

**EVALUATION OF PARAMETERS INFLUENCING
INTERLAYER BOND STRENGTH OF BITUMINOUS
MIXES**

PROJECT REPORT

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of

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in

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DEPARTMENT OF CIVIL ENGINEERING

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DECLARATION

I, the undersigned, hereby declare that the project report “Evaluation of Parameters Influencing Interlayer Bond Strength of Bituminous Mixes”, submitted for partial fulfillment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Prof. Sai Niveditha M.G. This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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CERTIFICATE

This is to certify that the report entitled '**Evaluation of Parameters Influencing Interlayer Bond Strength of Bituminous Mixes**' is the report of project presented by **JISHMA L.H. (RollNo. : M20CETE06)** during **2021-2022** in partial fulfilment of the requirements for the award of the Degree of Mater of Technology in Transportation Engineering of the APJ Abdul Kalam Technological University.

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ABSTRACT

Slippage failures and delamination failures caused by frequent acceleration and turning movements by vehicles on flexible pavements are because of the inadequate bonding between the asphalt layers. Applying tack coat between these layers is a widely accepted solution for this problem. However, clarifications regarding many factors which affect the tack coat performance yet need to be found out. This paper intended to find out the effect of factors such as laying temperature, tack coat application rate, surface roughness on interlayer bonding strength between BC-2 (Bituminous Concrete) and DBM-2 (Dense Bituminous Macadam) layers of asphalt pavement. Leutner shear test was used to evaluate the interlayer shear strength of laboratory prepared 150 mm diameter cylindrical samples. 140°C, 150°C and 160°C were chosen for laying BC layer. Application rate of 0.2 kg/m², 0.25 kg/m² and 0.3 kg/m² as per MoRTH specification was chosen for applying RS-1 (Rapid Setting emulsion) as tack coat above the DBM-2 layer. For analyzing the effect of interlayer surface roughness, rough and smooth interfaced samples were considered. For rough interfaced samples, the top surface of DBM-2 layer was grooved and the tack coat was applied on this grooved surface. For smooth interfaced samples, the surface where the tack coat applied was leveled. Leutner test was conducted on rough interfaced and smooth interfaced samples for the above mentioned laying temperatures and application rates of tack coat and the results were compared. It was found that the laying temperature, application rate and interface surface roughness have impact on interlayer bond strength. Also, rough interfaced samples presented more shear strength than the smooth interfaced samples irrespective of laying temperature and application rate. For smooth interfaced samples, the interlayer bond strength decreased with increase in temperature while that for rough interfaced samples the trend was found to be opposite i.e., as the interlayer bond strength increased with increase in temperature. An application rate of 0.25 kg/m² was found to be optimum for both smooth and rough interfaced samples.

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LIST OF ABBREVIATIONS

AC	Asphalt Concrete
BC	Bituminous Concrete
CPAM	Cold Patching Asphalt Mixture
DBM	Dense Bituminous Macadam
DLA	Double Layered Asphalt
GDP	Gross Domestic Product
HMA	Hot Mix Asphalt
MC	Medium Curing
MoRTH	Ministry of Road Transport and Highway
MS	Medium Setting emulsion
OBC	Optimum Binder Content
PCC	Portland Cement Concrete
PG	Performance Graded
PMAE	Polymer Modified Asphalt Emulsion
RC	Rapid Curing
RS	Rapid Setting emulsion
SS	Slow Setting emulsion

1. INTRODUCTION

1.1 GENERAL

Roads play critical role in economic development and growth of a nation. A road network is a link for producers to markets, workers to jobs, students to schools, and the ill to hospitals etc. It is also a link to connect other modes of transport. In a developing nation like India, roads are seen as the most adaptable and versatile form of transportation. The majority of people use road transit as their primary and preferred form of transportation, and India has one of the most heavily utilised road transportation systems in the world.

The road sector primarily accounts to the transportation industry's 6.3% GDP contribution. Ninety percent of passenger traffic and more than fifty percent of freight are handled by roads. It is critical to a country's economic development by increasing productivity and competitiveness.

However, as a result of use and time, the road infrastructure is becoming aged. And what appears to be a minor problem on the surface may be concealing a major issue just beneath the surface. As a result, it necessitates maintenance, renewal, and modernization.

All developed as well as developing countries pursue a continuous program of constructing and developing road infrastructures. In case of existing road pavements requiring rebuilding in view of increased traffic, it is done by overlaying the existing one with one or more layers of appropriate material composition and depth. In case of new roads, different pavement layers are constructed one after another in stages. Normally, in a flexible pavement, there should exist good bonding between two adjacent layers so that the entire pavement structure functions satisfactorily. In case of granular layers, the roughness between the two layers provides the necessary bond.

A strong bonding is required to transfer tensile and shear stresses from the overlay to the existing pavement and other structural layers of pavement. One way to improve the existing road infrastructure in view of increased traffic is to strengthen the existing bituminous layer by overlaying with another bituminous layer of appropriate material composition and thickness. Even in new constructions, the upper bituminous layer is laid much after the lower bituminous layer is constructed.

The boundary between two consecutive layers is the layer interface and it is usually believed that, the pavement stress distribution is highly influenced by the adhesion conditions at the layer interface. Poor adhesion at layer interface may cause adverse effects on the structural strength of the pavement system. A number of premature failures such as slippage failure (Fig.1.1) and delamination (Fig. 1.2) failures may take place.



Fig. 1.1 Slippage cracking
(Source: Buchanan and Woods, 2004)



Fig. 1.2 Surface delamination
(Source: Giri and Panda, 2018)

There are numerous techniques that can be used to improve the bonding between pavement layers. Chemical (tack coats, emulsions) and mechanical (milling, tinning, etc.) bonding methods are used to improve bonding.

A tack coat is normally applied to an existing pavement surface before a new layer of HMA is placed. It is a light application of low viscosity bituminous binder (mostly bitumen emulsion) between successive bituminous layers designated to create a strong adhesive bond between the two layers without separation. Tack coat application to an existing pavement surface is so simple and inexpensive. It can significantly improve the bond between pavement layers, improving pavement strength, reducing surface-course sliding and reducing top-down cracking. Adequate bonding between constructed lifts (especially between the existing road surface and an overlay) is critical for the constructed pavement structure to behave as a single unit and provide adequate strength.

1.2 PROBLEM STATEMENT

Although each layer can be designed, built and rehabilitated independently for a pavement, the layers must be bonded together to respond to loads as intended. Many highway pavement problems are caused by poor bonding between two layers of Hot Mix

Asphalt (HMA). If the bonding is insufficient, the pavement layers act independently, reducing the pavement's service life. It is possible that the pavement will fail instantly under heavy loads. The most vulnerable locations of occurrences of such failure are where traffic is accelerating or decelerating, such as at traffic signals and on horizontal curves.

This happens due to improper bonding between the two bituminous layers and the two layers do not act together in unison. When a layer is unable to withstand the strains applied, cracking occurs. Therefore, bonding between pavement layers is necessary for maintaining the structure as monolithic. To increase the adhesions between two layers, bitumen emulsion is normally used as tack coat prior to overlay on an existing or newly constructed pavement layer. A tack coat material can be a PG binder or an emulsion layer applied between HMA pavement lifts to promote bonding.

Even though tack coats are widely used, clarifications regarding many factors that affect the shear strength of pavement layers that needed to be taken care of have not been specified. The Ministry of Road Transport and Highway (MoRTH) has only specified an application rate of 0.2-0.3 kg/m² of tack coat with bitumen emulsion in overlays. There are many other factors affecting tack coat performance and interlayer bond strength including: tack coat type, temperature, surface roughness, humidity etc. A bond strength study (Giri and Panda, 2018) showed that, interlayer bond strength was 39.75% greater at 25°C compared to 40°C on an application rate of 0.2 kg/m². At higher temperatures the tack coat adhesion becomes relatively insignificant. Therefore it would be beneficial if more clarifications regarding the factors influencing shear strength between the pavement layers are understood.

1.3 OBJECTIVES

The main objective of the proposed study is to clarify the degree of influence of various factors and reveal the dominant factors that affect the interface bonding characteristics. The specific objectives of study are as follows:-

- To identify the factors influencing interlayer bond strength of bituminous mixes by extensive literature review.
- To investigate the influence of factors such as tack coat application rate, laying temperature, surface roughness and moisture induced on interface shear strength.

1.4 METHODOLOGY

The methodology planned in order to achieve the mentioned objectives is described below:

- **Study of literature-** Background study was done on the different interface characteristics of bituminous mixes. An extensive literature review was done to identify the different parameters influencing interface bond strength of bituminous pavement.
- **Laboratory study-** Material characterization of aggregate and bitumen (VG-30) was done in the laboratory study. The strength and properties of aggregate, bitumen and emulsion were determined.
- **Preparation of compacted specimen-** Compacted cylindrical specimens of 150 mm diameter consisting of two layers with lower layer for Dense Bituminous Macadam (DBM-2) mix and upper one for Bituminous Concrete (BC-2) mix was made according to the MoRTH specifications.
- **Experimental analysis on interface shear strength-** The interlayer bond strength between two successive bituminous layers was estimated by conducting shear test on Leutner shear test device. The variation in interlayer shear strength for various parameters have been assessed.
- **Interpretation of results and discussion**

1.5 SCOPE

The scope of study is limited to RS-1 emulsion only. The gradation used for surface course was BC-2 gradation and binder course was DBM-2 gradation. The factors such as tack coat application rate, laying temperature of the upper layer BC, surface roughness and moisture induced were only considered. There are several other factors which influences the bonding characteristics such as effect of type of tack coat used, type and degree of compaction, curing time, cracking resistance, fatigue performance etc. Application rate of tack coat considered were 0.2 kg/m², 0.25 kg/m² and 0.3 kg/m². Laying temperature considered were 140°C, 150°C and 160°C. For analysing the effect of surface roughness, groove depth of 3 mm with a spacing of 1.5 cm is only considered. The change in dimension of groove may provide increment or decrement in shear

strength. Pavement failure mechanisms and the interactions between influence factors are needed to be investigated in future.

2. LITERATURE REVIEW

One of the most important factors in achieving high interface bonding strength and improving pavement quality is proper tack coat application in the field. It is necessary to spread the precise amount of tack coat on the pavement layer in order to achieve proper interlayer bonding strength between the pavement layers. Several factors which affects the tack coat distribution are nozzle patterns, spray bar height, and distribution pressure within the distributor etc.

Researchers have been trying to find out the factors which affects the performance of tack coat. There are so many studies conducted to studies conducted in this area. The following sections lays emphasis on different factors which affects the tack coat performance and interlayer bond strength.

