The Bond Between the Bituminous Paving Layers: Lab Scale Assessment.

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Abstract

A bituminous surface is a multi-layered structure consisting of surfacing, base, and subbase courses on a subgrade. An interface is defined as a boundary between any two consecutive layers. As a result, adequate bonding between the layers at the interfaces is required to ensure that multiple layers function as a single composite structure. In the case of non-bituminous or bituminous-non-bituminous layers, an adequate bond is formed because of the mechanical interlocking of the aggregate surfaces. However, the state of the bond at the interface of any two bituminous layers has a significant impact on the stress distribution across pavement layers under traffic loads, as well as the pavement's overall performance. Bituminous tack coats are applied before overlay to improve adhesion or bonding between the two bituminous layers. This study assesses the interface bond strength of two types of bituminous layer mixtures in the laboratory. The cylindrical specimens were tested for bond strength at four normal service temperatures, 250, 300, 350, and 400C, using different types of tack coats at varying application rates. The specimens were prepared according to the normal Marshall Procedure, first for the underlying layer, then for the tack coat, and finally for the top layer in the same mould. Two types of layer combinations have been tried, namely (i) Bituminous Concrete (BC) layer on Dense Bituminous Macadam (DBM) samples and (ii) Semi Dense Bituminous Concrete (SDBC) layer on Bituminous Macadam (BM) samples. Similarly, different types of tack coat materials namely bitumen, Cationic Rapid Setting with low viscosity (CRS-1) and Cationic Medium Setting with high viscosity (CMS-2) emulsions have been used for the interface bond between the said bituminous layers. The prepared samples were tested using a bond strength device attached to the loading frame of the Modified Marshall Testing Apparatus. The interlayer bond strength is observed to be temperature-dependent, and it decreases as the test temperature increases. It has also been observed that the bond strength is affected by the type of tack coat used and the conditions of the type of combination. The optimal amount of tack coat varies depending on the type of tack coat used and the layer combination.

Keywords*: Interlayer Bond strength, Tack coat, Bituminous layer combination, Bond strength device.*

Introduction

Highways are the foundation of a country's progress and development. All developed and developing countries typically have an ongoing strategy of maintaining and building road infrastructure or improving existing roads. To improve the existing road infrastructure in response to increased traffic, reinforce the existing pavement layer by combining it with another layer of the appropriate material composition and thickness. Flexible pavements are typically designed and built-in multiple layers to ensure effective stress distribution across the layers under varying heavy traffic loads. The viscous nature of the flexible pavement allows its various layers to withstand significant plastic deformation, despite distresses caused by repeated heavy loading over time, which is the most common failure mode. The flexible pavement functions as a single structure due to good bonding between the different layers interfacing. The adhesion conditions at the layer interface are thought to have a significant impact on the pavement stress distribution. Poor adhesion at the layer interface can reduce the structural strength of the pavement system and lead to premature failures. Bituminous tack coats are applied before overlay to improve layer bonding. Bituminous emulsions are typically used as tack coats. Despite their widespread use, pavement engineers disagree about the effectiveness of tack coats in improving adhesion between the two layers. This tack coat is also made of a thin layer of bitumen residue, and its purpose is to provide adequate adherence between the layers. If the quantity of bituminous emulsions used is greater or less than the required one, the interface bonding will not be satisfactory.

1.1 Failures arise due to inadequate bonds.

Several premature pavement failures have been caused by a loss of bond between two layers of hot mix asphalt (HMA). Poor adhesion between pavement layers has been widely observed to contribute to significant pavement overlay distresses and many premature failures. Slippage failure and layer delamination. Slippage failure worsens as the pavement layers slide against one another, and the top layer typically separates from the lower layer. This type of failure occurs because of a lack of bond between two top important pavement layers, and it is most visible at high horizontal force at points where traffic is accelerating or decelerating, such as traffic signals and horizontal curves. Delamination is a section of a surface layer that has separated from the pavement. This type of failure is caused by layer slippage and weak interlayer bonds between pavement layers. Other pavement problems have been linked to reduced bond strength between pavement layers in the shape of a crescent. The word "tack" refers to a type of stickiness. The coat is a thin layer. A tack coat is a light application of a bituminous emulsion between pavement layers, typically applied in a thin layer between an existing and newly constructed bituminous surface.

The purpose of glue or sticky materials, such as tack coats, is to provide appropriate adhesive interlock between paving layers so that they react as a monolith. The emulsifying agent could be soap, dust, or colloidal clays. The emulsifying agent keeps bituminous particles suspended in water, reducing the bitumen consistency at ambient temperature from semi-solid to liquid. As a result, at normal temperatures, liquefied bitumen is easier to spread over a surface. When this liquid bitumen is applied to a clean bitumen surface, the water evaporates from the emulsion, leaving a thin layer of bituminous residue on the pavement.

