EVALUATION OF BOND BETWEEN BITUMINOUS PAVEMENT LAYERS

A thesis submitted in
Partial Fulfilment of the Requirements
For the Award of the Degree of

MASTER OF TECHNOLOGY
In
CIVIL ENGINEERING

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By
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Under the guidance of
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CERTIFICATE

This is to certify that the thesis entitled "**Evaluation of bond between bituminous pavement layers**" submitted by **Bidyut Bikash Sutradhar** bearing roll no. **210ce3033** to the National Institute of Technology, Rourkela, in partial fulfillment of the requirements for the award of **Master of Technology** in **Civil Engineering** with specialization in "**Transportation Engineering"** during 2010-2012 session at the National Institute of Technology, is a record of bonafide research work carried out by him under my supervision and guidance.

To the best of my knowledge, the results contained in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Date:
Place: Rourkela

Prof. Mahabir Panda
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Last but not the least I would also like to thank my parents and the Almighty whose blessings have helped me in achieving great strides.

(Bidyut Bikash Sutradhar)

ABSTRACT

The interlayer bonding of modern multi-layered pavement system plays an important role to achieve long term performance of a flexible pavement. It has been observed that poor bonding between bituminous pavement layers contributes to major pavement overlay distresses such as premature fatigue, top down cracking, potholes, and surface layer delamination. One of the most common distresses due to poor bonding between bituminous layers is a slippage failure, which usually occurs where heavy vehicles are often accelerating, decelerating, or turning. To enhance the bonding between layers, a tack coat is sprayed in between the bituminous pavement layers. A tack coat is an application of a bituminous emulsion or bituminous binder between an existing bituminous / concrete surface and a newly constructed bituminous overlay. Normally, hot bituminous binders, cutback bitumens or bituminous emulsions are used as tack coat materials.

This study is aimed to evaluate the bond strength at the interface between pavement layers by performing laboratory tests. To carry out this objective, three special attachments are fabricated for use in Marshall Loading Frame for finding the performance of tack coat laid at the interface between Bituminous Concrete (BC) and Dense Bituminous Macadam (DBM) layers in the laboratory. In this study, the results of the specimens prepared with 100 mm and 150 mm diameter specimens using two types of normally used emulsions, namely CMS-2 and CRS-1 as tack coat at application rates varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 made at 25^{0}C temperature are presented.

It is observed that CRS-1 as tack coat provides higher interface bond strength value compared to CMS-2. Similarly, irrespective of the types of emulsions used as tack coat, the optimum rate of application is found to be 0.25 kg/m^2 as recommended in MORT&H’s specifications.

Keywords: Interlayer, bond strength, shear strength, tack coat, performance

TABLE OF CONTENTS

Chapter 4 RESULTS AND DISCUSSION

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

RS = Rapid Setting
MS = Medium Setting
SS = Slow Setting
RC = Rapid Curing
MC = Medium Curing
CRS = Cationic Rapid Setting
CMS = Cationic Medium Setting
CSS = Cationic Slow Setting
HMA = Hot Mix Asphalt
mm = Millimeter
kN = Kilonewton
cm = Centimeter
in = Inch
MTS = Material Testing System
psi = Pound-force per square inch
AC = Asphalt Cement
PG = Performance Graded
PCC = Portland Cement Concrete
gal = Gallon
yd = Yard
DBM = Dense Bituminous Macadam
BC = Bituminous Concrete
IS = Indian Standard

ASTM = American Society for Testing and Materials

Kg = Kilogram

g = Gram

sec = Second

MORT&H = Ministry Of Road Transport and Highways

kPa = Kilopascal

CHAPTER I
INTRODUCTION

1.1 Problem Statement

The modern flexible pavement is generally designed and constructed in several layers for effective stress distribution across pavement layers under the heavy traffic loads. The interlayer bonding of the multi-layered pavement system plays an important role to achieve long term performance of pavement. Adequate bond between the layers must be ensured so that multiple layers perform as a monolithic structure. To achieve good bond strength, a tack coat is usually sprayed in between the bituminous pavement layers. As a result, the applied stresses are evenly distributed in the pavement system and subsequently, reduce structural damage to the pavements.

It has been observed that poor bonding between pavement layers contributes to major pavement overlay distresses. One of the most common distresses due to poor bonding between pavement layers is a slippage failure, which usually occurs where heavy vehicles are often accelerating, decelerating, or turning. The vehicle load creates dynamic normal and tangential stresses in the pavement interfaces from horizontal and vertical loads. With the vehicle load being transferred to each underlying bituminous layer, the interface between the layers is vital to the pavements integrity. Slippage failure develops when the pavement layers begin to slide on one another usually with the top layer separating from the lower layer. This is caused by a lack of bond and a high enough horizontal force to cause the two layers to begin to separate. Other pavement problems that have been linked to poor bond strength between pavement layers include premature fatigue, top down cracking, potholes, and surface layer delamination. One such result is the formation of cracks in the shape of a crescent as shown in figure 1.1.

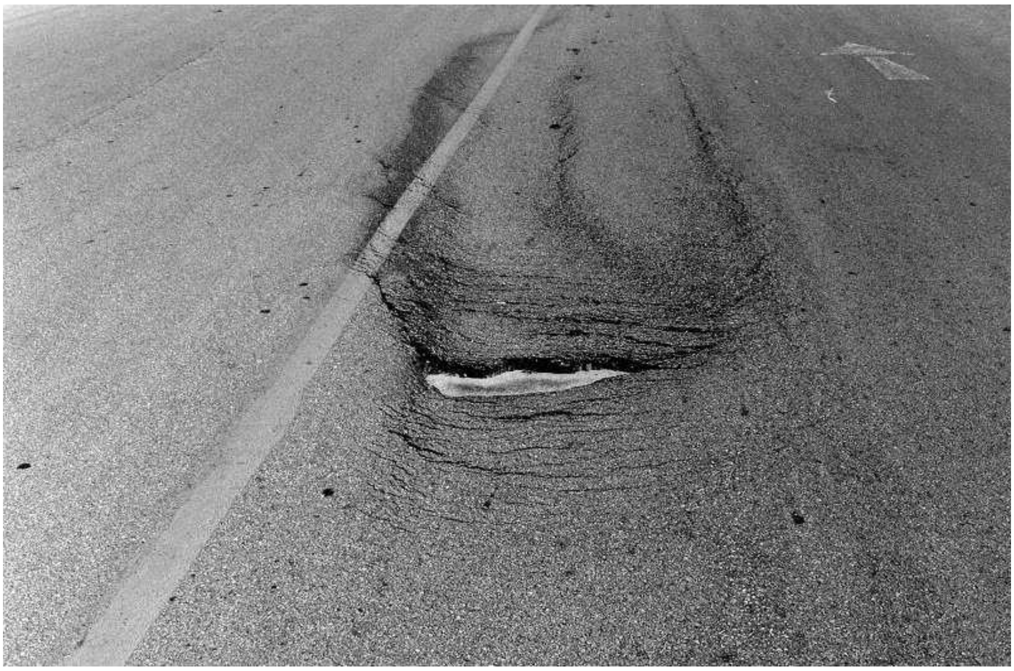


Figure 1.1: Slippage Crack (http://www.surface-engineering.net)

1.2 Background on Tack Coat

A tack coat is an application of a bituminous emulsion or bituminous binder between an existing bituminous / concrete surface and a newly constructed bituminous overlay. A tack coat is also known as bond coat as it is used to bond one pavement layer to another. A tack coat acts as an adhesive or glue so that combined pavement layers perform as a monolithic structure rather than individual sections. Typically, tack coats are emulsions consisting of bituminous binder particles, which have been dispersed in water with an emulsifying agent. Bituminous particles are kept in suspension in the water by the emulsifying agent and thus bitumen consistency is reduced at ambient temperature from a semi-solid to a liquid form. This liquefied bitumen is easier to distribute at ambient temperatures. When this liquid bitumen is applied on a clean surface, the water evaporates from the emulsion, leaving behind a thin layer of residual bituminous on the pavement surface. When the bituminous binder is used as a tack coat, it requires heating for application (Rahman, 2010).