2.1 EFFECT OF TACK COAT TYPE

Generally, hot asphalt cement, asphalt emulsion and cut back asphalt have been used as tack coat materials but the latter one is not commonly used because of its environmental concerns. Asphalt emulsion was the most common type of tack coat and its properties can be improved with polymer modifiers and other additives. Furthermore, research findings (Chen et al., (2020), Mohammad et al. (2002) and West et al. (2005)) revealed that the type of tack coat has a significant impact on the interlayer bonding strength. Asphalt emulsions are more commonly used than hot asphalt binder or cutback asphalt because they are easier to apply at lower temperatures, resulting in a more uniform, energy-saving, and safer application. Cationic emulsions have been found to have higher shear strengths and fatigue lives than other tack coats when subjected to repeated loads. Ghaly et al. (2014) in his study indicated that when compared to cutback asphalt, tack coat asphalt or modified tack coat asphalt emulsion has higher shear strength values. Chen et al., (2020) studied the interface shear strengths of the various tack coats. The shear strength of the five binders considered were found to be in the same order of their viscosity. This information indicates that the higher the viscosity of the binder, the greater the interfacial shear strength. As a result, when using CPAM (Cold Patch Asphalt Mix) to repair a pothole, a high viscosity tack coat should be used.

2.2 EFFECT OF APPLICATION RATE

The amount of liquid asphalt sprayed by the distributor is known as the tack coat application rate. To provide good interface bonding at a low cost, an optimal tack coat application rate is required. For several years, researchers have been trying to figure out if there is an optimal tack rate and how to find it.

Chen et al., (2020) and Ghaly et al., (2014) showed the results of interfacial shear strength at various tack coat spreading levels. Initially the interfacial shear can be seen to increase as the amount of binder increases and then after reaching a certain level the shear strength declines. It can be concluded from the curve trend that there is an optimal spreading amount of tack coat for maximum shear strength.

For fine graded mixes, West et al., (2005) found that low application rates usually resulted in higher interface bond strength than high application rates. Table No. 2.1 shows optimal spreading amount for various types of tack coat.

Table No. 2.1 Optimal spreading amount for various types of tack coats.

Sl. No.	Type of Tack Coat	Optimal Spreading Amount	Reference
1	Rapid setting bitumen emulsion in DBM-BC	0.25 kg/m ²	Jyoti Prakash Giri & Mahabir Panda (2018)
2	Rapid setting bitumen emulsion in BM-SDBC	0.15 kg/m ²	
3	Medium setting bitumen emulsion	0.15 kg/m ²	
4	VG 10	0.15 kg/m ²	
5	VG 30	0.15 kg/m ²	
6	Crumb Rubber Modified (CRM)	0.6 kg/m ²	Moein Biglari et al., (2018)
7	Grade 60/70 binder	0.6 kg/m ²	
8	Cationic Slow-Setting (CSS)	0.2 kg/m ²	
9	Cationic Rapid-Setting (CRS)	0.2 kg/m ²	
10	New Asphalt Concrete	0.1 L/m ²	Mohammad (2012)
11	Old Asphalt Concrete	0.24 kg/m ²	

2.3 EFFECT OF TEMPERATURE

The temperature has a significant impact on asphalt behaviour. The characteristics of asphalt binder and tack coat would change as the temperature rise or fall. With increasing temperature, the shear resistance at the interface decreased significantly (Ghaly et al., 2014). This is because the viscosity of the tack coat decreases with increasing temperature, causing the bonding ability to worsen with the old pavement.

Chen et al., (2020) studied the interface between CPAM (Cold Patching Asphalt Mixture) and the old pavement changes with temperature due to the asphalt material's temperature sensitivity. Consequently, the effect of temperature on interfacial bonding properties was investigated. Fig. 2.1 depicts the oblique shear test results of three types of CPAM at various temperatures. It can be seen that the interface shear strength of the three types of CPAM decreases as the temperature increases.

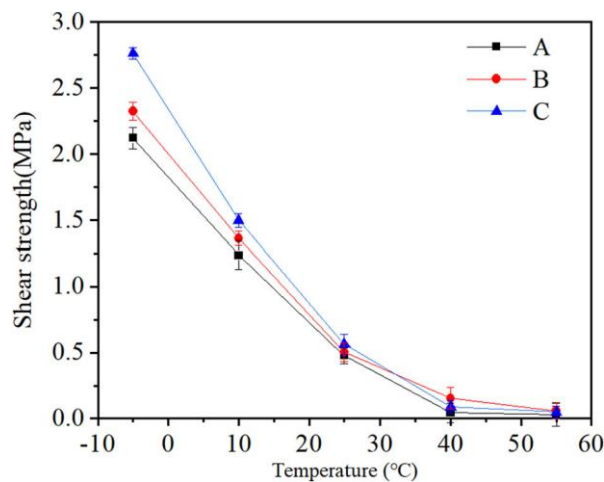


Fig. 2.1 Interfacial shear strength at different temperatures
(Source: Chen et al., 2020)

2.4 EFFECT OF MOISTURE

When moisture penetrates the pavement interface, the dynamic water pressure generated by the intermittent dynamic vehicle easily breaks the interface, allowing the moisture to pass through the interface. Therefore it is necessary to investigate the effects of moisture on the characteristics of interface bonding.

Chen et al., (2020) in their study discovered that, the greater the immersion time, the lower the interfacial shear strength. This indicates that as the moisture immersion time increases, moisture infiltrates the interface and acts as a lubricant, causing an obvious

decrease in the interface bonding strength. As a result, before repairing the pothole, it is necessary to drain the water and keep the surface dry.

Water is generally inevitable during construction stage of a pavement. Sholar et al. (2004) observed differences between samples with and without water on the surface of the tack coat. Water applied to the surface of the tack coat, representing rainwater, was found to significantly reduce shear strength when compared to no water applied. Therefore watering the surface had a negative effect on adhesion. As a matter of fact, the water potential of tack coats should not be neglected.

2.5 EFFECT OF SURFACE CHARACTERISTICS

Existing pavement paving surface conditions such as surface roughness and cleanliness on the surface are important factors influencing shear strength at the interlayer. The effect of different surface roughness on surface bonding characteristics was investigated in a study by Chen et al. (2020). Some grooves were added to the surface to increase the roughness of the surface of HMA at 0.5, 1, 1.5, and 2 mm intervals and the interlayer shear strength at various roughness levels were determined. It was found that it is essential to mention the groove interval appropriate for maximum shear strength.

According to field cores and laboratory-compacted specimens, the milled surface of both asphalt and PCC pavements has significantly higher shear strength than the non-milled pavement surface (Mohammad et al., 2012). Milling is expected to have this effect because the rough scratches in the pavement surface created by the milling machine will provide greater interlock between pavement layers, resulting in higher shear resistance.

2.6 EFFECT OF CURING TIME

The amount of time it took for the emulsion to cure was also a significant factor, indicating that pavement could be laid immediately after the emulsion was broken (Chen and Huang, 2010). Since different emulsifying agents are used in different types of tack coat, the curing time varies. Most tack coats take 1–2 hours to cure completely. According to Hasiba et al. (2012), the optimum curing time was 2 hours, and this value was used when a conventional paver was used.

2.7 EFFECT OF COMPACTION

In laboratory conditions, Piotr Jaskula (2014) investigated four compaction techniques: rolling with and without vibrations, gyratory compaction, and slab compactor compaction, including both hot-to-cold and hot-to-hot. It was discovered that the interlayer bonding strengths were highly dependent on the compaction technique used, as well as the compaction effort.

2.8 SUMMARY OF LITERATURE REVIEW

This study provided a comprehensive overview of the use of tack coat in pavement engineering. The evaluations of tack coat properties and test methods were discussed based on previous literature and research. Finally, the factors that influence tack coat properties were presented. The following statements and conclusions can be drawn based on the findings of the researchers.

During pavement construction, a tack coat is required to improve bonding strength between two layers. Among all types of tack coats, emulsified asphalt was the most common. Different modifiers resulted in different tack coat performances. Tack coat was removed from the surface by construction equipment, so trackless emulsions were used as a solution.

It was suggested that the tack coat should be applied to a clean, dry and well-compacted layer. Moreover to achieve good paving quality, the uniformity of nozzle spray patterns, the size of the nozzles, the height of the spray bar, the application pressure, and the temperature of the tack coat all needed to be considered.

Shear tests were the most commonly used methods for verifying interlayer bonding strengths because the shear mode was similar to actual debonding and slippage cases and they were simple to perform.

The intrinsic factors and application conditions both had an impact on the interlayer bonding properties. Choosing the right material, application rate and construction conditions are critical for forming a high shear strength interface layer.

However the bonding effects between binder layers on flexible pavement failure mechanisms and long-term pavement behaviour, on the other hand, were not well understood.

3. METHODOLOGY

Fig. 3.1 shows the research methodology adopted for the study.

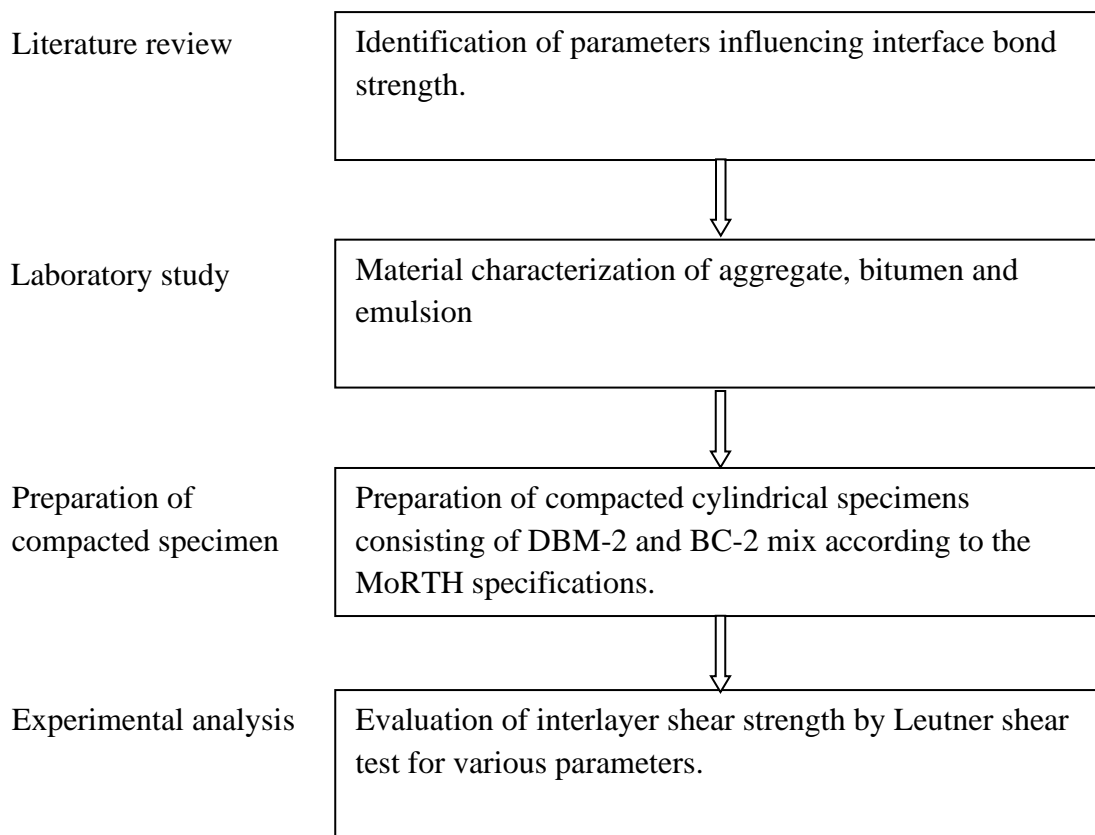


Fig. 3.1 Research methodology

3.1 LITERATURE REVIEW

Background study was done on the different interface characteristics of bituminous mixes. An extensive literature review was done to identify the different parameters influencing interface bond strength of bituminous pavement.