Usually, hot bituminous binder, cutback bitumen or bituminous emulsions are used as tack coat materials for construction purposes. The use of bituminous emulsions as a tack coat material is escalating instead of cutting back asphalt or hot bituminous binder. It can be applied at lower application temperatures compared to cutback bitumen or hot bituminous binder, so it is easy to handle in field conditions. Emulsified bitumen does not contain any harmful volatile chemicals, comparatively pollution-free and environmentally friendly.

Review of Literature

Bituminous pavements are typically built in multiple layers, and proper bonding between adjacent layers is required for optimal performance. However, this is not always the case, and poor bonding conditions have resulted in numerous premature pavement failures. The failure of interface bonds in paving layers is primarily caused by shear forces. Interlayer shear performance has recently received significant attention. These studies have typically resulted in the development of a novel test method or instrument for determining interface bond strength. Various organizations and researchers have used a variety of test methods to evaluate pavement interlayer bond strength performance.

Uzan et al. (1978) used a direct shear test device to evaluate a 60-70 penetration asphalt binder as a tack coat at five application rates. The tests were carried out at two different temperatures: 77-131^0 F (25 and 55^0 degrees Celsius). The tack coat was applied to the bottom layer, and 3cm (1.8in) of mix was compacted on top. The direct shear device was designed with the specimen size in mind, and the displacement rate was kept constant at 2.5 mm/min (0.098 in/min). The shear strength was measured at five different normal loading pressures: 0.05, 0.5, 1.0, 2.5, and 5 Kg/cm2. When the test temperature drops and normal pressure rises, the shear strength increases. The observed optimum tack coat application rate for this study was 1.0 Kg/m2 at 25°C.

Molenaar et al. (1986) at Delft University of Technology used a shear test device to assess the shear resistance of the tack coat at the asphalt layer interface. The device was mounted on a standard Marshall Stability loading press, which applied a load at a rate of 0.85 mm/second. This device held the bottom part of the compacted cylindrical specimens while applying shear load perpendicular to the top layer's specimen axis.

In Canada, Mrawira and Damude (1999) used a direct shear test to determine the interface bond strength. The specimens were obtained as field cores from active pavements. Cores were assembled in six subsets based on pavement age. The mix and materials used in all specimens were identical. The cores were trimmed to a height of 8cm (3.15 inch), and 0.2 to 0.3 L/m2 of SS1 emulsion was applied to the top surface of the layer, with set times of less than one hour. After the tack coat has cured, a 16mm nominal maximum aggregate size is compacted on the core in two lifts using 75 Marshall blows per lift as an overlay. The specimens were allowed to cure for two weeks at room temperature before being cut into rectangular shapes and placed in a water bath at 22^{0}C (75^{0}F) for thirty minutes. The specimens were sheared using a guillotine-style machine with a constant displacement rate of 1 mm/min.

Mohammad et al. (2002) evaluated the bond strength of the tack coat used in the interface of the bituminous paving layers by using the Superpave shear tester shown in Figure 2.2, which consists of a shear box set up for 150 mm (6 inches) diameter specimens. The specimens were compacted up to 50 mm and a tack coat was applied at five different application rates (0.0 to 0.9 L/m^2),the samples were allowed to cure, and a second lift was placed on top and compacted. The tack coat bond strength was evaluated with two PG asphalt binders (PG 64-2P and PG 76-22M) and four emulsified asphalts (CRS-2P, CSS-1, SS-1 and SS-1h). The test was conducted on two test temperatures 25 and 55^{0}C (77 and 131^{0}F). They observed CRS-2P emulsion as the best performer and 25^{0}C (77^{0}F) test temperature gives five times more shear strength than 55^{0}C (131^{0}C).

Sangiorgi et al. (2002) modified the Leuter shear strength test device in Germany to evaluate interlayer bond strength using a simple direct shear test method. The device was mounted on the Marshall and CBR loading presses. The specimens were used for a test with a diameter of 150 mm, which could be field cores or laboratory fabricated. The load was transferred to the specimen at a constant displacement rate of 50 mm/min while keeping the temperature at 200°C. To reduce friction, the shearing planes were separated by a 4.8mm gap. This testing device is standard in Austria and has been adopted in the United Kingdom. To simulate actual conditions, three different interface treatments were considered: (i) with tack coat emulsion, (ii) contaminated with dirt but without tack coat emulsion, and (iii) with tack coat emulsion and a thin film of dirt. The results revealed that the best interface bond strength was achieved with an interface treatment prepared with an emulsified tack coat, whereas the poorest bond conditions were observed on a dirty surface without emulsion.