Normally, hot bituminous binder, cutback bitumen or bituminous emulsions are used as tack coat materials. However, the use of bituminous emulsions as a tack coat material is escalating instead of cutback asphalt or hot bituminous binder because of the following advantages:

1. Bituminous emulsions can be applied at lower application temperatures compared to cutback bitumen or hot bituminous binder.
2. As bituminous emulsions do not contain harmful volatile chemicals, they are relatively pollution free.
3. As bituminous emulsions are water based, they have no flashpoint and are not flammable or explosive. Therefore, they are safer to use as they do not pose health risk to workers. (Patel, 2010)

Bituminous emulsion is a mixture of bituminous binder, water and emulsifying agent. The emulsifying agent could be soap, dust or colloidal clays. The microstructures as reported by Roberts et al. is shown in figure 1.2.

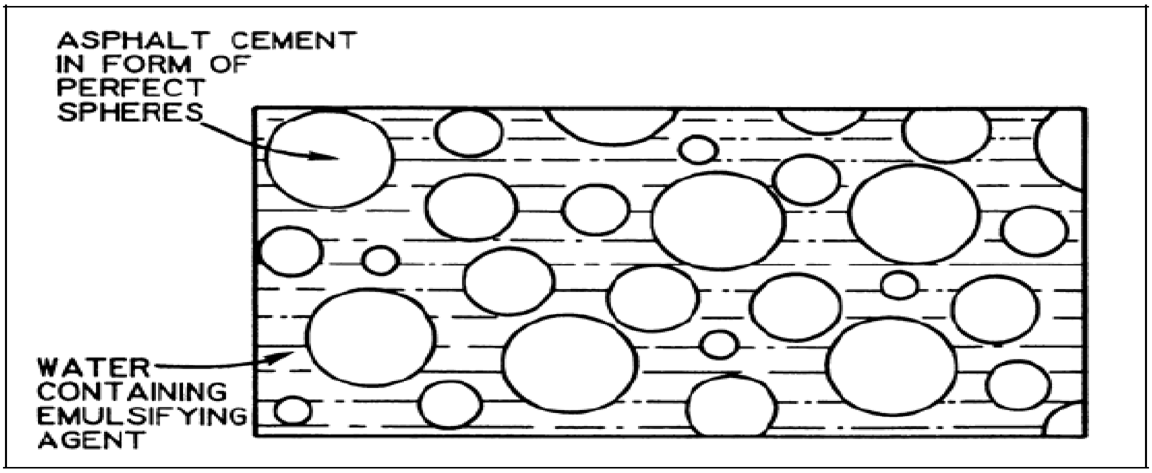


Figure 1.2: Composition of Bituminous Emulsion (Roberts et al., 1996)

Bituminous emulsions, unlike bituminous binder, are liquid at ambient temperatures. The type of emulsifying agent used in the bituminous emulsion will determine whether the

emulsion will be anionic, or cationic. Cationic emulsions have bituminous droplets which carry a positive charge. Anionic emulsions have negatively charged bituminous droplets.
Base on their setting rate, which indicates how quickly the water separates from the emulsion, both anionic and cationic emulsions are further classified into rapid setting (RS), medium setting (MS), and slow setting (SS). The setting rate is basically controlled by the type and amount of the emulsifying agent. The principal difference between anionic and cationic emulsions is that the cationic emulsion gives up water faster than the anionic emulsion. The anionic grades are: RS-1, RS-2, MS-1, MS-2, MS-2h, SS-1 and SS-1h. The cationic grades include CRS-1, CRS-2, CMS-2, CMS-2 h, CSS-1, and CSS-1h. It should be noted that the absence of letter "C" in an emulsion type denotes an anionic emulsion and vice-versa. The letter "h" stands for hard grade asphalt cement (low penetration) and the numbers "1" and "2" indicates low and high viscosity respectively (Patel, 2010).

Cutback bitumen is also liquid bitumen produced by adding petroleum solvents to bituminous binder. Typical petroleum solvent includes gasoline and kerosene. They are used as tack coats because they reduce bitumen viscosity for lower temperature use. The use of cutback bitumen as a tack coat material has declined rapidly over the years due to environmental concerns and the health risk as the solvents evaporate into atmosphere. Cutback bitumen is divided into two classifications Rapid Curing (RC) and Medium Curing (MC) based on the type of solvent used. Rapid curing cutback uses gasoline while medium curing cutback uses kerosene.

Hot bituminous binders are obtained from distillation of crude oil. Unlike emulsions, bituminous binder particles do not carry any charge. Any grade of bituminous binder is acceptable as a tack coat material, although it is generally preferable to use the same grade of bituminous binder used in the HMA for tack coat (CPB 03-1, Tack Coat Guidelines).

1.3 Research Objective

The primary objective of this study is to fabricate a few simple testing devices for the evaluation of the bond strength offered by the tack coats at the interface between bituminous pavement layers in the laboratory scale by performing several laboratory tests with different tack coat application rates. The ideal design will be that the standard setup which produces consistent results comparable to others. A secondary goal of this study is to provide helpful information for the selection of the best type of tack coat materials and optimum application rate.

1.4 Organization of the Thesis

The thesis consists of five chapters as described below:

i. A general information about bond strength between pavement layers is presented in Chapter 1. The objectives of the present studies are also described.

ii. Chapter 2 deals with a review of previous work on laboratory studies that were conducted to evaluate of bond strength between pavement layers.

iii. Chapter 3 provides a description of the experimental investigations for evaluation of bond strength between pavement layers.

iv. Analysis of the results and discussion on the experimental investigations is discussed in Chapter 4.

v. Conclusions and scope for future work of this research work is summarized in Chapter 5.

CHAPTER II
REVIEW OF LITERATURE

2.1 Introduction

In this chapter, extensive literature survey on the various laboratory studies conducted for the evaluation of bond strength between bituminous pavement layers has been discussed.

2.2 Tests to Evaluate the Interface Bond Strength of Pavement

Numerous studies have been performed investigating adhesive properties of the interface between layers. These studies have typically developed a unique test method or instrument for analysis of the interface bond strength. Literature on bond strength clearly indicates that shear force is mainly responsible for interface bond failure.

Different organizations and different researchers have used various tests for evaluating the pavement interface bond strength including the following:

- Layer-Parallel Direct Shear (LPDS);
- Ancona Shear Testing Research and Analysis (ASTRA);
- Superpave Shear Tester (SST), which has been recently modified by the Louisiana Transportation Research Center by building a shear mold assembly;
- Leutner test, originally developed in Germany;
- FDOT Shear Tester;
- LCB shear test;
- Modified Marshall Test developed by the Pennsylvania Department of Transportation;
- NCAT bond strength device developed by National Center for Asphalt Technology ;

- Shear-Testing Device developed at Mcasphalt Lab.

An overview of some of these commonly used test procedures is provided in the subsequent sections.

2.2.1 Layer-Parallel Direct Shear (LPDS)

The Swiss Federal Laboratories for Material Testing and Research developed a shear testing device known as Layer-Parallel Direct Shear (LPDS) which is a modified version of equipment developed in Germany by Leutner (1979). The modified LPDS test is used to test the 150 mm diameter cylindrical specimens using Marshall testing as reported by Raab and Partl (2002). The bottom layer of a double-layered specimen is placed on a u-bearing and the upper layer is moved with a constant displacement rate of 50.8 mm/min at a temperature of 20^0C by means of a yoke, allowing the application of a shear force at the interface as shown in figure 2.1. The shear force and the corresponding displacement are continuously recorded to find the maximum load. The nominal shear stress (τ_{LPDS}) is calculated as follows:

$$\tau_{LPDS} = F/A$$
$$= 4F/ (d^2\pi)$$

Where, F = maximal force;

A = nominal cross sectional area; and

d = specimen diameter.