3.2 LABORATORY STUDY

Material characterisation was done for aggregate, bitumen and emulsion. This section lays emphasis various tests that were conducted on the chosen materials for preparation of samples.

3.2.1 Materials Used

For preparation of cylindrical specimens composed of two types of bituminous layers in the laboratory, with lower layer DBM-2 (Nominal aggregate size of 26.5 mm) mix and upper one for BC-2 (Nominal aggregate size of 13.2 mm), aggregates were graded as per MoRTH specifications. The specific gravity of aggregates used was found to be 2.64. The composition of bituminous concrete pavement and dense graded bituminous macadam is shown in Table No. 3.1 and Table No. 3.2 respectively. In this investigation viscosity graded VG 30 bitumen collected from local source was used as binder for preparation of samples. For binding the two different bituminous layers bitumen emulsion has been used as tack coat namely, Cationic Rapid Setting (CRS-1) emulsion.

Table No. 3.1 Composition of BC-2 layer

IS Sieve (mm)	Cumulative % by weight of total aggregate passing	Mid value	Cumulative % weight retained	% weight retained	Weight retained (g)
19	100	100	0	0	0
13.2	90-100	95	5	5	81.83
9.5	70-88	79	21	16	261.85
4.75	53-71	62	38	17	278.22
2.36	42-58	50	50	12	196.39
1.18	34-48	41	59	9	147.29
0.6	26-38	32	68	9	147.29
0.3	18-28	23	77	9	147.29
0.15	12-20	16	84	7	114.56
0.075	4-10	7	93	9	147.29
Bitumen content %	5.4	Pan	100	7	114.56

Table No. 3.2 Composition of DBM-2 layer

IS Sieve (mm)	Cumulative % by weight of total aggregate passing	Mid value	Cumulative % weight retained	% weight retained	Weight retained (g)
37.5	100	100	0	0	0
26.5	90-100	95	5	5	123.97
19	71-95	83	17	12	297.53
13.2	56-80	68	32	15	371.91
9.5	-	-	-	-	-
4.75	38-54	46	54	22	545.47
2.36	28-42	35	65	11	272.73
1.18	-	-	-	-	-
0.6	-	-	-	-	-
0.3	7-21	14	86	21	520.67
0.15	-	-	-	-	-
0.075	2-8	5	95	9	223.35
Bitumen content %	4.5	Pan	100	5	123.97

3.2.2 Material Characterisation

Tests on Aggregate

Aggregates for surface course and binder course used for the study were obtained from a quarry and its properties were studied. As per MoRTH (5th Revision) physical properties and tests conducted for coarse aggregate for bituminous concrete are shown in Table No. 3.3. Physical properties and tests conducted on coarse aggregate for DBM are shown in Table No. 3.4. The following tests were conducted on aggregates:

1. Aggregate Impact Test.
2. Shape Test (Combined Flakiness and Elongation Index).
3. Los Angeles Abrasion Test
4. Water Absorption Test
5. Stripping of Bitumen Aggregate mix
6. Specific Gravity

Table No. 3.3 Physical requirements for coarse aggregate for BC as per MoRTH

Property	Test	Specification	Method of Test
Cleanliness (dust)	Grain size analysis	Max. 5% passing 0.075 micron	IS:2386 Part I
Particle shape	Combined Flakiness and elongation Indices	Max. 35%	IS:2386 Part I
Strength	Los Angeles Abrasion Value or Aggregate Impact Value	Max. 35% Max. 27%	IS:2386 Part IV
Durability	Soundness either: Sodium Sulphate or Magnesium Sulphate	Max. 12% Max. 18%	IS:2386 Part V
Water Absorption	Water Absorption	Max. 2%	IS:2386 Part III
Stripping	Coating and Stripping of Bitumen Aggregate Mix	Minimum retained coating 95%	IS:6241
Water Sensitivity	Retained Tensile Strength	Max. 80%	AASHTO 283

Table No. 3.4 Physical requirements for coarse aggregate for DBM as per MoRTH

Property	Test	Specification	Method of Test
Cleanliness (dust)	Grain size analysis	Max. 5% passing 0.075 micron	IS:2386 Part I
Particle shape	Combined Flakiness and elongation Indices	Max. 35%	IS:2386 Part I
Strength	Los Angeles Abrasion Value or Aggregate Impact Value	Max. 30% Max. 24%	IS:2386 Part IV
Durability	Soundness either: Sodium Sulphate or Magnesium Sulphate	Max. 12% Max. 18%	IS:2386 Part V
Polishing	Polished Stone Value	Max. 55	BS:812-114
Water Absorption	Water Absorption	Max. 2%	IS:2386 Part III
Stripping	Coating and Stripping of Bitumen Aggregate Mix	Minimum retained coating 95%	IS:6241
Water Sensitivity	Retained Tensile Strength	Max. 40%	AASHTO 283

The results obtained after conducting laboratory tests are as shown in Table No. 3.5. The aggregate impact value was obtained as 26%. Hence the aggregates are suitable for DBM. Los Angeles abrasion value obtained was 22%. According to MoRTH specifications, the maximum value for Los Angeles abrasion test for BC is 30% and that for DBM is 35%. Combined flakiness and elongation index obtained was 16%. According to MoRTH specifications, maximum value for combined flakiness and elongation index for BC and DBM is 35%. Water absorption for the aggregate was found to be 0.81%. According to MoRTH specification the maximum water absorption for BC and DBM is 2%. Stripping of bitumen aggregate mix was found to be 96%. According to MoRTH specification the minimum value of stripping of bitumen aggregate mix for BC and DBM is 95%. Specific gravity of aggregate was found to be 2.64. All the physical properties of aggregate found to be within the required range specified by MoRTH. Therefore the aggregate is suitable for BC and DBM construction of pavement.

Table No. 3.5 Physical properties of aggregate

Property	Value %	Required Value	
		BC	DBM
Aggregate impact value (%)	26	Max 24	Max 27
Los Angeles abrasion value (%)	22	Max 30	Max 35
Combined flakiness and elongation index (%)	16	Max 35	Max 35
Water Absorption	0.81	Max 2	Max 2
Stripping of Bitumen Aggregate mix	96	Min 95	Min 95
Specific Gravity	2.64	2.5 to 3	2.5 to 3

Tests on Bitumen

Bitumen used for the study (VG 30) was obtained from local source and the following tests were conducted for bitumen characterization. The tests are as follows:

1. Softening Point Test
2. Ductility Test
3. Penetration Test

The results obtained after conducting physical tests for bitumen are as shown in Table No. 3.6. Penetration value at 25°C of VG 30 bitumen was obtained as 63. As per IS 73:2006, penetration value for VG 30 bitumen should be between 50 – 70 at 25°C . Softening point of the bitumen was obtained as 55°C. As per BIS 73 (2010) specification VG 30 binder grade should have a minimum softening point of 47°C. The ductility value was obtained as 82 cm. As per IS 73:2006, minimum ductility value for VG 30 bitumen is 40 cm at 25°C. Therefore the bitumen was found to be suitable for construction of pavement.

Table No. 3.6 Physical properties of VG-30

Property	Value	Required Value	Test method
Penetration at 25°C	63	50 to 70	IS:1203
Softening point test (°C)	55	Min 47	IS:1205
Ductility test (cm)	82	Min 40	IS:1208

Tests on Emulsion

Bitumen emulsion used for the study was obtained from the public works department. Rapid Setting-1 (RS-1) emulsion was used. Residue by evaporation test was conducted Fig. 3.2. In the left-over residue, ductility (IS 1208) and penetrating test (IS 1203) is conducted in order to evaluate the residue bitumen.



Fig. 3.2 Residue by evaporation

The results obtained after conducting tests on emulsion are as shown in Table No. 3.7. The value of residue by evaporation for the emulsion was found as 68%. As per IS:8887 (2004), the minimum value for residue by evaporation is 60% for RS-1 emulsion. Penetration value was obtained as 90. As per IS:8887 the penetration value of RS-1 at 25°C/100g/5 sec is in the of range 80-150. Ductility value was found to be 100 cm. The minimum ductility value for RS-1 emulsion at 27°C/cm is 50 as per IS:8887.

Table No. 3.7 Properties of RS-1 emulsion

Property	Value	Required Value	Test Method
Residue by evaporation	68%	Min 60%	IS:8887 (2004)
Penetration	90	80 to 150	IS:1203
Ductility	100 cm	Min 50 cm	IS:1208

3.3 PREPARATION OF COMPACTED SPECIMEN

For preparation of a single cylindrical specimen composed of two types of bituminous layers in the laboratory, with lower layer DBM-2 (Nominal aggregate size of 26.5 mm) mix and upper one for BC-2 (Nominal aggregate size of 13.2 mm) was done in two stages. For preparation of one specimen, as first stage, the DBM layer was prepared for a height of 60 mm and diameter 150 mm in the laboratory according to the Marshall Procedure (ASTM D1559) using automatic marshall compactor (Fig. 3.3) providing 75 blows by using a hammer of weight 10.2 kg. This forms the lower part of the specimen. The specimen is not to be extracted at this stage.



Fig. 3.3 Automatic Marshall Compactor

After 24 hours, tack coat (RS-1 emulsion) was applied at a given rate on the top of the DBM surface inside the mould using paint brush. The curing time has then been estimated by visual observation. Curing time is defined as the time when the brown colour of the tack coat becomes black. Fig. 3.4 and Fig. 3.5 shows the specimen before and after curing of RS-1 emulsion on DBM layer. Immediately after curing of tack coat, the BC mix (about

40 mm) is placed over the DBM compacted mix in the mould and compacted as per normal procedure.