Sholar et al. (2002) developed a simple direct shear test device to measure the shear strength of field cores at their interface. The test was performed at 25^{o}C (77oF), with a constant rate of loading of 50.8 mm/min (2in/min). The field cores were obtained from test sections with no tack, and with 0.091, 0.266 and 0.362 l/m^2 (0.02, 0.06, 0.08gal/yd2) tack coat application rate.

Several organizations and researchers described in the preceding paragraphs developed and studied various devices using various testing methodologies to assess the bond strengths of the bituminous pavement interlayer. Tack coats should be applied in an optimal quantity in a thin layer to cover the entire surface of the application area. Too little tack coat is equivalent to no tack coat and does not provide a strong interface bond. On the other hand, too much tack coat can cause slippage failure. The application rate must be determined by the texture of the surface that will receive the tack coat.

Methodology

The study's experimental methodology involved determining the maximum interlayer bond strength of two different bituminous layer combinations (DBM/BC and BM/SDBC). In this experiment, the specimens were subjected to direct shear force at a constant displacement rate of 50.8 mm/min until they failed. A customized simple device referred to as the modified Marshall test apparatus was fabricated for the testing of the double-layer composite bituminous samples to evaluate the interlayer bond strength. The methodology adopted for this project is shown in Figure 3.1.

