshall test results were analyzed to determine the OAC for the AC-WC and AC-BC mixtures. The measured volumetric and mechanical parameters were plotted against asphalt content to establish the trends needed for OAC determination using the narrow-range method.

Second, the direct shear test results were analyzed by comparing the average shear strength and displacement values obtained for each combination of tack coat type, application rate, and curing time. The optimum condition was identified based on the highest average interlayer shear strength while considering the corresponding displacement response and the consistency of the trend across the test matrix.

Finally, the experimental findings were interpreted together with the BISAR 3.0 modeling results. The laboratory-observed interlayer shear strengths were compared with the shear stress values obtained from BISAR 3.0, particularly under standard and overload conditions, in order to assess whether the measured bond strengths exceeded the minimum mechanistic demand. This combined approach was used to establish a coherent relationship between laboratory performance and pavement structural response.

4. RESULTS AND DISCUSSION

4.1. Marshall Characteristics for Determining OAC

The result of the mix design is the determination of OAC for 5 variations of the mix. The determination of OAC is based on Marshall characteristics (volumetric characteristics and mechanical characteristics) and is analyzed using the narrow range method. This method produces a range of OAC, and then the amount of OAC can be determined by the amount of value in the range. The OAC value is determined based on the middle value of the OAC range in each mix variation.

Based on the calculation of the Marshall characteristics of the data from the calculation of volumetric characteristics (density, VMA, VITM, and VFWA) and mechanical characteristics (MS, MF, and MQ), each variation of asphalt content obtained OAC values, as shown in the following table:

Table 4. Marshall test results of the AC-WC PG 76 mixture

Criteria	Specification	Bitumen Content					Unit
		5.0	5.5	6.0	6.5	7.0	
Density	-	2.319	2.330	2.348	2.359	2.364	gr/cm ³
VMA	> 15	18.6	18.6	18.4	18.4	18.7	%
VITM	3 - 5	8.3	7.1	5.8	4.6	3.7	%
VFWA	> 65	55.3	61.6	68.8	75.1	80.2	%
MS	> 1000	1779	1905	1926	1839	1749	kg
MF	2 - 4	3.4	4.5	5.1	6.1	6.4	mm

Table 5. Marshall test results of AC-BC Pen 60/70 mixture

Criteria	Specification	Bitumen Content					Unit
		5.0	5.5	6.0	6.5	7.0	
Density	-	2.343	2.363	2.369	2.369	2.383	gr/cm ³
VMA	> 15	17.7	17.4	17.7	18.0	18.1	%
VITM	3 - 5	5.7	4.2	3.2	2.3	1.3	%
VFWA	> 65	68.0	76.2	81.7	87.2	93.0	%

MS	> 800	1412	1485	1502	1433	1300	kg
MF	2 - 4	3.4	3.8	3.9	4.1	5.0	mm

The Marshall mix design results were used to determine the Optimum Asphalt Content (OAC) of the AC-WC and AC-BC mixtures before the interlayer shear test was carried out. As shown in Table 4 and Table 5, the Marshall parameters changed systematically with increasing asphalt content. For the AC-WC mixture using PG 76, density increased from 2.319 to 2.364 gr/cm³ as the asphalt content increased from 5.0% to 7.0%, while VITM decreased from 8.3% to 3.7%. At the same time, VFWA increased from 55.3% to 80.2%, and Marshall stability reached its highest value at 6.0% asphalt content before slightly decreasing at higher asphalt contents. For the AC-BC mixture using Pen 60/70, density also increased with asphalt content, while VITM decreased from 5.7% to 1.3% and VFWA increased from 68.0% to 93.0%. Marshall stability reached its highest value at 6.0% asphalt content and then decreased with further asphalt addition.

These results indicate the typical balance between mixture stiffness, void structure, and binder content. At low asphalt contents, the mixtures tended to have higher air voids and insufficient binder coating, which may reduce cohesion and durability. As the asphalt content increased, the mixtures became denser and the internal void structure was progressively filled, improving the compactness of the mixture. However, excessive asphalt contents tended to reduce mixture stability and increase flow, indicating that too much binder may reduce aggregate interlock and make the mixture more susceptible to deformation. This behaviour is consistent with the general understanding of Marshall mix design, where the optimum binder content is obtained by balancing volumetric requirements and mechanical performance.

Based on the narrow-range method and the compliance of the Marshall parameters with the specification requirements, the OAC values obtained in this study were 6.68% for the AC-WC mixture using PG 76 and 5.75% for the AC-BC mixture using Pen 60/70, as presented in Table 6. The corresponding mixture densities were 2.363 gr/cm³ for AC-WC and 2.360 gr/cm³ for AC-BC. These OAC values were then used to prepare the composite specimens for the interlayer shear test.