Fig. 3.4 Before curing



Fig. 3.5 After curing

For preparation of rough interfaced samples, a grooved plate as shown in Fig. 3.6 was placed below the cylindrical mould during the compaction of lower layer. This create a rough surface on the DBM layer (Fig. 3.7).



Fig. 3.6 Metal plate for providing groove on sample



Fig. 3.7 Rough interfaced samples

After 24 hours, tack coat was applied at this grooved surface at a given rate. Fig. 3.8 and Fig. 3.9 shows the grooved sample before curing and after curing. Then immediately after the curing of tack coat, the BC mix (about 40 mm) is placed over the compacted DBM mix as per normal procedure.



Fig. 3.8 Before curing



Fig. 3.9 After curing

Marshall blows are given only on the top. As per normal procedure, when this composite specimen (Fig. 3.10) attains normal room temperature, the specimen can be extracted and is ready for testing its shear strength.



Fig. 3.10 Composite Specimen

3.4 EXPERIMENTAL ANALYSIS

This section discusses the interface bond testing experimental setup and experiments carried out with tack coat laid in between wearing course and binder course.

3.4.1 Leutner Shear Test

Leutner shear test device (Fig. 3.11) was equipped to evaluate the interlayer shear strength between the bituminous layers. The test was performed on 150 mm diameter specimen comprising of two layers (BC and DBM).



Fig. 3.11 Leutner Shear Test Device

The specimen was located in the Leutner testing frame, taking care to ensure that interface was properly aligned with the shear axis. One specimen part (lower layer) is fixed by mechanical clamping and another part (upper layer) was provided with a static load at a constant 10mm/min speed. The equipment records the shear force applied at the interface between two layers when sheared at the controlled rate of 10mm/min. Recording of displacement allows a Shear load (kN) v/s Displacement (mm) graph to be plotted. From

these results, it is possible to calculate the peak shear stresses, dividing the peak load by the area of the interface.

Evaluation of Interlayer Bond strength

It is assumed that the shearing takes place vertically along the predefined interlayer, in which the tack coat has been applied. Fig. 3.12 and Fig. 3.13 shows specimen before and after shear testing.



Fig. 3.12 Specimen before testing



Fig. 3.13 Specimen after testing

The interlayer bond strength (ILBS) between two successive bituminous paving layers has been estimated by conducting shear experiments on cylindrical specimens by using the following expression.

$$ILBS = \frac{F_{\max}}{A} \quad \text{Eq.1}$$

where F_{\max} is the maximum load (kN) to cause shearing and A is the cross-sectional area of specimen.

3.4.2 Effect of Different Parameters on Interfacial Bonding Characteristics

The methodology of the experiments is as shown in Fig. 3.14.

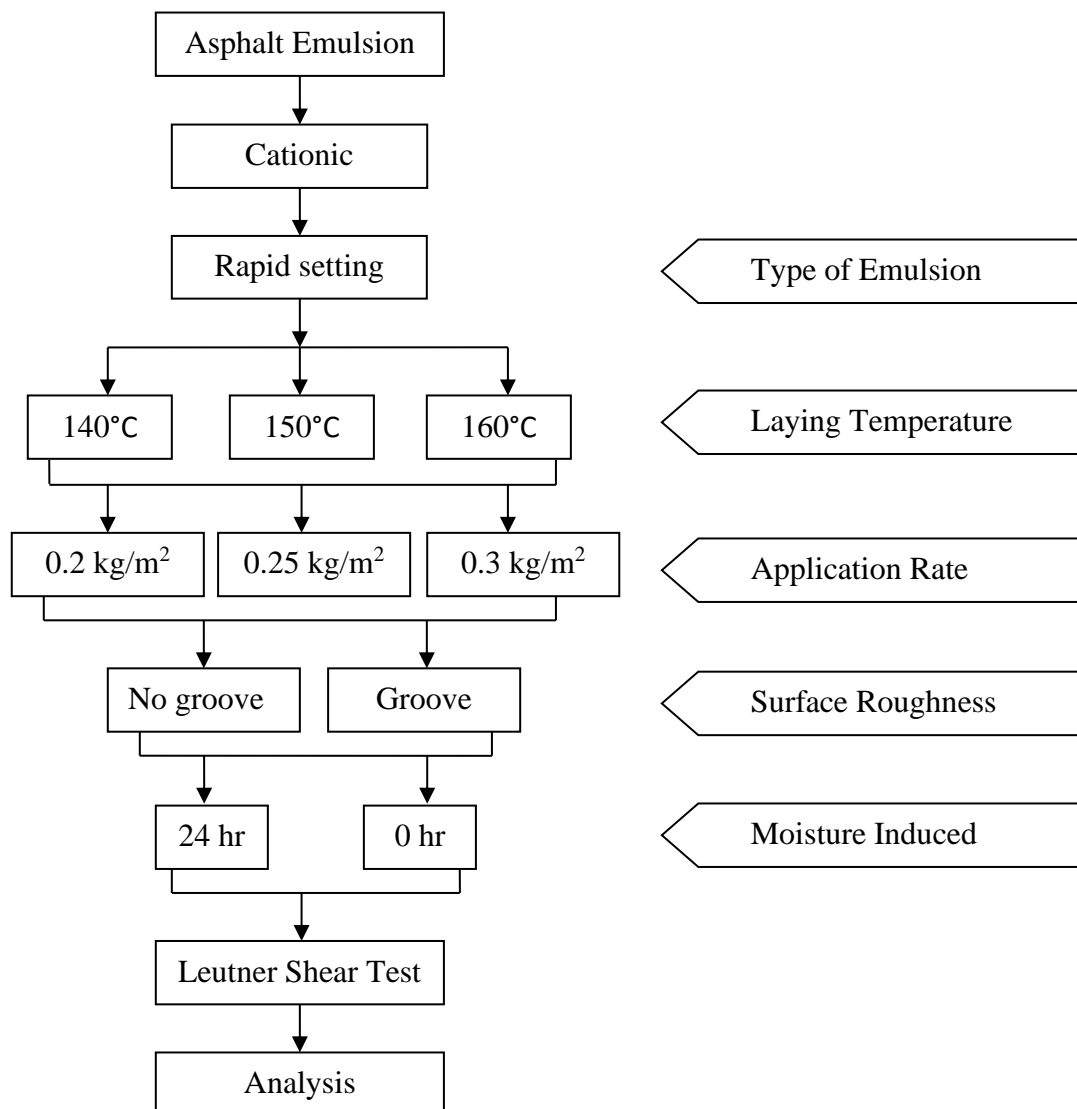


Fig. 3.14 Methodology of experiments

Effect of Temperature

In order to study the effect of temperature on interlayer bonding strength the Leuter test was conducted for different laying temperatures of upper layer BC of the specimens such as 140°C, 150°C and 160°C.

Effect of Application Rate

The effect of application rate of tack coat was studied by varying the amount of tack coat by 0.2, 0.25 and 0.3 kg/m².

Effect of Surface Roughness

For the purpose of increasing the interface roughness, grooves were made on the surface of the DBM layer and then the tack coat is applied over it. The specimens with groove and without groove were compared to study the effect of surface roughness.

Effect of Moisture

In order to study the effect of moisture state on interfacial bonding characteristics, the specimen which gave the greatest shear strength with groove and without groove were immersed in water for 24 hours. Then shear strength is evaluated using the Leutner shear test.

4. RESULTS AND DISCUSSION

This section lays emphasis on different test results and interpretations obtained after conducting leutner shear test on different combinations of parameters influencing interlayer bond strength.

4.1 LEUTNER SHEAR TEST

The load-deflection graphs obtained by conducting Leutner shear test on the smooth interfaced and rough interfaced samples for various application rates of tack coat at different laying temperatures are discussed in this section.

4.1.1 Application rate at 0.2 kg/m²

Fig. 4.1 and Fig. 4.2 represents the load-deflection graph plotted for different laying temperatures (140°C, 150°C and 160°C) at an application rate of 0.2 kg/m² for smooth and rough interfaced samples.

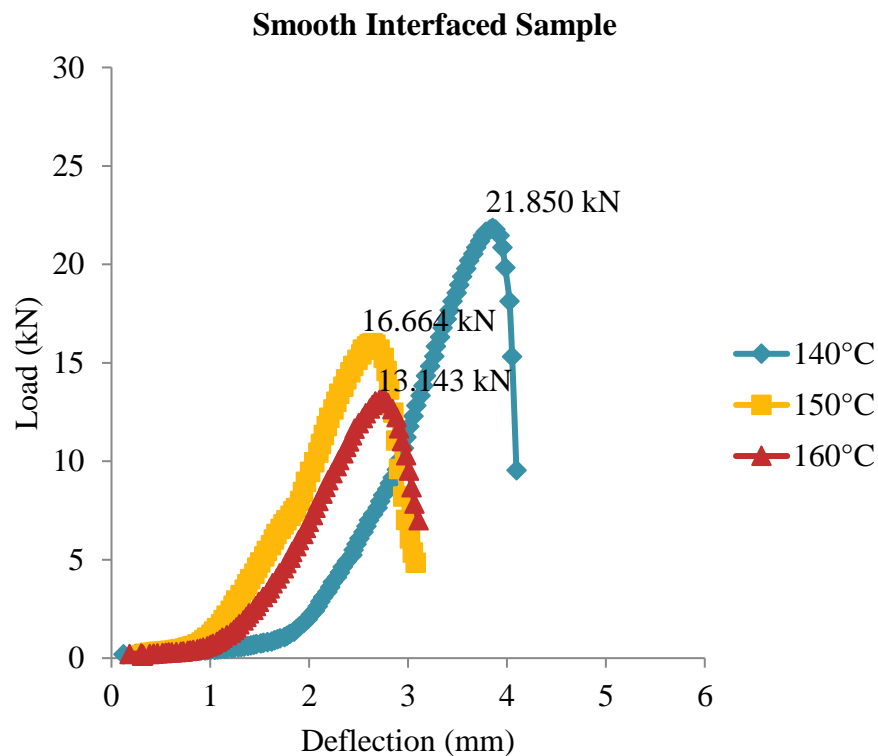


Fig. 4.1 Load deflection graph for smooth interfaced specimen for different temperatures at an application rate of 0.2 kg/m²