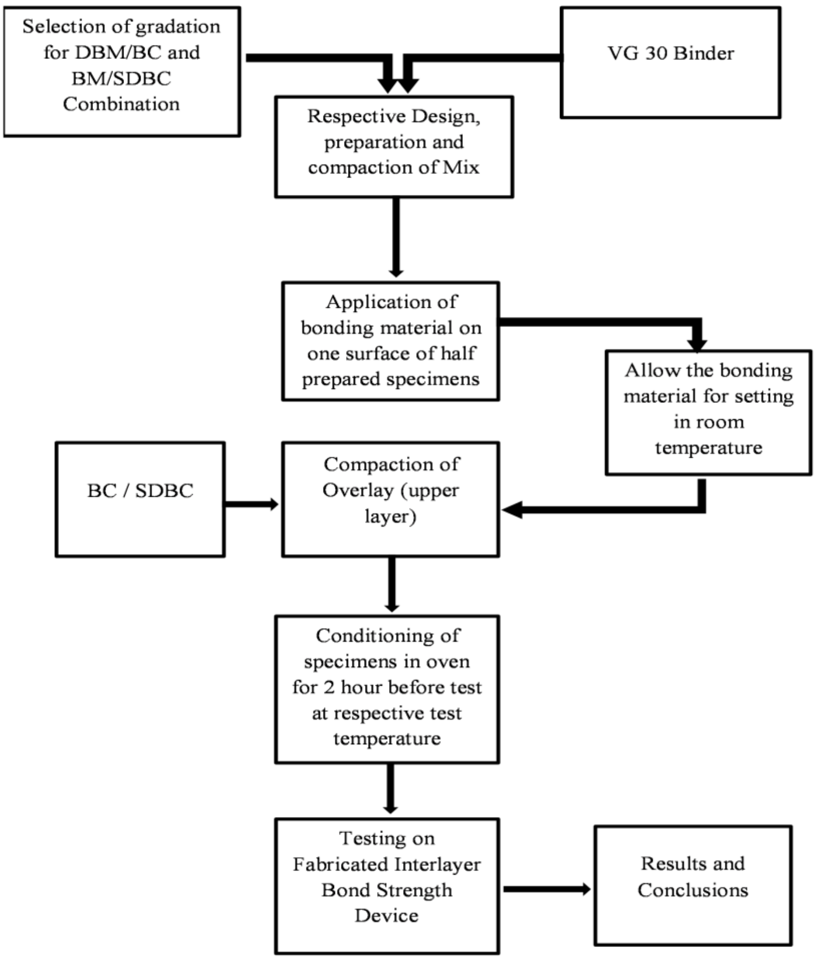

Figure 3.1 Methodology of the experimental work

1.2 Materials Used

1.2.1 Aggregates

This laboratory case study includes two types of bituminous layers on cylindrical specimens. One has been created using a composite of a lower layer of dense bituminous macadam (DBM) and an upper layer of bituminous concrete. Another type has been created using bituminous macadam (BM) as the base course (lower layer) and semi-dense bituminous concrete (SDBC) as the overlay. Two bituminous-composed layers were prepared using aggregates graded according to the Ministry of Road Transport and Highways (2001), as shown in Tables 3.1, 3.2, 3.3, and 3.4, respectively. DBM and BM mixes, which use relatively larger aggregates, are not only stiff or stable but also cost-effective because they use less bitumen and require less breaking and crushing energy or effort. BC and SDBC mix with smaller aggregates with higher bitumen content, which adds flexibility and increases durability. The aggregates must be clean, hard, durable, cubical in shape, and free of dust, friable matter, organic or other harmful material. The coarse aggregates are crushed gravel hard material that must be retained on a 4.75 mm sieve, while the fine aggregates must pass through a 4.75 mm sieve and be retained on a 75-micron sieve. MORT&H recommended a 25 mm nominal maximum aggregate size (NMAS) for the DBM Base Course and 13 mm NMAS for the BC Binder Course. It also recommended 19 mm NMAS for the BM base course and 13 mm NMAS for the SDBC course. The specific gravity of aggregates used for preparing the specimens in the laboratory is 2.80. The physical properties of the aggregates found in the laboratory are given in below table 3.5.

1.2.2 Filler

Portland slag cement (Grade 43) collected from the local market passing 0.075 mm IS sieve was used as filler material to increase the binding property between the aggregates in the preparation of specimens. Its specific gravity has been found in laboratory 3.0.

Table 3.1 MORTH gradation for DBM (NMAS 25mm)

BIS Sieve (mm)	Percent Passing	
	Specification Grading	Grading adopted
37.5	100	-
26.5	90-100	95
19.0	71-95	83
13.2	56-80	68
4.75	38-54	46
2.36	28-42	35
0.300	7-21	14
0.075	2-8	4
Binder Content % by weight	Min. 4.5	5

Table 3.2 MORTH gradation for BC (NMAS 13 mm)

BIS Sieve (mm)	Percent Passing	
	Specification Grading	Grading adopted
19.0	100	-
13.2	79-100	89.5
9.5	70-88	79
4.75	53-71	62
2.36	42-58	50
1.18	34-48	41
0.600	26-38	32
0.300	18-28	23
0.150	12-20	16
0.075	4-10	7
Binder Content % by weight	5-7	7

Table: 3.3 MORTH gradations for BM (NMAS 19 mm)

BIS Sieve (mm)	Percent Passing	
	Specification Grading	Grading adopted
26.5	100	-
19.0	90-100	95
13.2	56-88	72
4.75	16-36	26
2.36	4-19	11.5
0.300	2-10	6
0.075	0-8	4
Binder Content % by weight	3.3-3.5	3.5

Table: 3.4 MORTH gradations for SDBC (NMAS 13 mm)

BIS Sieve (mm)	Percent Passing	
	Specification Grading	Grading adopted
19.0	100	-
13.2	90-100	95
9.5	70-90	80
4.75	35-51	43
2.36	24-39	31.5
1.18	15-30	22.5
0.300	9-19	14
0.075	3-8	5.5
Binder Content % by weight	Min. 4.5	5

Table 3.5 Physical properties of aggregates

Property	Test Method	Test Result
Aggregate Impact Value (%)	IS: 2386 (Part-IV)	14.28
Aggregate Crushing Value (%)	IS: 2386 (Part-IV)	13.02
Los Angeles Abrasion Value (%)	IS: 2386 (Part-IV)	18
Flakiness Index (%)	IS: 2386 (Part-I)	18.83
Elongation Index (%)		21.50
Specific Gravity	IS: 2386 (Part-III)	2.75
Water Absorption (%)	IS: 2386 (Part-III)	0.13

1.2.3 Binder

VG 30 bitumen from a local source was used as a binder to prepare the specimens for this study. Some common tests were run to determine the important physical properties of these binders. Table 3.6 summarizes the physical properties obtained. (Sutradhar, B. B. 2012).

1.2.4 Tack Coat

The tack coat materials selected for this study include two emulsions CMS-2 and CRS-1. Standardized tests were conducted to determine their physical properties as summarized in Table 3.7 (Sutradhar, B. B. 2012).