The study was conducted to evaluate the influence of compaction (50 and 204 gyrations), surface texture (smooth and rough), moisture, heat and water on the interface shear bond of pavements by using 20 different types of tack coats. The study concluded that higher shear strengths were observed for the specimens with the smooth surface than the specimens with rough surface. The results clearly indicated the negative influence on adhesion due to the presence of moisture and absence of tack coat. The study also reported the improvement of shear adhesion up to 10% for a top-layer compaction at 240 gyrations by using a certain tack coat, while such improvement was not observed for 50 gyrations.

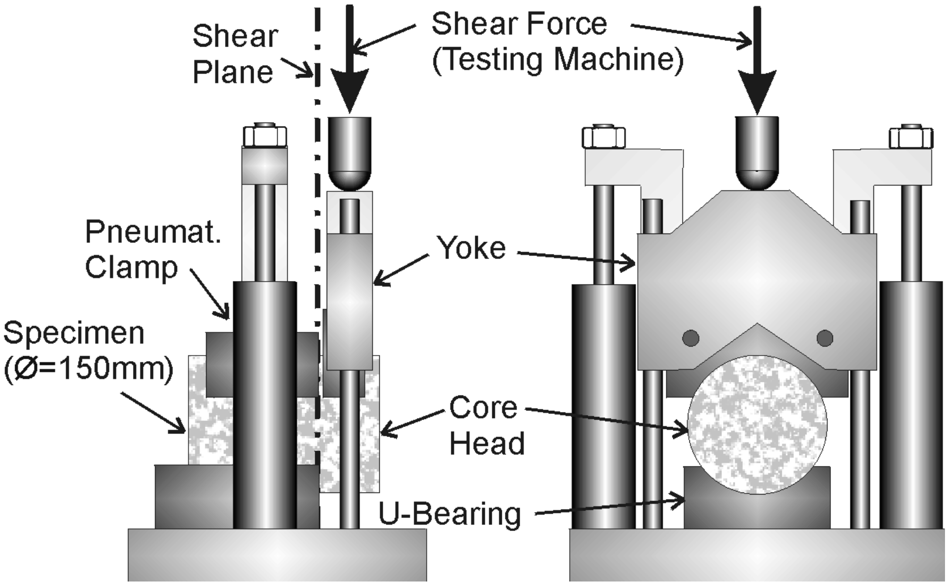


Figure 2.1: Schematic view of the LPDS (Layer-Parallel Direct Shear) test device (Raab and Partl; 2002)

2.2.2 Ancona Shear Testing Research and Analysis (ASTRA)

This device was designed in Universita Politecnica delle Marche in Italy (Santagata et.al., 1993) to evaluate the shear resistance property of interface. A horizontal load is applied along the interface of double-layered cylindrical specimens of 100 mm diameter at a constant displacement rate of 2.5 mm/min until failure; in the meantime, a constant normal load is applied on top of the specimen as shown in figure 2.2. The study was conducted to examine influence of tack coat type, temperature, and applied normal load, on the interlayer shear resistance. The study concluded that the interface shear strength increased with an increase in normal stress for a given temperature. The interface shear strength was found to increase with a decrease in temperature for a given normal stress. Also irrespective of the temperature and normal stress, interfaces with tack coat treatment provided higher shear strengths compared to interfaces with no treatment.

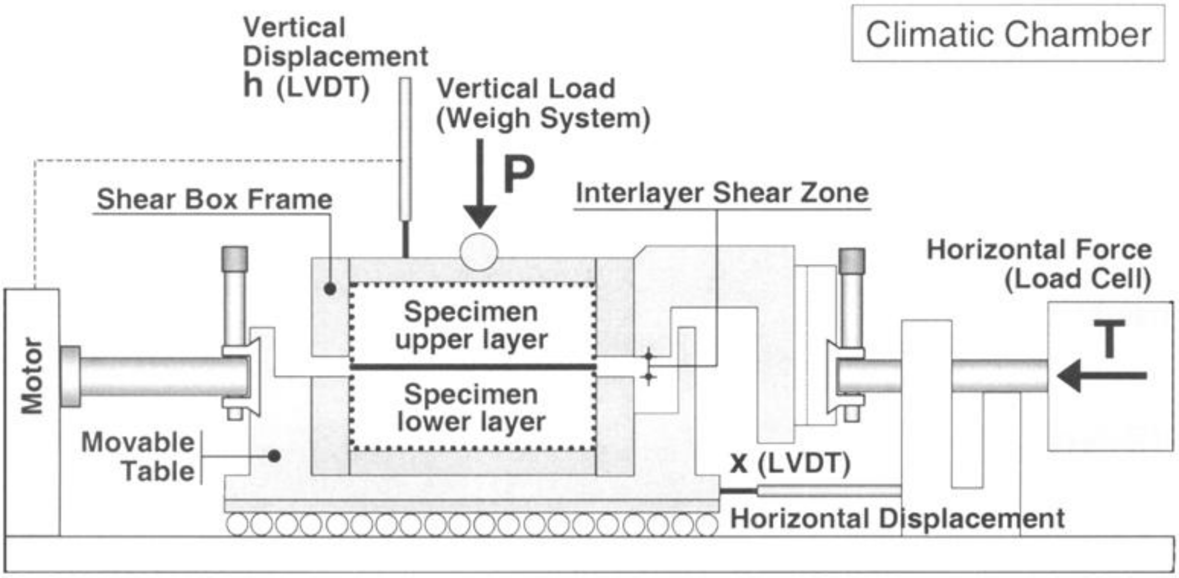


Figure 2.2: Schematic view of the Ancona Shear Testing Research and Analysis (ASTRA) device (Santagata et al., 2005)

2.2.3 Superpave shear tester (SST)

Mohammad et al. (2002) evaluated the influences of tack coat types, application rates, and test temperature on the interface shear strength using the Superpave Shear Tester (SST). The shear apparatus has two chambers to hold the specimen during testing, which are mounted inside the SST as shown in figures 2.3.1 and 2.3.2. The specimen can be tested at different temperatures as the environmental chamber of the SST controls the test temperature. The shear load is applied at a constant rate of 0.2 kN/min on the specimen until failure. The shear stress on the interface is calculated by dividing the shear load by the cross sectional area of the interface.

Shear Stress = Shear Load/ Area

Where, Area=π (R)^{2} and

R= radius of the sample.

Laboratory tests were conducted on double-layered specimens prepared using four emulsions (CRS-2P, SS-1, CSS-1, and SS-1h) and two asphalt binders (PG 64-22 and PG 76-22M) as tack coat materials applied at five different rates from 0.0 to 0.2 gal/yd^2 (0.0 to 0.9 L/m^2) at two different test temperatures 77^{0}F and 131°F (25^{0}C and 55°C). The study concluded CRS-2P as the best tack coat material and 0.02 gal/yd^2 (0.09 l/m^2) as the optimum application rate for both test temperatures. The study also indicated that the shear strengths were generally about five times greater at 77^{0}F (25^{0}C) compared to 131ºF (55^{0}C).

Figure 2.3.1: Shear Box with Prepared (Mohammad et al., 2002)

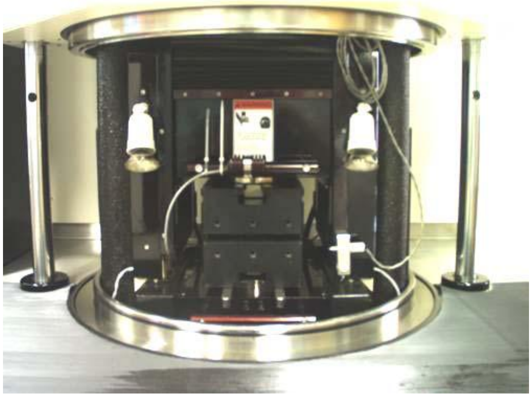


Figure 2.3.2: Shear Box Inside SST Sample (Mohammad et al., 2002)

2.2.4 Leutner Test

Sangiorgi et al. (2002) developed a shear testing device called a Leutner test as shown in figure 2.4. This testing device is standard in Austria, has also been adopted in the UK. A vertical shear load is applied to a 150 mm double-layered cylindrical specimen at a constant deformation rate of 50 mm/min at 20^{0}C until failure. The study was investigated to evaluate bond condition between surfacing and binder course materials, and binder course and base course materials. Three different interface treatments were considered to simulate actual conditions: (1) with tack coat emulsion, (2) contaminated by dirt and without tack coat emulsion, and (3) with tack coat emulsion and a thin film of dirt. Results indicated that the best bond strength was achieved with an interface treatment prepared using an emulsified tack coat, while the poorest bond conditions were observed on a dirty surface without emulsion.