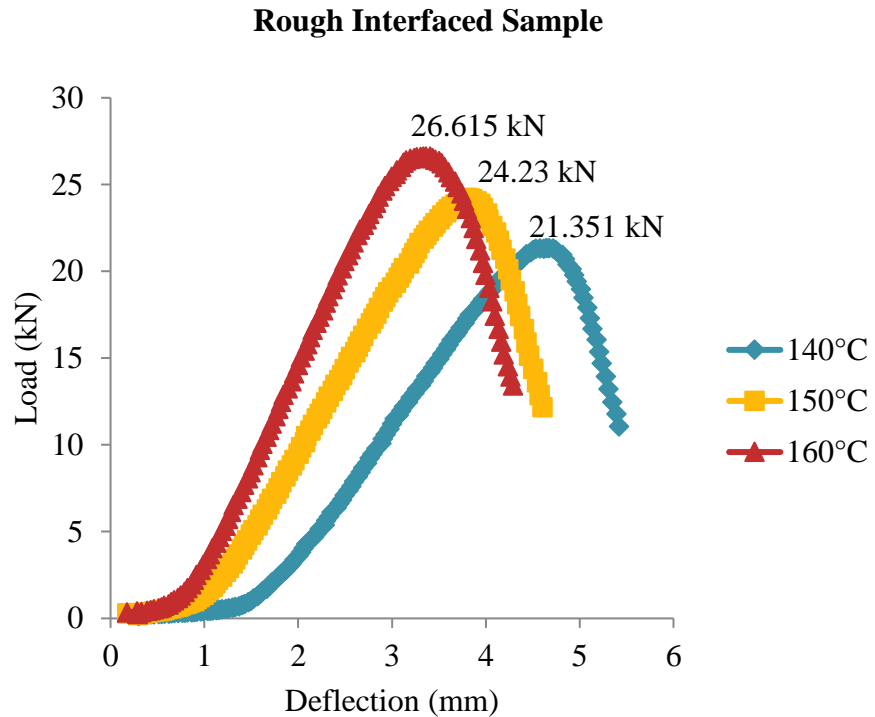


Fig. 4.2 Load deflection graph for rough interfaced specimen for different temperatures at an application rate of 0.2 kg/m²

For smooth interfaced samples, the maximum load was obtained at 140°C as 21.854 kN with deflection 3.785 mm. At 150°C the peak load obtained was 16.664 kN which was less than the peak load at 140°C and for 160°C, it was much lesser that is equal to 13.143 kN. As temperature was increased from 140°C to 160°C, the peak load was reduced by about 32%. The deflection at 150°C was 2.668 mm and that for 160°C was 2.74 mm. The deflection was maximum for 140°C and minimum for 150°C at 0.2 kg/m² application rate of tack coat.

For rough interfaced samples, the maximum load was obtained at 160°C as 26.615 kN . At 150°C the peak load obtained was 24.23 kN which was less than the peak load at 160°C and for 140° the value was much lesser that is equal to 21.351 kN. As temperature was increased from 140°C to 160°C, the peak load was increased by about 17%. The deflection value at 140°C, 150°C and 160°C was obtained as 4.535 mm, 3.901 mm and 3.237 mm respectively. From the graph, it is clear that as temperature increases the deflection value decreases for the rough interfaced samples at 0.2 kg/m² .

4.1.2 Application rate at 0.25 kg/m²

Fig. 4.3 and Fig. 4.4 represents the load-deflection graph plotted for different laying temperatures (140°C, 150°C and 160°C) at an application rate of 0.25 kg/m² for smooth and rough interfaced samples.

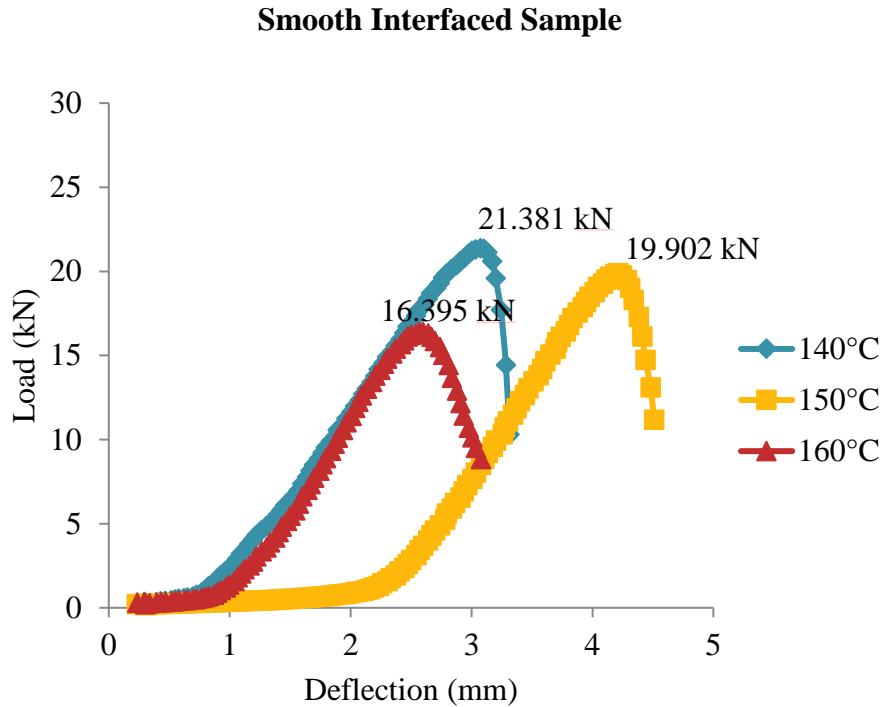


Fig. 4.3 Load-deflection graph for smooth interfaced specimen for different temperatures at an application rate of 0.25 kg/m²

For smooth interfaced samples, the maximum load obtained was at 140°C as 21.381 kN with a deflection of 2.974 mm. At 150°C the peak load obtained was 19.902 kN which was less than the peak load at 140°C and for 160°C, it was much lesser that is equal to 16.395 kN. As temperature was increased from 140°C to 160°C, the peak load was reduced by about 7%. The deflection at 150°C was 4.284 mm and that for 160°C was 2.471 mm. The deflection was maximum for 150°C and minimum for 160°C at 0.25 kg/m² application rate of tack coat.

For rough interfaced samples, the maximum load was obtained at 160°C as 28.778 kN . At 150°C, the peak load value obtained was 25.568 kN which was less than the peak load at 160°C and for 140° the value was much lesser that is equal to 22.339 kN. As temperature was increased from 140°C to 160°C, the peak load was increased by about 22%.

The deflection value at 140°C, 150°C and 160°C was obtained as 4.145 mm, 3.636 mm and 3.553 mm respectively. From the graph, it is clear that as temperature increases the deflection value decreases for the rough interfaced samples at 0.25 kg/m².

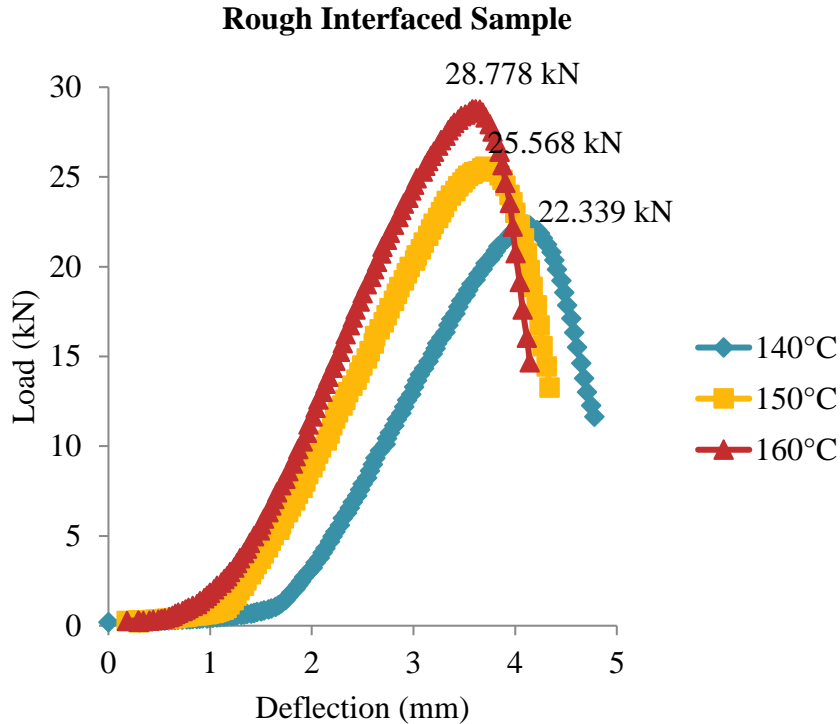


Fig. 4.4 Load deflection graph for rough interfaced specimen for different temperatures at an application rate of 0.25 kg/m²

4.1.3 Application rate at 0.3 kg/m²

Fig. 4.5 and Fig. 4.6 represents the load-deflection graph plotted for different laying temperatures (140°C, 150°C and 160°C) at an application rate of 0.3 kg/m² for smooth and rough interfaced samples.

For smooth interfaced samples, the maximum load obtained was at 140°C as 19.550 kN with a deflection of 3.309 mm. At 150°C the peak load obtained was 15.971 kN which was less than the peak load at 140°C and for 160°C, it was much lesser that is equal to 14.629 kN. As temperature was increased from 140°C to 160°C, the peak load was reduced by about 25%. The deflection at 150°C was 1.982 mm and that for 160°C was 3.215 mm.

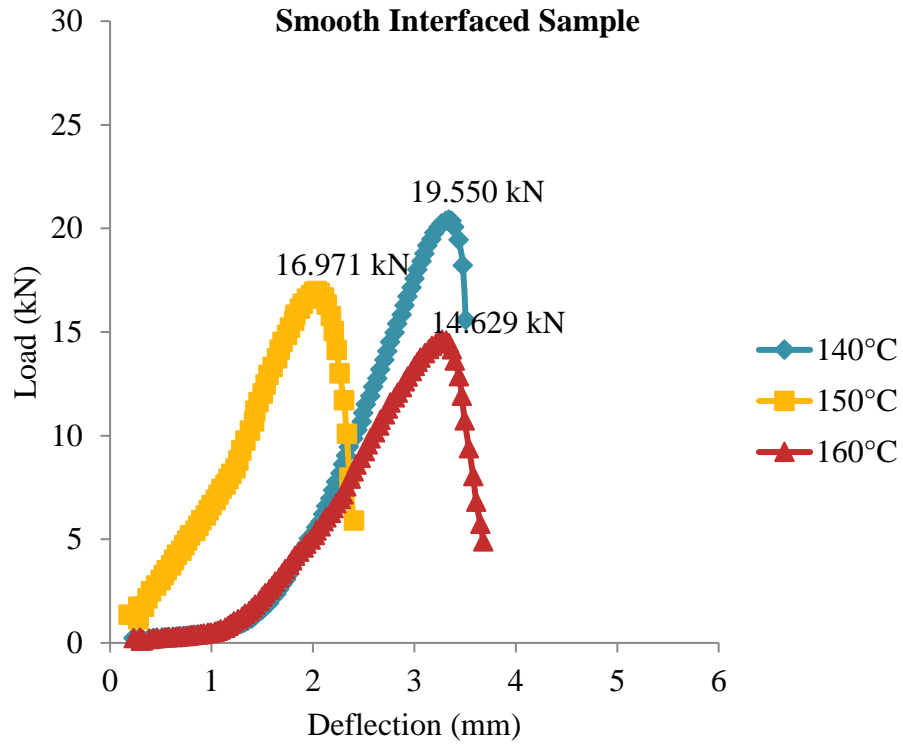


Fig. 4.5 Load deflection graph for smooth interfaced specimen for different temperatures at an application rate of 0.3 kg/m²