Table 3.6: Physical properties of VG 30 bitumen binder

Property	Test Method	Test Result
Penetration at 25°C	IS: 1203-1978	67.7
Softening Point (R&B), °C	IS: 1205-1978	48.5
Viscosity (Brookfield) At 160°C, CP	ASTM D 4402	200

Table 3.7 Physical Properties of Tack Coats

Property	Test Method	Emulsion Type	Test Results
Viscosity by Saybolt Furol Viscometer, seconds: At 50^0 C	ASTM D 6934	CRS-1	37
		CMS-2	114
Density in g/cm^3	As per Chehab. et al. (2008)	CRS-1	0.986
		CMS-2	0.986
Residue by evaporation, %	ASTM D 244	CRS-1	61.33
		CMS-2	67.59
Residue Penetration 25^0 C/100 g/5 sec	IS: 1203-1978	CRS-1	86.7
		CMS-2	106.7
Residue Ductility 27^0 C cm	IS: 1208-1978	CRS-1	100+
		CMS-2	79

1.3 Preparation of Samples

The specimens were prepared to evaluate the interlayer bond strength between the bituminous paving layers either made in the laboratories or collected from the field as a core. The laboratory-prepared samples were mixed according to the Marshall procedure specified in ASTM D1559, with MORT&H grading of course and fine aggregate for both types of composite specimens. The specimens for bond strength testing have a 101 mm diameter and a total height of 100 mm, and they are prepared using a specially designed mould. These samples were compacted into two layers: DBM and BM with a base course of 60mm and top layers of BC and SDBC with heights of 40mm, respectively. In between these two layers, a tack coat is applied. To increase the binding property, the base and surface courses were mixed with VG-30 binder and 0.075mm passing cement as filler.

The specimens were made up of two layers, with a tack coat applied in between. The study was also conducted with bitumen as the tack coat material and without a tack coat between the two bituminous layers. Graded aggregates were sampled and baked in an oven at 1600 degrees Celsius for at least two hours before being combined with a binder to create a design mix. The lower half of the specimen, known as the base course, was prepared by compacting the design mix to the required height of 60mm giving 75 blows with a Marshall Hammer. Once the lower layer had been compacted with the same number of blows on both sides, it was allowed to cool at room temperature for a few days. A layer of sticky material (tack coat and bitumen) was then applied to one of the previously compacted specimens' surfaces. The number of emulsions was determined by multiplying the application rates by the surface area of the specimen. The rate of tack coat application was determined according to MORT&H (2001), as shown in Table 3.8.

Table 3.8 Rate of application of Tack Coat as per MORT&H Specification

Type of Surface	Quantity in Kg/m^2 area
Normal bituminous surface	0.20 to 0.25
Dry and hungry bituminous surface	0.25 to 0.30
Granular surface treated with primer	0.25 to 0.30
Non bituminous surface	-
Granular base (not primed)	0.35 to 0.40
Cement Concrete pavement	0.30 to 0.35

After being tacked, the specimens were allowed to be cured in a dust-free environment until the setting/breaking process was complete. Visual observation is commonly used to estimate an emulsion's minimum setting period. Normally, the tack coat was brown, but when the water evaporated, its colours turned deep black. The process is known as emulsion setting. After the emulsions had set, a thin layer of bitumen residue acted as a glue between the two layers, resulting in a strong bond. The study used two types of emulsions: CRS-1 and CMS-2. CMS stands for cationic medium setting emulsion, while CRS denotes cationic rapid setting. Normally, rapid-setting emulsions are set in less than half an hour. When bitumen is used as a sticky material in place of a tack coat, application rates are considered as per MORTH specification and the setting of it normally varies from half an hour to one-hour maximum for creating a better bonding between two layers.

Once the tack coat had been applied and cured on one surface of the lower layer of specimens, the top layer's loose design mix was applied over it. The total required height for the samples was achieved by compacting the loose mix using a Marshall Hammer with 100 blows. All prepared specimens were left to cure at room temperature for a few days before testing. The specimens were prepared without a tack coat, and the top layer was compacted as soon as the lower layer had been compacted. To observe the variation in bond strength without using a tack coat, a time gap between the compaction of two layers can be maintained.

After a few days of curing at room temperature, the specimens are fully prepared for testing. Before testing, these specimens were cured in an oven at various temperatures (250, 300, 350, and 400C) for two hours. The specimens were tested using a fabricated bond strength attachment mounted on a modified Marshall test apparatus.

1.4 Fabrication of simple attachment to measure the Interlayer Bond Strength

In the study, laboratory-prepared specimens were tested using a fabricated attachment attached to a modified Marshall apparatus. This device was modelled after the shearing apparatus at McAsphalt Lab (Kucharek et al., 2011). The device was intended for 101 mm diameter field cores or laboratory-prepared samples. The device had two parts for holding the specimens, upper and lower. One was a U-shape that allowed the upper part (40 mm) to move freely with minimal friction, along with two guiding rods fixed to the top of the base plate and another clamping the lower half of the specimen. Figure 3.2 shows the schematic diagrams of the fabricated Interlayer Bond Strength device, while Figure 3.3 shows photographic views. The vertical load was transferred to the U-shaped plate to shear the specimens at a constant rate of 50.8 mm/min (2 in/min).