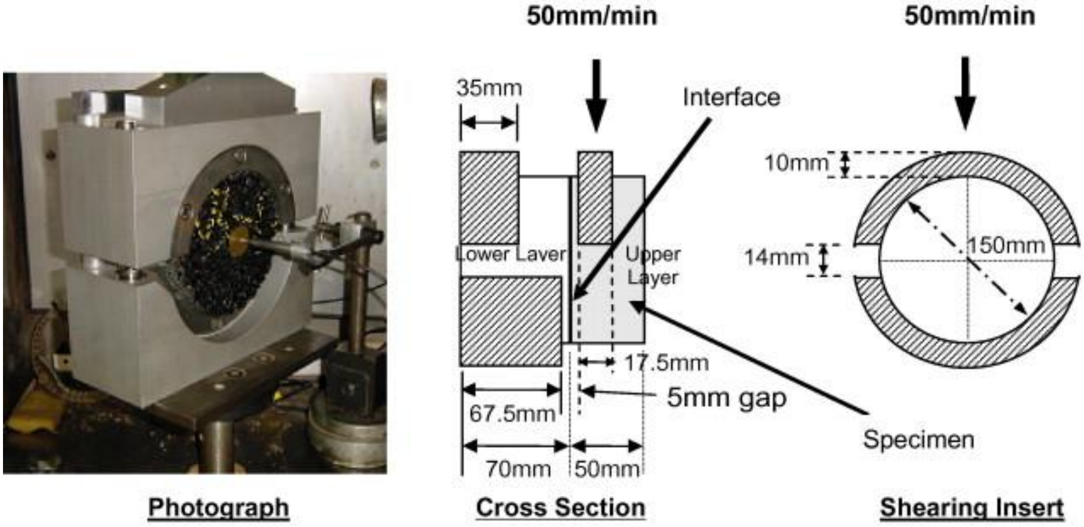


Figure 2.4: Leutner Shear Strength Tester (Sangiorgi et al., 2002)

2.2.5 FDOT Shear Tester

In 2003, the Florida Department of Transportation (FDOT) developed a simple direct shear device that was used in a universal testing machine or a Marshall Stability apparatus after an extensive literature review and laboratory testing, as well as field investigation.

This device allows the testing of 150 mm cylindrical samples using two rings. The space between the two rings is 4.76 mm which is to account for the uneven surface of the cored specimens. The load application is strain controlled at a rate of 50.8-mm/min, which can be easily achieved in the Marshall Stability test apparatus. Before performing the test, the field core is conditioned at a temperature of 25±1°C for a minimum of 2 hours. The core is then placed between the shear plates so that the direction of traffic marked on the core is parallel to the shear direction. The core is then deformed at a constant rate of 50 mm/min until failure occurs. The shear strength is then calculated by using the following equation:

$S_B = 4P_{max}/ (\pi D^2)$

Where, S_B = the shear strength (psi)

P_{max} = the maximum load applied to the specimen (lbf)

D= the diameter of the specimen (in)

The study involved the evaluation of several variables such as application rate, surface condition, surface texture, and mixture type on field core specimens obtained from test sections prepared by applying 0.0, 0.02, 0.05 and 0.08 gal/yd^2 (0.00, 0.091, 0.226, and 0.362 l/m^2 respectively) as tack coat application rate. Based on their investigations, an application rate of 0.05 gal/yd^2 (0.266 l/m^2) was found to an optimum rate of application. Also significant reduction of shear strengths was observed due to the presence of moisture at the interface. The shear strengths for fine graded mixtures were significantly lower as compared to coarse graded mixtures. Also the highest strength was observed for the milled interface.

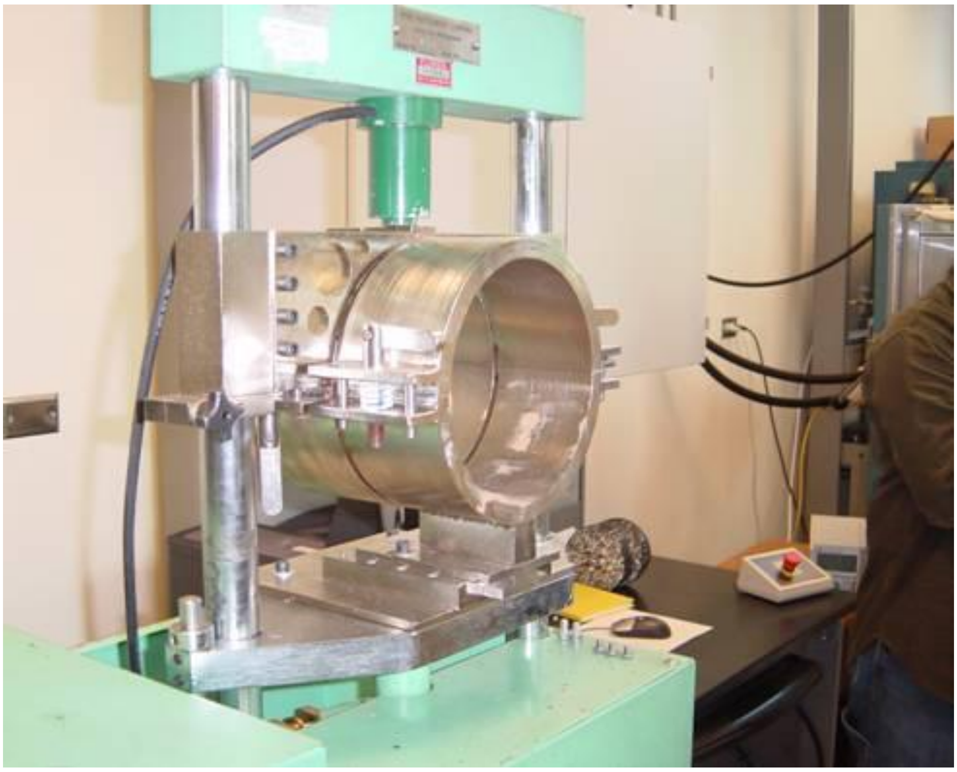


Figure 2.5: FDOT Shear Tester device inside an MTS (Courtesy of FDOT)

2.2.6 LCB TEST

In 2006, the Road Research Laboratory of the Technical University of Catalonia designed a simple shear testing device which was intended to measure bond strength between the two bituminous layers. The cylindrical specimen is considered as a beam located over two supports such that the bonded interface is very close to one of the supports in order to avoid the generation of bending stress and the specimen fails due to shear stress only.

The specimen is placed inside the mould so that the bonded interface is 5 mm beyond the top of the mould. The mould with the specimen inside is laid horizontally over two supports 20 cm apart. The mould rests on one support and the top layer of the specimen on the other one so that the bonded interface is at a distance of 5 mm from this support. A load of constant deformation rate of 1.27 mm/min is applied over the metallic mould at a distance of 10 cm from each support until the failure occurrs as shown in figure 2.6.

The shear strength is then calculated using the following equation:

$\tau = (P / 2)/ S$

Where τ = the shear strength,

P = the maximum failure load and

S = the surface area of the specimen.