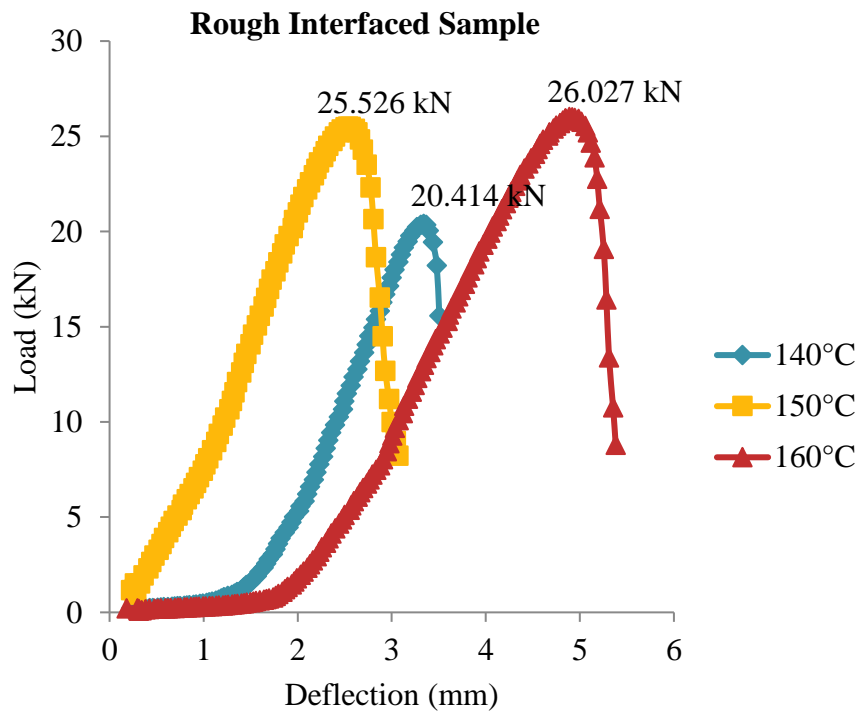


Fig. 4.6 Load-deflection graph for rough interfaced specimen for different temperatures at an application rate of 0.3 kg/m²

For rough interfaced samples, the maximum load was obtained at 160°C as 26.027 kN . At 150°C the peak load obtained was 25.526 kN which was less than the peak load at 160°C and for 140° the value was much lesser that is equal to 20.414 kN. As temperature was increased from 140°C to 160°C, the peak load was increased by about 20%. The deflection value at 140°C, 150°C and 160°C was obtained as 3.365 mm, 2.634 mm and 5.057 mm respectively

4.2 EFFECT OF APPLICATION RATE, LAYING TEMPERATURE AND SURFACE ROUGHNESS

The effect of tack coat application rate, laying temperature of BC layer and interlayer surface roughness on interlayer bond strength of bituminous mixes are discussed in this section. Fig. 4.7 shows the variation in Interlayer Shear Strength of smooth interfaced sample at different application rates for different laying temperatures.

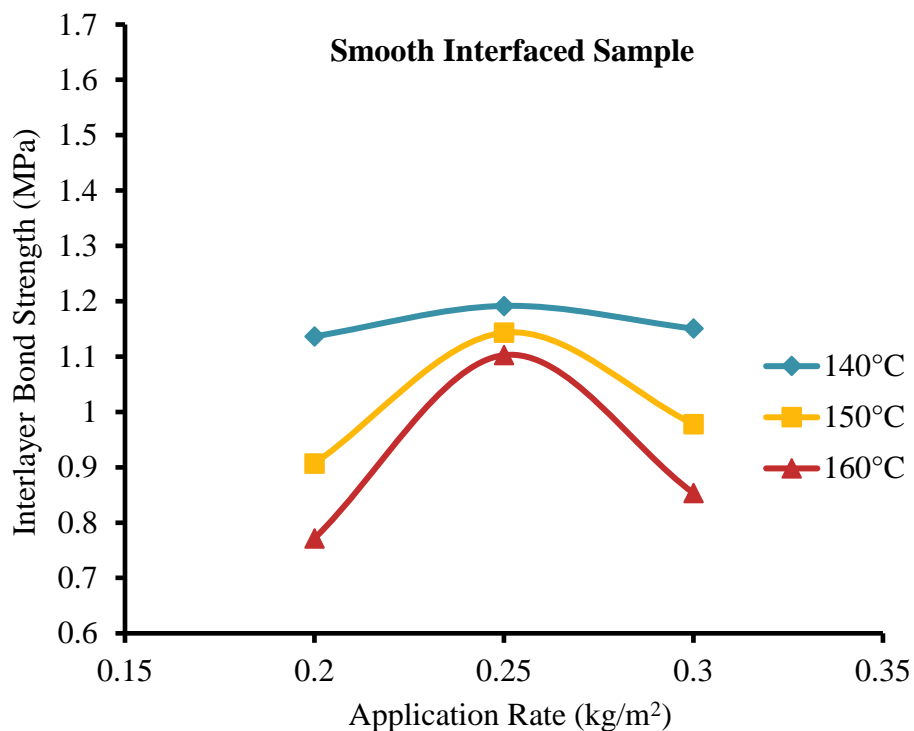


Fig. 4.7 Interlayer Bond Strength at different application rates for smooth interfaced samples

Table No. 4.1 Interlayer bond strength values for different application rate at varying laying temperature for smooth interfaced samples

Sl. No.	Application Rate (kg/m ²)	Laying temperature (°C)	Interlayer Bond Strength (MPa)
1	0.2	140	1.137
		150	0.907
		160	0.771
2	0.25	140	1.192
		150	1.143
		160	1.103
3	0.3	140	1.151
		150	0.978
		160	0.853

Table No. 4.1 shows Interlayer Bond Strength (ILBS) values for different application rate at varying laying temperature for smooth interfaced samples. From the Fig. 24, it is clear that the ILBS increases as the application rate of tack coat increases upto a specific point. After reaching that point, the ILBS begins to decrease. This can be seen in every laying temperature of 140°C, 150°C and 160°C. Therefore an optimum application rate of tack coat is present at different laying temperatures. For 140°C, 150°C and 160°C, the maximum interface bond strength obtained were 1.192, 1.143 and 1.103 respectively and these were found at 0.25 kg/m² application rate of tack coat. Therefore, the optimum tack coat application rate for every laying temperature was found to be at 0.25 kg/m². The reduction in shear strength at 0.2 kg/m² application rate of tack coat was because there might not adequate amount of tack coat at the interface in order to bind the two layers together. The reduction of shear strength at much higher amount of tack coat, that is at 0.3 kg/m² tack coat application rate, might be because the amount of tack coat may be in excess and created a slipping layer in between the layers. This might have reduced the shear strength.

For 140°C, 150°C and 160°C, the maximum interface bond strength obtained were 1.192 MPa, 1.143 MPa and 1.103 MPa respectively. From the Fig. 24, it is also evident that, as the laying temperature increases the bond strength decreases. As the laying temperature was increased from 140°C to 160°C for 0.25 kg/m² application rate, the shear strength

was decreased from 1.192 MPa to 1.103 MPa which is a 7% reduction in shear strength. The reduction in shear strength might be because as temperature increases, the viscosity of the tack coat decreases which might have reduced the binding property of the tack coat.

For smooth interfaced samples, the maximum Interlayer Bond Strength (ILBS) value was obtained as 1.191 MPa at 140°C for 0.25 kg/m² of tack coat application rate.

Fig. 4.8 shows the variation in Interlayer Shear Strength of rough interfaced sample at different application rates for varying laying temperatures.

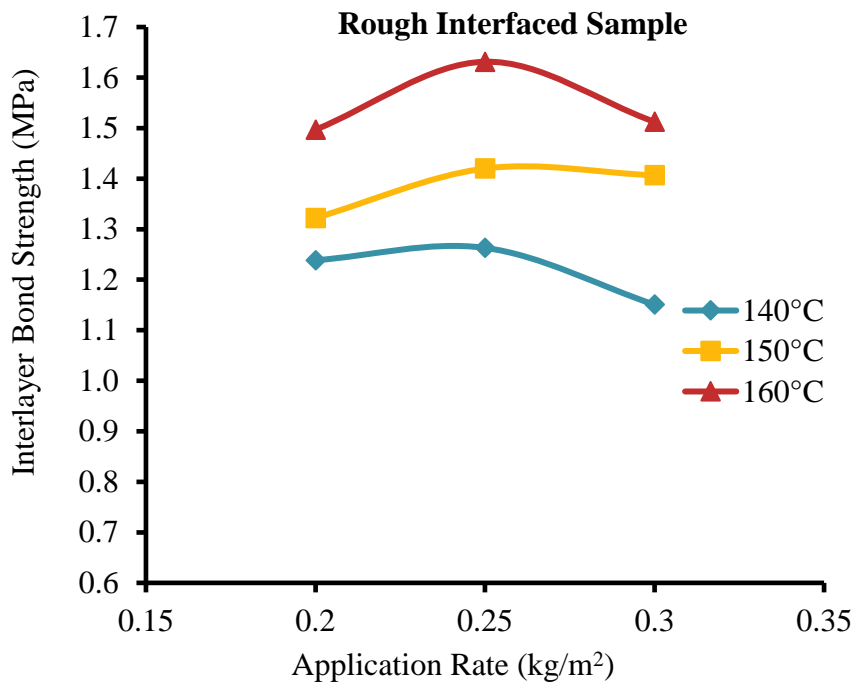


Fig. 4.8 Interlayer Bond Strength at different application rate for rough interfaced samples

From the Fig. 4.8, it is clear that the ILBS increases as the application rate of tack coat increases upto a specific point for rough interfaced samples also. After reaching the point, the ILBS began to decrease. This have been seen in every laying temperature of 140°C, 150°C and 160°C. Therefore, an optimum application rate of tack coat is present for every laying temperatures. Table No. 10 shows Interlayer Bond Strength (ILBS) values for different application rate at varying laying temperature for rough interfaced samples.

Table No. 4.2 Interlayer bond strength values for different application rate at varying laying temperature for rough interfaced samples

Sl. No.	Application Rate (kg/m ²)	Laying temperature (°C)	Interlayer Bond Strength (MPa)
1	0.2	140	1.238
		150	1.322
		160	1.497
2	0.25	140	1.263
		150	1.420
		160	1.631
3	0.3	140	1.203
		150	1.406
		160	1.512

For 140°C, 150°C and 160°C, the maximum interface bond strength obtained were 1.263 MPa, 1.420 MPa and 1.631 MPa respectively and these were found at 0.25 kg/m² application rate of tack coat. Therefore, the optimum tack coat application rate was found to be at 0.25 kg/m².