Laboratory Test Results

The results of various tests performed to assess interlayer bond strength in various combinations are shown below.

1.5 Interlayer Bond Strength for Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC) Combination

1.5.1 Variation of ILBS with application rate for CRS-1 type tack coat at various setting times.

The following paragraphs present the bond strength test results for CRS-I type tack coat cured at various setting times.

Table 4.1 shows the average interlayer bond strength when the setting time is 0.5 hours. At all test temperatures, the CRS-1 type of tack coat exhibits the highest bond strength values when applied at a rate of 0.25 Kg/m2.

Table 4.1 ILBS of CRS-1 type tack coat (Considering 0.5 hour setting time)

Type of Tack Coat	Application rate (Kg/m^2)	Average ILBS at different test temperatures (kPa)			
		25^{0}C	30^{0}C	35^{0}C	40^{0}C
CRS-1	0.2	691.40	530.10	411.25	286.95
	0.25	716.85	635.30	460.50	323.80
	0.3	609.90	511.40	332.30	249.50

The maximum interlayer bond strength was found at a 0.25 Kg/m2 application rate in all test temperatures with a setting time of 0.5 hours, and the bond strength decreased as the test temperature and application rate increased.

Table 4.2 shows the average interlayer bond strength when the setting time is one hour. At all test temperatures, the CRS-1 type of tack coat exhibits the highest bond strength values when applied at a rate of 0.25 Kg/m2.

Table 4.2 ILBS of CRS-1 type tack coat (Considering 1 hour setting time)

Type of Tack Coat	Applicationrate (Kg/m^2)	Average ILBS at different test temperatures (kPa)			
		25⁰C	30⁰C	35⁰C	40⁰C
CRS-1	0.2	874.75	556.45	443.50	311.95
	0.25	892.90	773.30	543.30	344.25
	0.3	805.14	548.75	378.20	293.30

Table 4.2 shows that the highest interlayer bond strength was achieved at a 0.25 Kg/m2 application rate at all test temperatures, with a setting time of 1 hour. Bond strength decreased with higher test temperatures and application rates.

Table 4.3 displays the average interlayer bond strength when the setting time is 1.5 hours. The CRS-1 type of tack coat has the highest bond strength values when applied at a rate of 0.25 Kg/m2 at all test temperatures.

Table 4.3 ILBS of CRS-1 type tack coat (Considering 1.5 hour setting time)

Type of Tack Coat	Applicationrate (Kg/m^2)	Average ILBS at different test temperatures (kPa)			
		25⁰C	30⁰C	35⁰C	40⁰C
CRS-1	0.2	760.98	535.66	423.90	293.20
	0.25	842.90	662.95	499.50	337.40
	0.3	748.65	522.80	361.64	287.36

Table 4.3 shows that the maximum interlayer bond strength was found at a 0.25 Kg/m2 application rate in all test temperatures when the setting time was 1.5 hours, and that bond strength decreased as the test temperature and application rate increased.

Tables 4.4 to 4.7 show that at all test temperatures, the maximum interlayer bond strength was found at a 0.25 Kg/m2 application rate when the setting time for rapid setting emulsions (CRS-1) was 1 hour rather than 0.5 or 1.5. The highest bond strength was achieved at 250C, and the strength decreased as the test temperature increased.

1.5.2 Variation of ILBS with application rate for CMS-2 type tack coat at various setting times.

Table 4.4 presents the average interlayer bond strength when the setting time is 6 hours. The highest bond strength values are observed at an application rate of 0.15 Kg/m^2 at all test temperatures for the CMS-2 type of tack coat.

Table 4.4 ILBS of CMS-2 type tack coat (Considering 6-hour setting time)

Type of Tack Coat	Applicationrate (Kg/m^2)	Average ILBS at different test temperatures (kPa)			
		25⁰C	30⁰C	35⁰C	40⁰C
CMS-2	0.1	962.50	691.47	479.55	318.11
	0.15	1013.56	704.14	535.30	342.98
	0.2	918.40	697.75	497.85	311.80
	0.25	887.50	672.40	423.58	255.90
	0.3	729.30	616.70	392.60	230.85

From Table 4.8 it is observed that in 6 hours of setting time of the CMS-2 type tack coat, the maximum interlayer bond strength was found with an application rate of 0.15 Kg/m^2 and it decreased when test temperature and application rate increased.