Table 6. Determination of OAC values

No.	Layer Type	Optimum Asphalt Content	Density
1	AC-WC PG 76 mixture	6.68 %	2.363 gr/cm ³
2	AC-BC Pen 60/70 mixture	5.75 %	2.360 gr/cm ³

4.2. Interlayer Shear Testing at OAC

After the OAC values had been determined, composite AC-WC/AC-BC specimens were prepared for direct shear testing using CRS-1P and CRS-1 tack coats. Based on the specimen interface area of 0.008103 m² and the tack coat bulk density of 1.015 gr/cm³, the required tack coat amounts for the target application rates of 0.25, 0.35, and 0.45 L/m² were 2.06 g, 2.88 g, and 3.70 g per specimen, respectively, as shown in Table 7.

Table 7. Spread of tack coat

No.	Target Spread	Area of Test Item	Distribution needs		Bulk density of tack coat	Use of tack coats
			liters	gram		
	liters/m ²	m ²	(3) = (1)x(2)	(4) = (3)x1000	gr/cm ³	gram
	(1)	(2)	(3)	(4)	(5)	(6) = (4)x(5)
1	0.25	0.008103	0.00203	2.03	1.015	2.06
2	0.35	0.008103	0.00284	2.84	1.015	2.88
3	0.45	0.008103	0.00365	3.65	1.015	3.70

The average shear strength and displacement results for all test conditions are presented in Table 8. In general, both CRS-1P and CRS-1 exhibited a similar response pattern. For all application rates, the interlayer shear strength increased with curing time from 15 min to 45 min and then decreased at 60 min and 75 min. This indicates that the curing process enhanced the bond development up to an optimum point, after which prolonged curing no longer improved the interlayer bond and instead led to a reduction in shear resistance.

Table 8. Recapitulation of shear test results

Spread of Tack Coat	Curing Times	Shear Strength CRS-1P	Shear Strength CRS-1	Displacement CRS-1P	Displacement CRS-1
liters/m ²	minutes	Mpa	Mpa	mm	mm
0.25	15	1.36	1.17	2.40	2.21

	30	1.42	1.31	2.48	2.38
	45	1.54	1.37	2.50	2.49
	60	1.46	1.25	2.39	2.42
	75	1.42	1.23	2.28	2.30
	15	1.37	1.22	2.18	2.31
	30	1.47	1.32	2.22	2.42
0.35	45	1.61	1.39	2.67	2.56
	60	1.56	1.37	2.30	2.39
	75	1.46	1.28	2.22	2.33
	15	1.31	1.18	2.18	2.41
	30	1.38	1.28	2.24	2.48
0.45	45	1.48	1.31	2.33	3.27
	60	1.44	1.14	2.31	2.18
	75	1.40	1.09	2.10	1.80

From the shear strength test data obtained, the variation of curing time and the distribution of the most optimum tack coat to be used as a binder adhesive layer on the pavement at a curing time of 45 minutes and a dose of 0.35 liters / m² because at the maximum value, the pavement conditions have occurred large deformations and comparisons between 2 tack coats in Figure 1 and Figure 2 as follows:

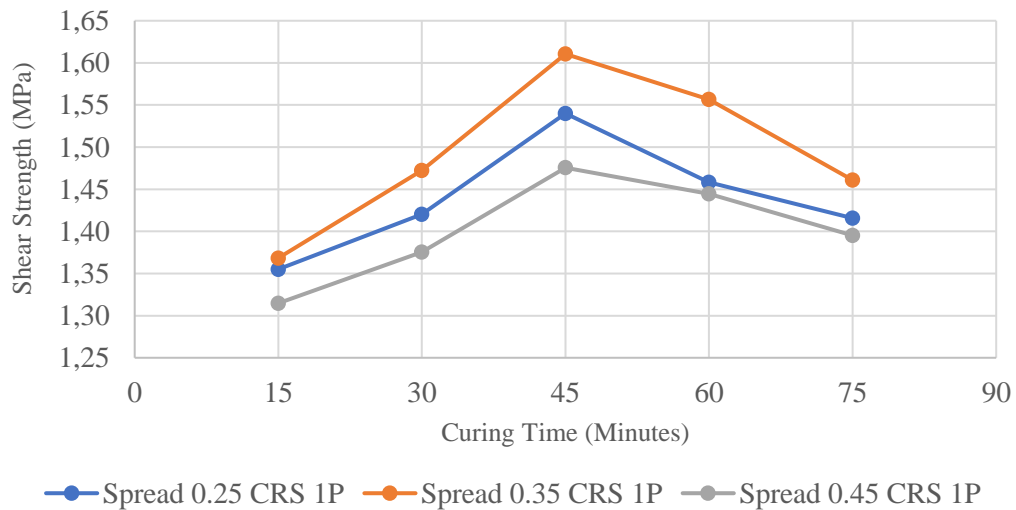


Figure 1. CRS-1P tack coat shear strength test results

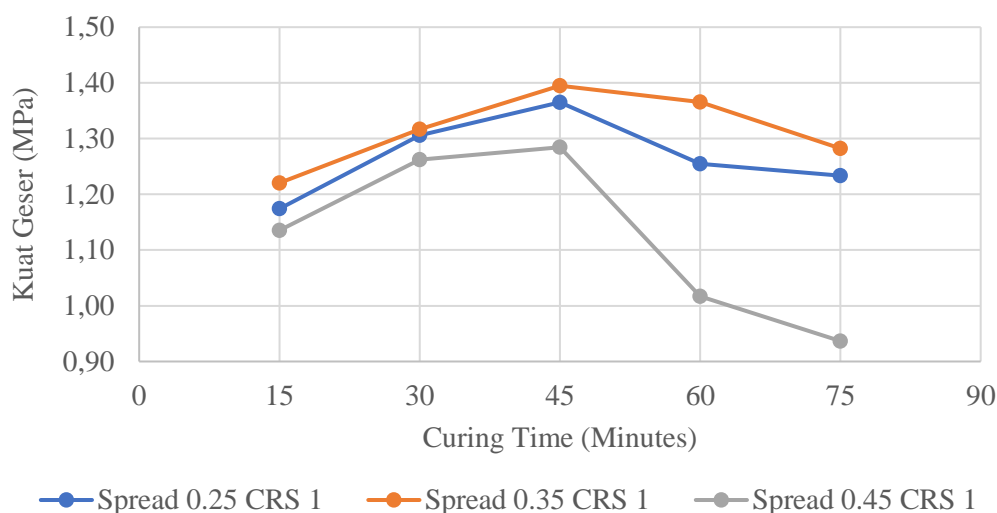


Figure 2. CRS-1 tack coat shear strength test results

Based on Figure 1 and Figure 2, the following can be explained:

At the application rate of 0.25 L/m², the maximum shear strengths were 1.54 MPa for CRS-1P and 1.37 MPa for CRS-1, both occurring at a curing time of 45 min. At 0.35 L/m², the maximum values increased to 1.61 MPa for CRS-1P and 1.39 MPa for CRS-1, again at 45 min. At 0.45 L/m², the maximum values decreased to 1.48 MPa for CRS-1P and 1.31 MPa for CRS-1. These results show that the optimum application rate for both tack coat types was 0.35 L/m² and that increasing the application rate beyond this level reduced the interlayer shear strength.

The existence of an optimum application rate can be explained by the role of tack coat as an adhesive interlayer. At insufficient application rates, the tack coat may not fully cover the interface and therefore cannot provide adequate bonding between the AC-WC and AC-BC layers. As the application rate increases to an appropriate level, the tack coat improves adhesion and interlayer shear transfer. However, when the application rate becomes excessive, the residual asphalt may form a lubricating film at the interface, reducing aggregate interlock and creating a slip-prone plane. This trend is clearly observed in the present results, where the 0.45 L/m² condition produced lower shear strengths than the 0.35 L/m² condition for both CRS-1P and CRS-1.

A similar explanation applies to the curing-time effect. A short curing time may not be sufficient for the emulsion to break properly and for the water phase to evaporate, resulting in a weaker adhesive bond. As curing progresses, the tack coat develops better adhesion and stronger interface bonding. Nevertheless, after the optimum curing time is exceeded, the bond strength decreases. In this study, the optimum curing time for both tack coat types was 45 min. This trend confirms that curing time is a critical variable in interlayer performance and that the bond strength does not increase indefinitely with longer curing periods.

The comparison between CRS-1P and CRS-1 indicates that CRS-1P consistently produced higher shear strength values under almost all test conditions. The highest value observed in this study was 1.61 MPa for CRS-1P at 0.35 L/m² and 45 min, whereas the highest value for CRS-1 was 1.39 MPa under the same conditions. This result suggests that the polymer-modified emulsion provided a stronger and more stable bond than the conventional emulsion. The superior performance of CRS-1P is likely related to the improved adhesive and cohesive characteristics of polymer-modified binders, which generally provide better film formation, greater resistance to shear deformation, and stronger interfacial bonding.