For 140°C, 150°C and 160°C, the maximum interface bond strength at 0.25 kg/m² application rate were obtained as 1.263 MPa, 1.420 MPa and 1.631 MPa respectively. From the Fig. 4.8, it is also evident that, as the laying temperature increases the bond strength increases. When the laying temperature was increased from 140°C to 160°C for 0.25 kg/m² application rate, the shear strength was increased from 1.263 MPa to 1.631 MPa which is about 22% increment in shear strength. The increment in shear strength might be because as temperature increases, the melting of the interface increases and helps in better bonding between the layers. The roughness in between the layers helps in better interlocking of the layers. The increase in temperature might have given more advantage in bonding.

Fig. 4.9 and Fig. 4.10 are bar graphs showing the values of interlayer bond strength for different application rates at different laying temperatures.

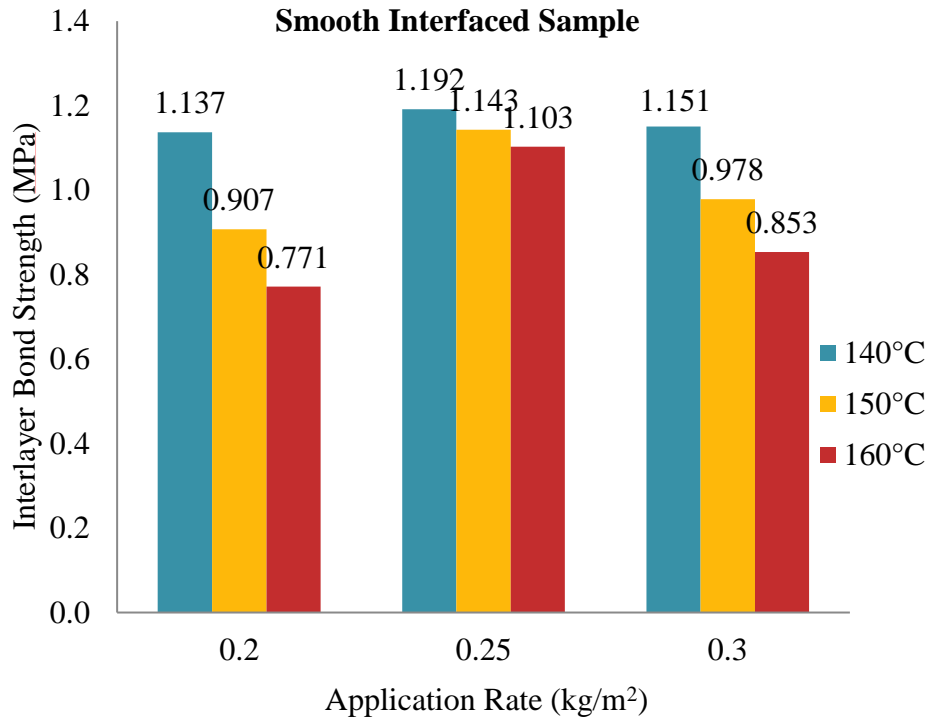


Fig. 4.9 Interlayer Bond Strength for different application rates at different laying temperatures for smooth interfaced samples

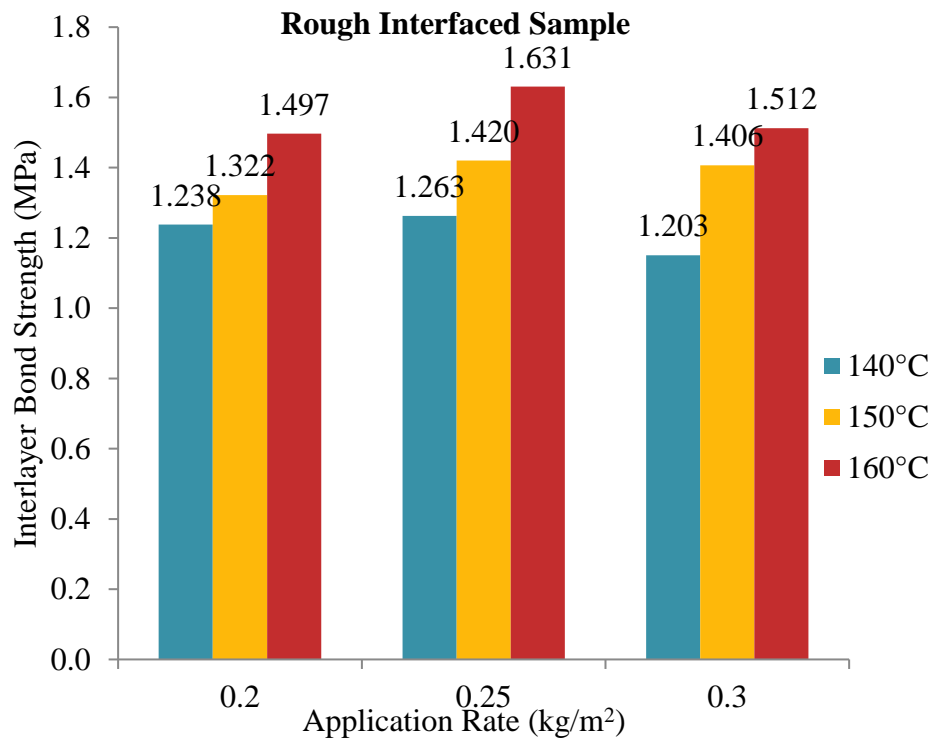


Fig. 4.10 Interlayer Bond Strength for different application rates at different laying temperatures for rough interfaced samples.

From the Fig. 4.9 and Fig. 4.10, at 140°C of laying temperature the values of ILBS comes in between 1.1 MPa and 1.2 MPa for every application rate considered and for both smooth and rough interfaced samples. Therefore, it is clear that at 140°C of laying temperature, the ILBS is less dependent on the application rate and interlayer surface roughness.

Table No. 4.3 Increase in ILBS for rough interfaced samples at various application rates and laying temperatures

Sl No	Application Rate (kg/m ²)	Laying Temperature (°C)	ILBS Without groove (MPa)	ILBS With groove (MPa)	Increase In ILBS (%)
1	0.2	140	1.137	1.238	8.2
		150	0.907	1.322	31.4
		160	0.771	1.497	48.5
2	0.25	140	1.192	1.263	5.6
		150	1.143	1.420	19.5
		160	1.103	1.631	32.4
3	0.3	140	1.151	1.203	4.3
		150	0.978	1.406	30.4
		160	0.853	1.512	43.6

The Table No. 4.3 shows increase in interlayer shear strength rough interfaced samples compared to that with smooth interfaced ones for different laying temperatures and application rates. The maximum variation in ILBS was shown at 160°C for 0.2 kg/m² of application rate. The ILBS value for smooth interfaced sample was found to be 0.771 and that for rough interfaced sample was found to be 1.497 MPa at this condition. This resulted in a percentage variation of 48.5% increment in ILBS for the rough interfaced samples than the smooth interfaced samples. This might be because, there might be too little amount of tack coat present in between the layers for providing proper binding and the high temperature would have resulted in loss in binding property of the tack coat. Therefore, inadequate amount of tack coat along with high temperature resulted in least value of ILBS for smooth interfaces samples in this combination. Meanwhile, the high temperature was favourable for the grooved surface in order to provide better interlocking

between the irregularities of the grooved surface. This resulted in increased ILBS for rough interfaced samples at this condition.

It is also obvious from the Table No. 4.3, that as the temperature increases the variation in ILBS between the smooth and the rough interfaced samples also increases for every application rates considered. At 140°C, as stated above, the value of ILBS obtained was independent of the application rate and the interlayer surface roughness. The maximum variation was only 8.2% for 140°C. This resulted in minimum variation of ILBS between smooth and rough interfaced samples. As, temperature increases, the ILBS of smooth interfaced samples decreases whereas, for rough interfaced samples, increased temperature is a favourable condition. Therefore, there is a larger variation of ILBS in 150°C and 160°C than in 140°C. Further increase in temperature resulted in additional increase in the percentage variation of ILBS shows that the increase in laying temperature reduces the ILBS for smooth interfaced samples and increases the ILBS for rough interfaced samples on a much greater rate.

4.3 EFFECT OF MOISTURE

In order to find the effect of moisture induced on interlayer bond strength, two sets of samples, ie., one set from the smooth interfaced sample and another with rough interfaced sample which gave the highest shear value was casted. For smooth interfaced sample, the condition which gave maximum value of ILBS was 0.25 kg/m² application rate at 140°C. For rough interfaced sample, the maximum value of ILBS was for sample with 0.25 kg/m² at 160°C. Three samples were casted for each set and immersed in water for a period of 24 hours. Then the shear value is determined for each set by using Leutner shear test and compared with those sample which gave maximum shear value at the same condition.

Fig. 4.12 and Fig. 4.13 shows the load-deflection graph for normal sample and moisture induced sample for smooth interfaced sample and rough interfaced sample. For smooth interfaced sample, the maximum load value was 21.371 kN. The induction of water resulted in 13.763 kN as the peak load. For rough interfaced samples, the value of peak load obtained was 30.904 kN. The induction of water caused a reduction of the peak load to 18.401 kN.