Table 4.5 presents the average interlayer bond strength when the setting time is 9 hours. The highest bond strength values are observed at an application rate of 0.15 Kg/m² at all test temperatures for the CMS-2 type of tack coat.

Table 4.5 ILBS of CMS-2 type tack coat (Considering 9-hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
CMS-2	0.1	1000.77	949.88	635.48	423.22
	0.15	1045.70	968.98	659.98	441.88
	0.2	975.30	874.40	578.49	386.67
	0.25	924.40	811.20	516.90	330.75
	0.3	812.30	767.48	498.37	317.98

According to Table 4.5, the maximum interlayer bond strength was found with an application rate of 0.15 Kg/m2 in a 9-hour setting time of CMS-2 type tack coat, and it decreased as the test temperature and application rate increased.

Table 4.6 shows the average interlayer bond strength when the setting time is 6 hours. At all test temperatures, the CMS-2 type of tack coat achieves the highest bond strength value when applied at a rate of 0.15 Kg/m2.

Table 4.6 ILBS of CMS-2 type tack coat (Considering 12-hour setting time)

Type of Tack Coat	Applicationrate (Kg/m²)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
CMS-2	0.1	760.70	566.36	348.69	293.48
	0.15	798.50	584.86	373.7	318.27
	0.2	754.66	534.27	356.73	293.37
	0.25	729.16	496.67	332.77	224.47
	0.3	628.58	474.27	274.79	212.22

1.5.3 Variation of ILBS with the rate of application for CMS-2 type tack coat at various setting times

Table 4.4 presents the average interlayer bond strength when the setting time is 6 hours. The highest bond strength values are observed at an application rate of 0.15 Kg/m² at all test temperatures for the CMS-2 type of tack coat.

Table 4.7 ILBS of CMS-2 type tack coat (Considering 6-hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
CMS-2	0.1	962.57	691.37	479.16	318.01
	0.15	1013.50	704.10	535.16	342.93
	0.2	918.43	697.73	497.84	311.94
	0.25	887.45	672.27	423.56	255.92
	0.3	729.14	616.67	392.58	230.88

Table 4.8 presents the average interlayer bond strength when the setting time is 9 hours. The highest bond strength values are observed at an application rate of 0.15 Kg/m² at all test temperatures for the CMS-2 type of tack coat.

Table 4.8 ILBS of CMS-2 type tack coat (Considering 9-hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
CMS-2	0.1	1000.76	949.83	635.35	423.14
	0.15	1045.75	968.93	659.96	441.81
	0.2	975.30	874.29	578.47	386.64
	0.25	924.37	811.05	516.93	330.62
	0.3	812.32	767.34	498.26	317.88

Table 4.7 presents the average interlayer bond strength when the setting time is 6 hours. The highest bond strength value is observed at an application rate of 0.15 Kg/m² at all test temperatures for the CMS-2 type of tack coat.

Table 4.9 ILBS of CMS-2 type tack coat (Considering 12-hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperature (kPa)			
		25°C	30°C	35°C	40°C
CMS-2	0.1	760.68	566.15	348.69	293.27
	0.15	798.57	584.84	373.7	318.01
	0.2	754.60	534.21	356.73	293.34
	0.25	729.14	496.60	332.03	224.40
	0.3	628.56	474.01	274.18	212.00

1.5.4 Variation of ILBS with application rate when VG 30 bitumen focused as a tack coat considering various setting times.

Table 4.10 presents the interlayer bond strength when the upper layer has been compacted immediately after the application of the binding material (VG 30). The highest interlayer bond strength values are observed at an application rate of 0.2 Kg/m² at all test temperatures for bitumen as a tack coat.

Table 4.10 ILBS of VG 30 as a tack coat (Considering 0 hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
VG 30	0.1	672.27	600.12	392.58	355.66
	0.2	723.20	653.17	497.84	428.56
	0.3	628.13	491.47	355.66	280.96

Table 4.11 ILBS of VG 30 as a tack coat (Considering 0.5 hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
VG 30	0.1	773.28	672.27	642.14	435.45
	0.2	868.35	798.74	691.37	572.11
	0.3	811.05	640.86	560.65	367.97

Table 4.12 ILBS of VG 30 as a tack coat (Considering 1 hour setting time)

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
VG 30	0.1	760.97	653.17	522.45	392.16
	0.2	836.94	723.20	628.55	491.47
	0.3	735.51	610.30	491.47	324.25

1.5.5 Variation of ILBS considering various time intervals between successive layingbetween DBM and BC bituminous paving layers.

Table 4.10 presents interlayer bond strength when no tack coat is used for creating bonds between DBM and BC layers with varying time intervals between successive laying between them.