The study investigated the performance of different heat adhesive emulsions. The emulsions used for the study included two hard residual heat-adhesive emulsions a conventional one (E1-h) and one modified with polymers (E2-h-m) and one conventional type ECR-1 (E3) manufactured with a 150/200 penetration bitumen. It was observed that modified heat-adhesive emulsion performed best over the selected range of temperatures. Although the conventional heat adhesive emulsion performed well at medium temperatures, it did not achieve the same resistance at low temperatures as it was more temperature susceptible.

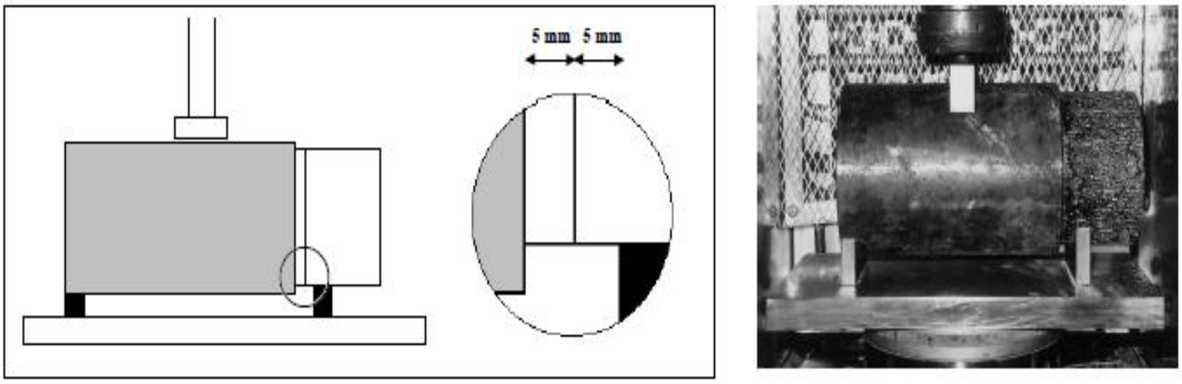


Figure 2.6: Schematic and actual view of LCB shear test (Miro et al., 2006)

2.2.7 Modified Marshall Jig

In 2008, the Pennsylvania Department of Transportation fabricated a modified Marshall jig which consists of two hollow cylinders aligned horizontally. One of the cylinders is fixed at its bottom to a base plate, while the other can move vertically with minimum friction along the four columns. A load of constant deformation at a rate of 50.8-mm/min is applied on a smooth horizontal stripe located on the top of the movable cylinder. This study presented the effectiveness of an ultra rapid-setting emulsion to that of a CRS-1h emulsion. Test results conducted on 150 mm diameter specimens at a temperature of 25^0C clearly indicated the similar shear strength value for both types of emulsions.

2.2.8 NCAT Bond Strength Device

National Center for Asphalt Technology (NCAT) developed a shear testing device that can be used in a Marshall Stability apparatus. A vertical shear force is applied to 150 mm cylindrical double-layered specimens along the interface with strain control mode at constant rate of 50 mm/min until failure as shown in figure 2.7. The bond strength, S_B is calculated based on the maximum load as follows:

$S_B = P_{MAX} / A$

Where ,

S_B = bond strength, psi

P_{MAX} = maximum load applied to specimen, lbf

A = cross-sectional area of test specimen, in^2.

West et al. [2005] conducted a two-phase project included both laboratory and field phases for evaluating the bond strength between pavement layers. For the laboratory phase, the following were evaluated: two types of emulsion (CRS-2 and CSS-1) and a PG 64-22 asphalt binder; three residual application rates (0.02, 0.05, and 0.08 gal/yd^2); and two mix types [19 mm nominal maximum aggregate size (NMAS) coarse-graded and 4.75 mm NMAS fine-graded].

Bond strengths were measured using normal Superpave mix design specimens at three temperatures (10, 25, and 60°C) and three normal pressure levels (0, 10, and 20 psi). The main observations drawn from the laboratory study were as follows:

1. As the temperature increased, bond strength decreased significantly for all tack coat types, application rates, and mixture types at all normal pressure levels.

2. PG 64-22 exhibited higher bond strength than the two emulsions, especially for the fine-graded mixture tested at high temperature.

3. For the application rates studied, tack coats with low application rates generally provided high bond strength for the fine-graded mixture; however, for the coarse graded mixture, bond strength did not change much when application rate varied.

4. At high temperature, when normal pressure increased, bond strength increased, while, at intermediate and low temperatures, bond strength was not sensitive to normal pressure.

In phase two, seven field projects were performed to validate the bond strength test results of phase one using the same tack coat material. Tack coat was sprayed on milled or unmilled pavement surface before the HMA overlay was placed and compacted. For projects using an emulsified asphalt tack coat material, the residual application rates were 0.03, 0.045, and 0.06 gal/yd^2 (0.15, 0.23 and 0.30 l/m^2). For projects using a paving paving grade binder as the tack coat material, the target application rates were 0.03, 0.05, and 0.07 gal/yd^2 (0.15, 0.25 and 0.35 l/m^2). The tack coats were applied by three methods; hand wand sprayer, distributor truck spray bar and Novachip spreader. A Novachip spreader featured a spray bar attached to the asphalt paver. The main observations of the field study were as follows:

1. Milled HMA surfaces appeared to significantly enhance bond strength with a subsequent asphalt pavement layer;
2. Despite the fact that paving-grade asphalt tack coats appeared superior to emulsified asphalt tack coats, the differences were not statistically significant; and
3. Bond strengths in sections that used the Novachip spreader for application of tack coat were significantly higher than similar sections that applied tack coat using a distributor truck.

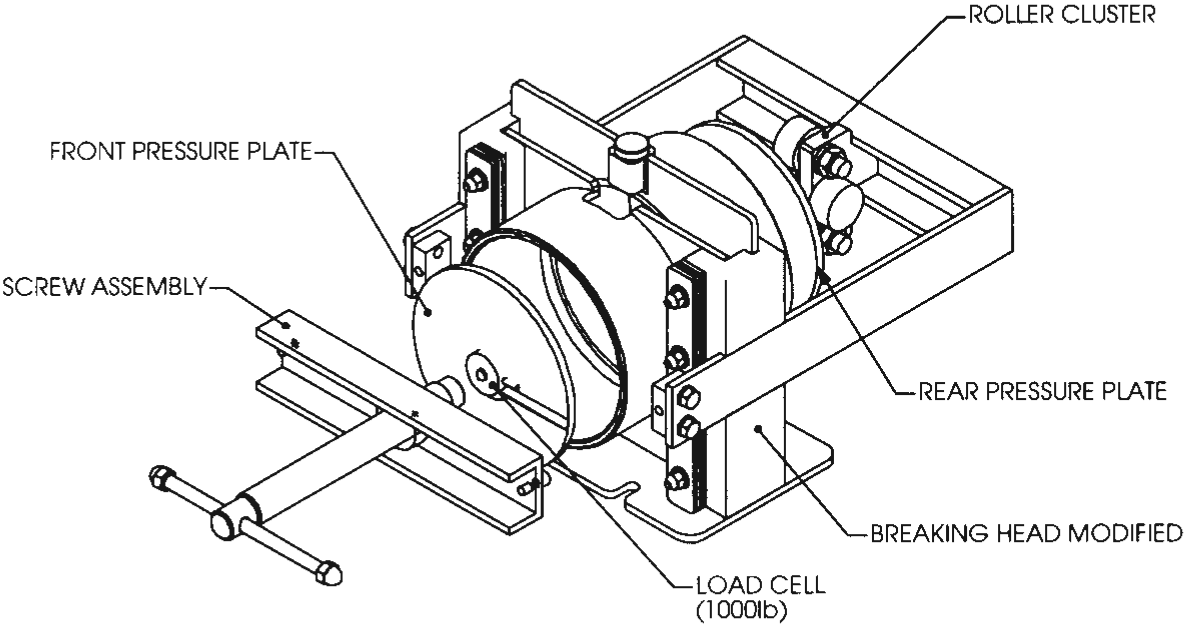


Figure 2.7: Illustration of NCAT Bond Strength Device (West et al., 2005)

2.2.9 Shear-Testing Device developed at Mcasphalt Lab

Tony Kucharek et al. developed Modified Marshall stability mould at Mcasphalt lab. One of the moulds is fixed at its bottom to a base plate, while the other semi circular sleeve can move vertically with minimum friction along the two guiding rods. A load of constant deformation at a rate of 50.8-mm/min is applied on a smooth horizontal stripe located on the top of the shear sleeve adjacent to the interface as shown in figure 2.8. This laboratory study was conducted on double-layered specimens prepared using 16 emulsions applied at 0.05, 0.1 and 0.15 kg/m^2 to evaluate the influence of substrate characteristics . The study concluded that the rougher substrate revealed higher shear strength compared to smoother surface.