The displacement results also support the interlayer shear-strength findings. The relatively higher displacement values observed near the peak shear-strength condition indicate that the interface was capable of sustaining larger deformation before failure. For example, at the optimum condition of 0.35 L/m² and 45 min, the displacement values were 2.67 mm for CRS-1P and 2.56 mm for CRS-1. This suggests that the optimum condition not only maximized shear resistance but also allowed the interface to accommodate deformation in a stable manner prior to failure.

Overall, the direct shear test results indicate that the optimum tack coat condition in this study was an application rate of 0.35 L/m² and a curing time of 45 min. Under this condition, CRS-1P showed better interlayer bonding performance than CRS-1. The observed trend of increasing and then decreasing shear strength with increasing curing time and tack coat dosage is also consistent with the interlayer bonding mechanism discussed in previous studies, in which insufficient tack coat leads to poor adhesion, whereas excessive tack coat may introduce a lubrication effect at the interface.

4.3. BISAR 3.0 Analysis and Comparison with Experimental Results

The mechanistic analysis was conducted using BISAR 3.0 to evaluate the shear-stress and displacement response of the multilayer pavement structure under standard and overload traffic conditions. The results are presented in Table 2 and Table 3. Under the standard loading condition of 80 kN, the highest shear stress occurred at a depth of 0.05 m, with values of 0.2753 MPa for the full-bonding condition and 0.3687 MPa for the full-slip condition. Under the overload condition of 100 kN, the corresponding values increased to 0.4638 MPa for full bonding and 0.5609 MPa for full slip at the same depth.

These results indicate two important points. First, the highest interlayer shear stress occurred near the upper interface region, showing that the most critical response was concentrated close to the AC-WC/AC-BC system. Second, the full-slip condition always produced a higher shear stress than the full-bonding condition, particularly under overload traffic. This finding is consistent with previous studies showing that inadequate interlayer bonding increases the shear demand and accelerates pavement distress. This confirms that poor interlayer bonding can significantly increase the shear demand within the pavement structure, thereby increasing the risk of interlayer distress and premature failure.

In this study, the maximum shear stress obtained from BISAR 3.0 under overload and full-slip conditions, namely 0.5609 MPa, was adopted as the minimum allowable interlayer shear strength. This value was then compared with the laboratory direct shear results. The comparison shows that all experimentally obtained shear strengths were higher than the mechanistically derived minimum allowable value. Even the lower measured values still exceeded the BISAR-based threshold, while the optimum laboratory conditions produced much larger safety margins. In particular, the optimum condition of CRS-1P at 0.35 L/m² and 45 min produced a shear strength of 1.61 MPa, and CRS-1 under the same condition produced 1.39 MPa, both of which were substantially higher than 0.5609 MPa.

This comparison demonstrates that the laboratory-derived optimum tack coat condition is not only the condition that maximized interlayer shear strength, but also the condition that clearly satisfied the minimum mechanistic demand predicted by BISAR 3.0. Therefore, the integration of experimental testing and mechanistic modelling provides a more robust basis for selecting tack coat application parameters. The laboratory tests identify the relative performance and optimum condition among the evaluated variables, while the BISAR 3.0 analysis confirms that the selected condition is structurally adequate when compared with the estimated pavement shear demand.

From a practical perspective, the combined results indicate that a tack coat application rate of 0.35 L/m² and a curing time of 45 min are recommended for the AC-WC/AC-BC system investigated in this study, with CRS-1P providing the best overall performance. This recommendation is particularly important for pavement construction and rehabilitation works, where inadequate interlayer bonding may reduce pavement service life, while excessive tack coat use may be uneconomical and potentially detrimental to performance.

5. CONCLUSION

This study showed that tack coat type, application rate, and curing time affected the interlayer shear strength between AC-WC and AC-BC mixtures. Based on the Marshall mix design, the Optimum Asphalt Content (OAC) was 6.68% for AC-WC using PG 76 and 5.75% for AC-BC using Pen 60/70.

The direct shear test results indicated that the optimum tack coat condition for both emulsions was an application rate of 0.35 L/m² with a curing time of 45 min. Under this condition, CRS-1P produced the highest shear strength of 1.61 MPa, while CRS-1 produced 1.39 MPa. This shows that CRS-1P provided better interlayer bonding performance than CRS-1.

The BISAR 3.0 analysis showed that the maximum shear stress under the critical loading condition was 0.5609 MPa. All laboratory shear-strength values were higher than this minimum requirement, indicating that the tested tack coat conditions were structurally adequate. Overall, the results confirm that proper control of tack coat dosage and curing time is essential for achieving effective interlayer bonding in asphalt pavements.

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