Table 4.13 ILBS without using any tack coat

Type of Tack Coat	The time interval between Successive laying (Hour)	Average ILBS at different test temperatures (kPa)			
		25°C	30°C	35°C	40°C
No Tack Coat	0	1039	994.45	729.60	578.57
	1	836.50	761.12	616.70	466.90
	2	761.01	628.95	553.90	417.26
	3	689.30	572.55	504.60	398.90
	6	572.55	435.97	348.85	305.60

1.6 Interlayer Bond Strength for Bituminous Macadam (BM) and Semi-Dense Bituminous Concrete (SDBC) Combination.

1.6.1 Variation of ILBS with application rate for a CRS-1 type tack coat considering a1-hour setting time.

Table 4.14 presents the interlayer bond strength when the setting time is 1 hour. The highest interlayer bond strength value is observed at an application rate of 0.15 Kg/m^2 at all test temperatures for CRS-I type tack coat for BM/SDBC combination.

Table 4.14 ILBS of CRS-1 type tack coat

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperature (kPa)			
		250C	300C	350C	400C
CRS-1	0.1	773.30	665.85	523.35	368.9
	0.15	930.70	786.1	597.20	448.20
	0.2	862.4	635.40	492.35	348.90
	0.25	754.65	566.20	423.60	293.30
	0.3	665.95	460.90	386.60	255.55

1.6.2 Variation of ILBS with application rate for a CMS-2 type tack coat considering 9-hour setting times.

Table 4.15 presents the interlayer bond strength when the setting time is 9 hours. The highest interlayer bond strength values are observed at an application rate of 0.15 Kg/m^2 at all test temperatures for a CMS-2 type tack coat for the BM/SDBC combination.

Table 4.15 ILBS of CMS-2 type tack coat

Type of Tack Coat	Application rate (Kg/m2)	Average ILBS at different test temperature (kPa)			
		250C	300C	350C	400C
CMS-2	0.1	760.98	578.50	491.5	305.60
	0.15	918.10	748.30	587.8	411.30
	0.2	855.20	597.20	448.55	274.60
	0.25	760.6	553.80	404.90	243.20
	0.3	654.1	448.20	361.55	211.80

CONCLUSION

This project included a laboratory study to assess the interlayer bond strength of various tack coats using laboratory-prepared samples for DBM/BC and BM/SDBC layer combinations. A special device has been designed and manufactured that can be attached to the loading frame of the Modified Marshall Test apparatus to measure the interlayer bond strength of two-layered bituminous specimens. The specimens were tested at four different test temperatures, 250, 300, 350, and 400 degrees Celsius, which are very common in our country. A specimen is made up of two bituminous layers held together by emulsion or bitumen. The upper- and lower-layer combinations are either DBM or BC or BM and SDBC. Various application rates have been tested, as well as different setting times for emulsion. All these variations in materials and sample casting methods have been tested to determine the best conditions for appropriate bond strength in each situation. The test results lead to the following conclusions.

The maximum interlayer bond strength for CRS-1 is achieved at 0.25 Kg/m2 application rate in all test temperature conditions, while for CMS-2 it is achieved at 0.15 Kg/m2 application rate regardless of test temperature. These optimum application rates apply to both types of emulsions at all setting times. The maximum interlayer bond strength was found in the cationic medium setting emulsion used as a tack coat when the setting time was 9 hours, and in the cationic rapid setting emulsion when the setting time was 1 hour. When traditional VG 30 asphalt is used as a tack coat, the maximum interlayer bond strength is achieved at a 0.2 Kg/m2 application rate and a setting time of 0.5 hours at all test temperatures. When no tack coat is used, the highest bond strength at the interface is achieved when the upper layer mix is laid and compacted immediately after the lower layer compaction is completed. As the duration of compaction between two layers increased, the interlayer bond strength weakened. At a test temperature of 250C, all types of tack coats were used, and other considerations were taken to observe the interlayer bond strength, which was found to be the highest value compared to other test temperatures. It has been determined that for CRS-1, maximum interlayer bond strength occurs at a 0.15 Kg/m2 application rate in all test temperature conditions used, and for CMS-2, at the 0.15 Kg/m2 application rate regardless of test temperature.

The interlayer bond strength decreases as the test temperature rises for both types of tack coat used. The maximum bond strength was discovered at 250C for both types of tack coats used. Future Scope of Works Bond strength is analyzed using the finite element method, and laboratory results are compared to theoretical work. Experimentation with the fabricated device and various loading combinations. Comparing the experimental results to those reported in the literature and previous experiments. Testing of field core samples and comparison to laboratory-prepared ones.

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