Figure 2.8: Shear-Testing device developed at McAsphal Lab (Tony Kucharek et al.)

2.3 Important factors affecting the interface bond strength of pavement

Existing literature clearly reveals the important factors affecting the interface bond strength of pavement include rate of displacement, tack coat type, tack coat application rate, testing temperature and normal pressure at the interface.

2.3.1 Influence of rate of displacement

The samples tested at greater displacement rates require a greater load to fail because of the viscoelastic nature of bituminous binder. Sholar et al. (2003) concluded from the experiments that the core samples tested at greater displacement rate exhibited a higher average failure shear stress (60 psi) compared to the samples tested at 0.75 in/min (38 psi).

2.3.2 Influence of tack coat type

Previous literature clearly indicates the use of hot bituminous binder, cutback bitumen or bituminous emulsions as tack coat materials. The most widely used tack coat material in the world is bitumen emulsion.

According to the Unified Facilities Guide Specification (UFGS) 02744N, the advantage of the slow-setting grades over the rapid-setting grades is that they can be diluted.

Diluted emulsions are reported to give better results because of the following reasons

(1) Diluted emulsion provides the extra volume required for the tack coat distributor to function at normal speed especially at lower application rates.

(2) Diluted emulsion allows for a more uniform application as it flows easily from the distributor at ambient temperatures. However, for longer setting period of slow setting emulsions compared to rapid setting emulsions, it is not desirable to use slow setting

emulsions as a tack coat in relatively cool weather, at night, or when there is a narrow construction window.

The International Bitumen Emulsion Federation (IBEF, 1999) conducted a world-wide survey of the use of tack coats. The survey reported that cationic emulsions are the most common bond coat material, with some use of anionic emulsions.

A survey conducted by Paul and Scherocman (1998) in the United States, to gather information on the state of practice with respect to tack coat operations, reported the use of slow-set emulsions by all the responding states. The most common among them are SS-1, SS-1h, CSS-1, and CSS-1h. Some states like California, Florida, and Vermont used the rapid setting type of emulsions such as RS-1 and RS-2. Florida and Georgia were the only states that used paving grade asphalts (AC-5, AC-20, and AC-30) as tack coats at the time of the survey. Some states used tack coat materials according to the construction situations. For example, Florida DOT used either a rapid setting emulsion RS-1 or RS-2 during day time, whereas the use of a viscosity-grade asphalt binder (AC-5) was specified for night time construction.

Cross and Shrestha (2004) conducted a phone survey in 13 mid-western and western U.S. states indicated that slow-setting emulsions are the primary materials for tack coat, except for California, where the AR-4000 was the most widely adopted as the tack coat material followed by either SS-1 or CSS-1. The only agency to report the used of cutback asphalt as a tack coat material on an occasional basis was Kansas DOT .New Mexico DOT and Texas DOT reported that performance-grade (PG) binders were occasionally used as tack coat materials.

2.3.3 Influence of tack coat application rate

An excessive tack coats may promote shear slippage at the interface while too little may result in de-bonding problems. Therefore, it is important to estimate the optimum amount of tack coat that will produce the best performance. To achieve a proper interface bond, pavement surfaces with different conditions (e.g., new, old, or milled) require different tack application rates. Generally, slow-setting grade emulsions require higher application rates than rapid-setting grade emulsions, and rapid-setting grade emulsions require higher application rates than paving grade asphalt binders. Furthermore, dense and gap-graded HMA overlays require less tack coat than open-graded overlays.

An international survey, conducted by the International Bitumen Emulsion Federation (1999) indicated that the residual asphalt content varied from 0.026 to 0.089 gal/yd^2 for tack coats applied on conventional asphalt surfaces.

In United States, the survey conducted by Paul and Scherocman (1998), reported that the residual application rates of the emulsions varied between 0.01 and 0.06 gal/yd^2, depending on the type of surface for application.

Cross and Shrestha (2004) found from their phone survey that application rates varied from 0.03 gal/yd^2 to 0.15 gal/yd^2.

The residual asphalt contents, as specified in The Hot-Mix Asphalt Paving Handbook (2000) should range from 0.04 to 0.06 gal/yd^2. As compare to open-textured surfaces, the requirement of tack coat is less for tight or dense. Also bleeding or flushed surfaces require less tack coat than surfaces that are dry and aged. The requirement of residual asphalt is even more for a milled surface because of the increased specific surface area, as much as 0.08 gal/yd^2. The requirement is only half as much residual asphalt typically for new HMA layers, 0.02 gal/yd^2.

The Asphalt Institute specified the application rate of tack coats ranged from 0.05 to 0.15 gal/yd^2 for an emulsion diluted with water at a ratio of 1:1.

Lavin recommended application rates of 0.044 gal/yd^2 for tack coats applied between new HMA layers. He further suggested that milled pavements may require application rates of 0.22 gal/yd^2 or more due to a larger surface area caused by grooving.

Mohammad et al. (2002) recommended an optimum residual rate of 0.02 gal/yd^2 by conducting interface shear strength using the Simple Shear Test on one type of HMA pavement.

As per the section "Proper Tack Coat Application (2001)" of the *Technical Bulletin* published by the Flexible Pavements of Ohio, the recommended typical tack coat application rates for various pavement types using a slow-setting asphalt emulsions (SS1, SS1-h) are shown in table 2.1.

Table 2.1: Recommended tack coat application rates in Ohio

Pavement Condition	Application Rate (gal/yd^2)		
	Residual	Undiluted	Diluted (1:1)
New HMA	0.03-0.04	0.05-0.07	0.10-0.13
Oxidized HMA	0.04-0.06	0.07-0.10	0.13-0.20
Milled Surface (HMA)	0.06-0.08	0.10-0.13	0.20-0.27
Milled Surface (PCC)	0.06-0.08	0.10-0.13	0.20-0.27
Portland Cement Concrete	0.04-0.06	0.07-0.10	0.13-0.20

According to the tack coat guidelines of the Construction Procedure Bulletin (2003) of California Department of Transportation, the recommended application rates for different types of tack coats and pavement conditions, which are used in the state of California as shown in table 2.2.

Table 2.2: Recommended Tack Coat Application Rates Used in California

Type of Overlay	Type of Surface	Slow Setting (gal/yd^2)	Rapid Setting (gal/yd^2)	Paving Asphalt (gal/yd^2)
HMA	Dense, Tight Surface (e.g., between lifts)	0.044-0.077	0.022-0.044	0.011-0.022
	Open Textured or Dry, Aged Surface (e.g., milled surface)	0.077-0.199	0.044-0.088	0.022-0.055
Open Graded HMA	Dense, Tight Surface (e.g., between lifts)	0.055-0.110	0.022-0.055	0.011-0.033
	Open Textured or Dry, Aged Surface (e.g., milled surface)	0.110-0.243	0.055-0.121	0.033-0.066

2.3.4 Influence of testing temperature

It was found from the analysis of the laboratory studies conducted by various Researchers and Highway agencies that the testing temperature had the most significant impact on the bond strength. As test temperature increases layer bond strength decreases due to reduced stiffness of tack coat material. The study conducted by West et al.(2005), concluded that, the average bond strength values were 2.3 times greater at 10º C compared to 25º C; while the average bond strength values were 1/6 times lesser at 60º C compared to 25º C.