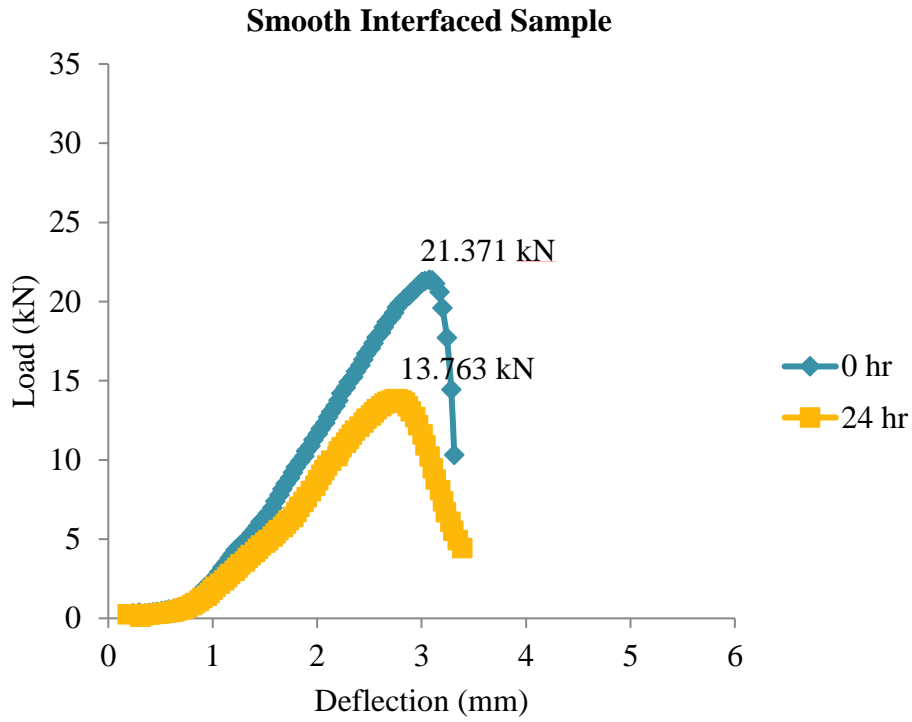


Fig. 4.11 Load-deflection graph for smooth interfaced sample

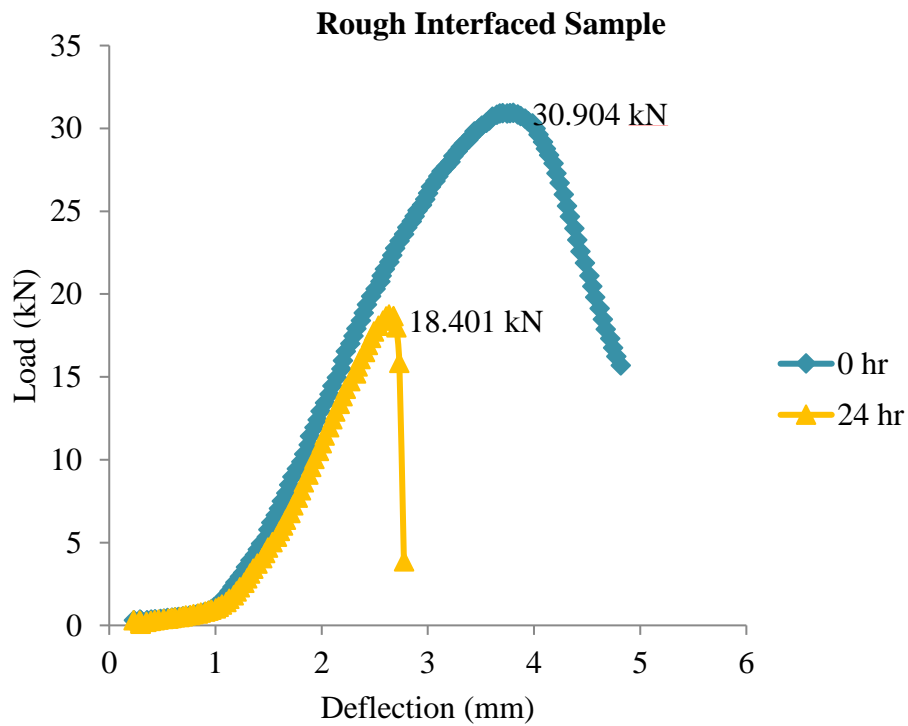


Fig. 4.12 Load-deflection graph for rough interfaced sample

Fig. 4.13 shows the bar graphs representing the difference in interlayer bond strength for moisture induced and normal sample for smooth interfaced and rough interfaced samples.

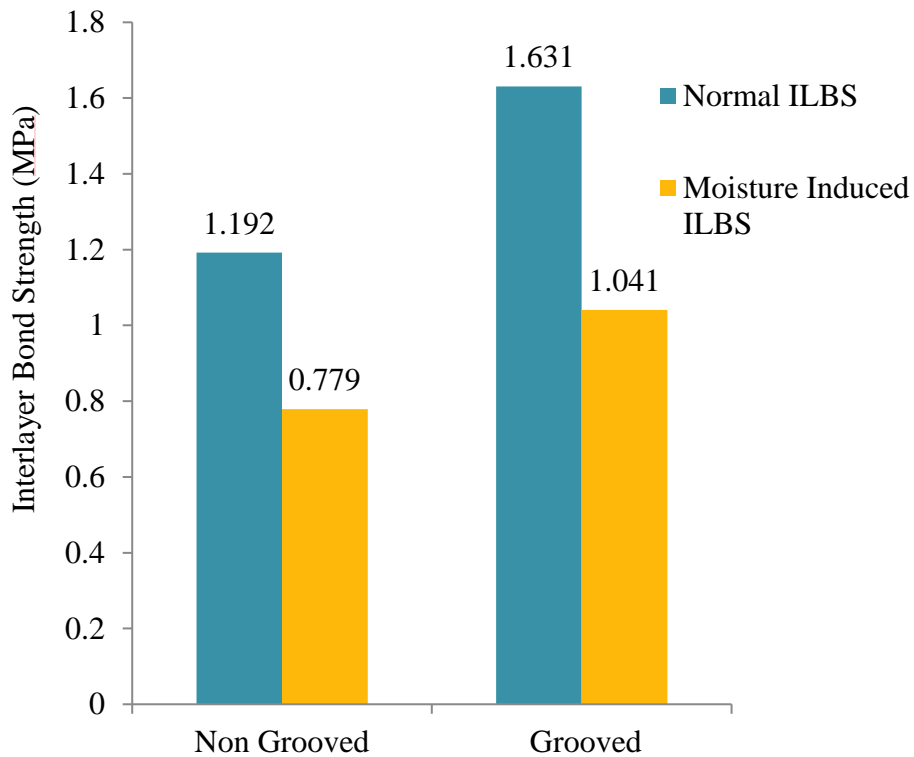


Fig. 4.13 Bar graph showing variation in ILBS for moisture induced for smooth and rough interfaced sample

For smooth interfaced (non-grooved) sample, the normal ILBS was 1.192 MPa whereas after the moisture induction for 24 hours, the ILBS value was reduced to 0.779 MPa. Therefore, there is about 36% decrease in ILBS for moisture induced smooth interfaced sample. For rough interfaced (grooved) sample, the normal ILBS was found to be 1.631 MPa and after the moisture induction for 24 hours the ILBS was reduced to 1.041 MPa. Therefore, for rough induced samples also, there is about 36% decrease in ILBS.

5. CONCLUSION

The physical properties of aggregate, bitumen (VG 30) and emulsion (RS-1) was done and found to be suitable for road construction as per MoRTH and IS:8887 specifications. Leutner shear test was conducted on prepared samples of varying parameters such as tack coat application rate, laying temperature of BC layer and interface surface roughness. It was found that 0.25 kg/m^2 as the optimum application rate of tack coat for all the laying temperatures considered. 140°C was found to be the optimum laying temperature of BC that gave maximum shear strength for smooth interfaced samples. When the laying temperature was increased from 140°C to 160°C for 0.25 kg/m^2 application rate, the shear strength was decreased from 1.192 MPa to 1.103 MPa which is a 7% reduction in shear strength. Whereas 160°C was found to be the optimum laying temperature for rough interfaced samples. When the laying temperature was increased from 140°C to 160°C for 0.25 kg/m^2 application rate, the shear strength was increased from 1.263 MPa to 1.631 MPa which is about 22% increment in shear strength.

For smooth interfaced samples, increase in temperature resulted in decrease in shear strength. This might be because increase in temperature may have resulted in decrease in viscosity which would have led to the reduction of binding property of the tack coat. Whereas, for rough interfaced sample, the increase in laying temperature resulted increase in shear strength. This might be because, high temperature may have promoted better interlocking between the grooved and the upper layer.

At 140°C , the interlayer shear strength was found to be less independent on the application rate and surface roughness. The maximum variation of ILBS between rough interfaced and smooth interfaced samples was found to be only 8.2% at 140°C laying temperature. The maximum variation in ILBS was shown at 160°C for 0.2 kg/m^2 of application rate. The ILBS value for smooth interfaced sample was found to be 0.771 and that for rough interfaced sample was found to be 1.497 MPa at this condition. This resulted in a percentage variation of 48.5% increment in ILBS for the rough interfaced samples than the smooth interfaced samples.

For smooth interfaced samples, the optimum condition was found to be at 0.25 kg/m^2 of tack coat application rate and 140°C of laying temperature of the upper layer. Whereas,

for rough interfaced samples, the optimum condition was for 0.25 kg/m² tack coat application rate and 160°C of laying temperature.

Moisture induced on the sample for 24 hours was found to result in about 36% reduction in ILBS for both smooth and rough interfaced samples.

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APPENDIX-A

Maximum load taken by the samples for different combinations of parameters

Sample No.	Application Rate (kg/m ²)	Laying temperature (°C)	Roughness	Max Load (kN)			Average (kN)
1	0.2	140	No groove	21.850	18.377	20.027	20.085
2			Groove	18.439	25.868	21.351	21.886
3		150	No groove	15.416	16.000	16.664	16.027
4			Groove	24.230	18.542	27.322	23.365
5		160	No groove	13.143	12.998	14.758	13.633
6			Groove	23.643	29.098	26.615	26.452
7	0.25	140	No groove	21.381	24.603	17.187	21.057
8			Groove	22.339	21.653	22.964	22.319
9		150	No groove	19.902	16.489	24.212	20.201
10			Groove	25.568	22.449	27.261	25.093
11		160	No groove	24.305	17.755	16.395	19.485
12			Groove	26.754	28.778	30.949	28.827
13	0.3	140	No groove	23.754	19.550	17.693	20.332
14			Groove	24.789	18.568	20.414	21.257
15		150	No groove	14.550	16.971	20.335	17.285
16			Groove	27.472	25.526	21.564	24.854
17		160	No groove	17.049	14.629	13.564	15.081
18			Groove	28.517	26.027	25.632	26.725

Shear stress taken by the samples for different combinations of parameters

Sample No.	Application Rate (kg/m ²)	Laying temperature (°C)	Roughness	Shear Stress (MPa)			Average (MPa)
1	0.2	140	No groove	1.236	1.040	1.133	1.137
2			Groove	1.043	1.464	1.208	1.238
3		150	No groove	0.872	0.905	0.943	0.907
4			Groove	1.371	1.049	1.546	1.322
5		160	No groove	0.744	0.736	0.835	0.771
6			Groove	1.338	1.647	1.506	1.497
7	0.25	140	No groove	1.210	1.392	0.973	1.192
8			Groove	1.264	1.225	1.299	1.263
9		150	No groove	1.126	0.933	1.370	1.143
10			Groove	1.447	1.270	1.543	1.420
11		160	No groove	1.375	1.005	0.928	1.103
12			Groove	1.514	1.629	1.751	1.631
13	0.3	140	No groove	1.344	1.106	1.001	1.151
14			Groove	1.403	1.051	1.155	1.203
15		150	No groove	0.823	0.960	1.151	0.978
16			Groove	1.555	1.444	1.220	1.406
17		160	No groove	0.965	0.828	0.768	0.853
18			Groove	1.614	1.473	1.450	1.512