2.3.5 Influence of normal pressure

Most of laboratory studies that varied the normal pressure applied to a sample have all concluded that as normal pressure increases layer bond strength increases especially at higher temperature. At higher temperatures, the effect of internal friction on bond strengths were more than the tack coat materials and application rates, and the internal friction is dependent on normal load and surface texture. At intermediate and low temperatures, bond strength was not very sensitive to the normal pressure levels.

2.4 Summary of Findings

Different organizations and different researchers as mentioned in the preceding paragraphs have developed and studied on various devices and determined the bond strengths of the interlayer of the bituminous pavement.

While some have used complicated devices, it has been decided to go for simpler devices by fabricating simpler setups and using the same in existing Marshall Stability Apparatus then saving the time and cost aspects.

CHAPTER III
EXPERIMENTAL INVESTIGATIONS

3.1 Introduction

This chapter describes the experimental works carried out in this present investigation.

This chapter has been divided into two parts. First part deals with the experiments carried out on the materials (aggregates, bitumen, and emulsions), second part deals with the fabrication of the shear testing devices for evaluation of pavement interface bond strength.

3.2 Materials Used

3.2.1 Aggregates

For preparation of cylindrical samples composed of Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC), aggregates were as per grading of Manual for Construction and Supervisions of Bituminous Works of Ministry of Road Transport and Highways (MORT&H, 2001) as given in Table 3.1 and 3.2 respectively.

3.2.1.1 Coarse Aggregates

Coarse aggregates consisted of stone chips collected from a local source, up to 4.75 mm

IS sieve size. Standard tests were conducted to determine their physical properties as summarized in Table 3.3.

3.2.1.2 Fine Aggregates

Fine aggregates, consisting of stone crusher dusts were collected from a local crusher with fractions passing 4.75 mm and retained on 0.075 mm IS sieve. Its specific gravity was found to be 2.62.

3.2.1.3 Filler

Portland slag cement (Grade 43) collected from local market passing 0.075 mm IS sieve was used as filler material. Its specific gravity was found to be 3.0.

Table 3.1: Adopted aggregate gradation for DBM

Property	Grading
Nominal Aggregate Size (mm)	25
IS Sieve (mm)	Percent Passing
37.5	100
26.5	95
19.0	83
13.2	68
4.75	46
2.36	35
0.300	14
0.075	5

Table 3.2: Adopted aggregate gradation for BC

Property	Grading
Nominal Aggregate Size (mm)	13
IS Sieve (mm)	Percent Passing
19.0	100
13.2	89.5
9.5	79
4.75	62
2.36	50
1.18	41
0.600	32
0.300	23
0.150	16
0.075	7

Table 3.3: Physical properties of coarse 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 Angels 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

3.2.2 Binder

One conventional commonly used bituminous binder, namely VG 30 bitumen collected from local source was used in this investigation to prepare the samples. Conventional tests were performed to determine the important physical properties of these binders. The physical properties thus obtained are summarized in Table 3.4.

3.2.3 Tack Coat Materials

The tack coat materials selected for this study include two emulsions CMS-2 and CRS-1. Standard tests were conducted to determine their physical properties as summarized in Table 3.5.

Table 3.4: 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 3.5: 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, percent	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

3.3 Preparation of Samples

The mixes were prepared according to the Marshall procedure specified in ASTM D1559. Laboratory specimens prepared to determine interface bond strength were generally 100 mm and 150 mm in diameter and 100 mm in total height. Each specimen consisted of two layers with tack coat applied at the interface. Test variables included 100 mm and 150 mm diameter specimen and two conventional emulsions namely CMS-2 and CRS-1 as tack coats with application rates varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2. The bottom layer consisted of a Dense Bituminous Macadam (DBM) with a VG 30 binder; the top layer was a Bituminous Concrete (BC) with a VG 30 binder. For the preparation of bottom layer, first the loose mix was compacted by giving 75 blows using Marshall Hammer and then it was allowed to cool down at room temperature.

Next, the amount of tack to be applied on the specimen surface was calculated by multiplying the tack coat application rate by the surface area of a specimen. The rate of application of tack coat was selected as per MORT&H Specification which is given in the Table 3.6.

Table 3.6: Rate of application of Tack Coat as per MORT&H Specification

Type of Surface	Quantity in kg per 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

The calculated amount of tack coat was then sprayed onto one face of the sample. Once the specimens had been tacked, they were allowed to cure until setting completed in a dust-free environment. The minimum setting period of emulsions is generally estimated by visual observation. Emulsions are mostly brown in color, and they become black as they set due to the evaporation of water from the emulsions. The water in an emulsion evaporates during or after its application to aggregates. This process is called setting of emulsions. Rapid setting emulsions set very fast, normally less than half an hour. Slow setting emulsions take longer to set.

Once the application and curing of the tack coat was complete, the top layer of the specimen was compacted by placing the bottom layer in a compaction mould and compacting loose mix on top of the tack-coated bottom half by giving the same no of blows. All prepared specimens were allowed to cure at room temperature for few days before testing.

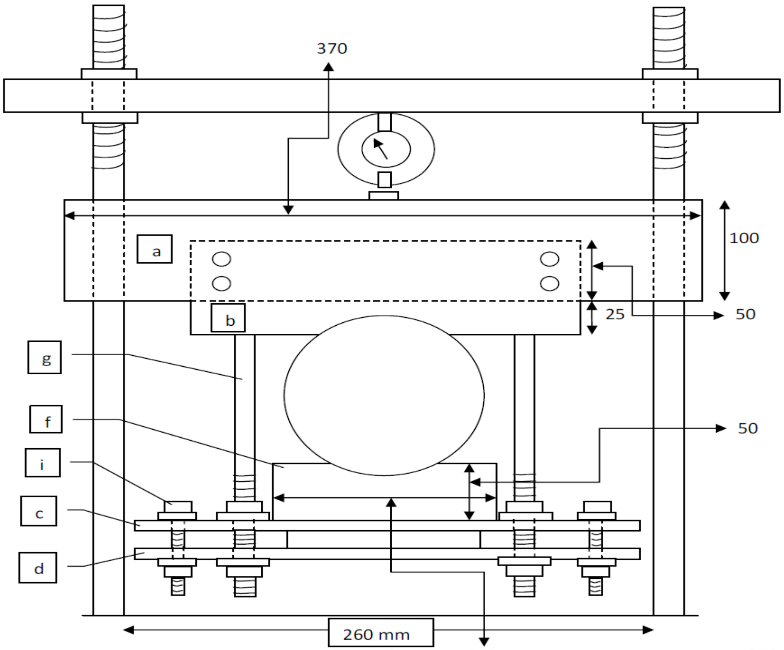
3.4 Fabrication of laboratory test procedure to measure the interface bond strength

For the purpose of testing the shear strength offered by tack coat at the bonded interface, the following three models were fabricated:

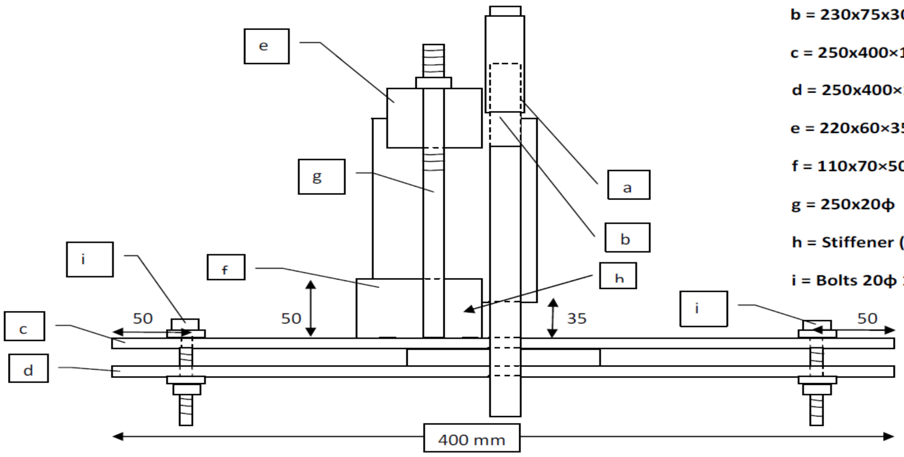
- Model no. 1, for testing 100 mm diameter laboratory specimens based on the concept of the Layer-Parallel Direct Shear (LPDS) developed by the Swiss Federal Laboratories for Material Testing and Research.
- Model no. 2, for testing 150 mm diameter laboratory specimens based on the concept of the Layer-Parallel Direct Shear (LPDS) developed by the Swiss Federal Laboratories for Material Testing and Research.
- Model no. 3, for testing 150 mm diameter laboratory specimens based on the concept of the FDOT shear tester developed by the Florida Department of Transportation (FDOT).

3.4.1 Model no. 1

This device could accommodate cylindrical specimens of 100 mm diameter and was so fabricated that the lower part of a specimen could placed on a semicircular u-bearing which was fixed on the top base plate and the specimen could hold firmly with the help of a semicircular clamping. The upper part of the specimen could move freely with minimum friction along the two existing guiding rods of the Marshall apparatus. A load of constant deformation at a rate of 50.8 mm/min was applied on a smooth horizontal stripe located on the top of the shear sleeve adjacent to the interface by means of a yoke, allowing the application of a shear force at the interface. The schematic view and photographic view of the model are shown in figures 3.1.1 and 3.1.2.

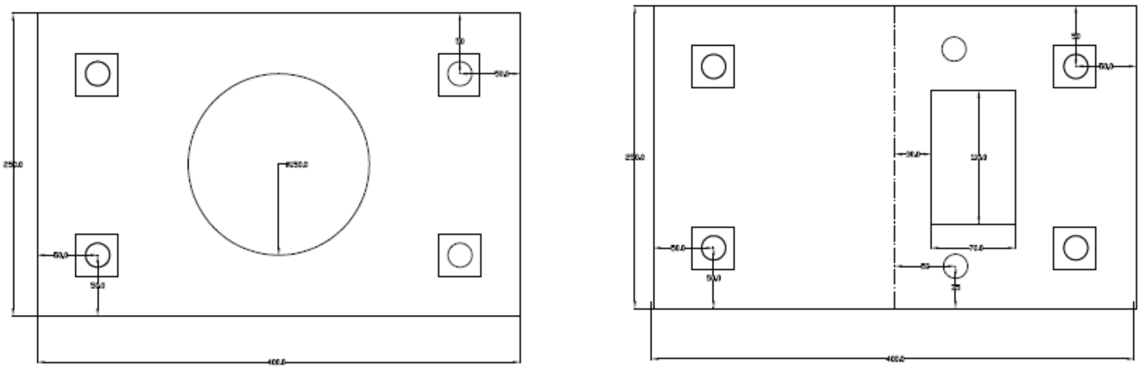


Front view



Side view

a = 370x100x10 mm
b = 230x75x30 mm
c = 250x400×12.0 mm
d = 250x400×12.0 mm
e = 220x60×35 mm
f = 110x70×50 mm
g = 250x20ϕ
h = Stiffener (flat)
i = Bolts 20ϕ 100mm length



Lower Base Plate 12 mm thick

Upper Base Plate 12 mm thick

Figure 3.1.1: Schematic diagrams of the Shear-Testing model no. 1

Figure 3.1.2: Photographs of the Shear-Testing model no. 1.

3.4.2 Model no. 2

This device could hold cylindrical specimens of 150 mm diameter and was so fabricated that the bottom layer of the double-layered specimen could place on a semicircular u-bearing which was fixed on the top base plate and the specimen could hold firmly with the help of a semicircular clamping. The upper layer of the specimen could move freely with minimum friction along the two existing guiding rods of the Marshall apparatus. A load of constant deformation at a rate of 50.8-mm/min was applied on a smooth horizontal stripe located on the top of the shear sleeve adjacent to the interface by means of a yoke, allowing the application of a shear force at the interface. The schematic view and photographic view of the model are shown in figures 3.2.1 and 3.2.2.

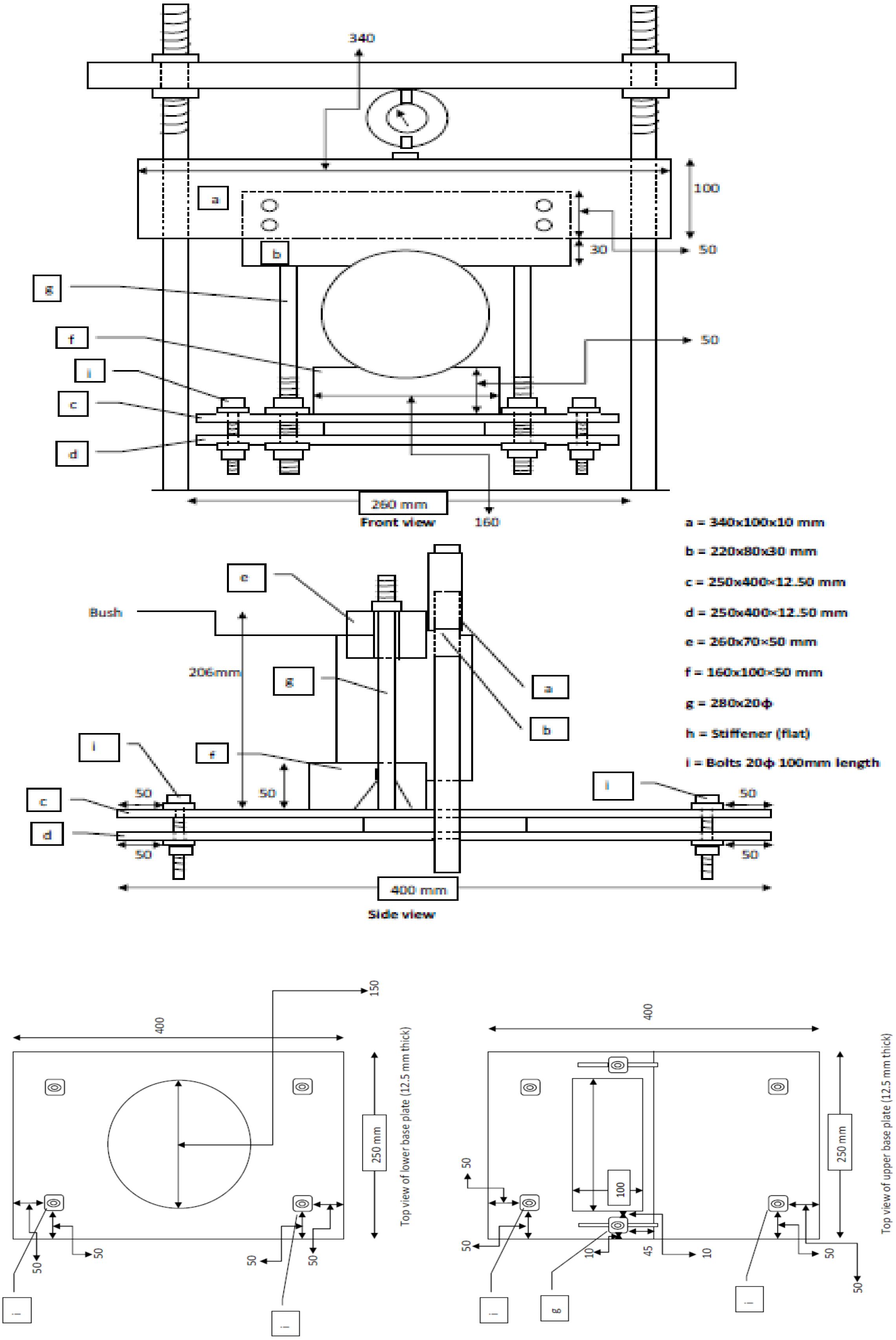


Figure 3.2.1: Schematic diagrams of the Shear-Testing model no. 2.

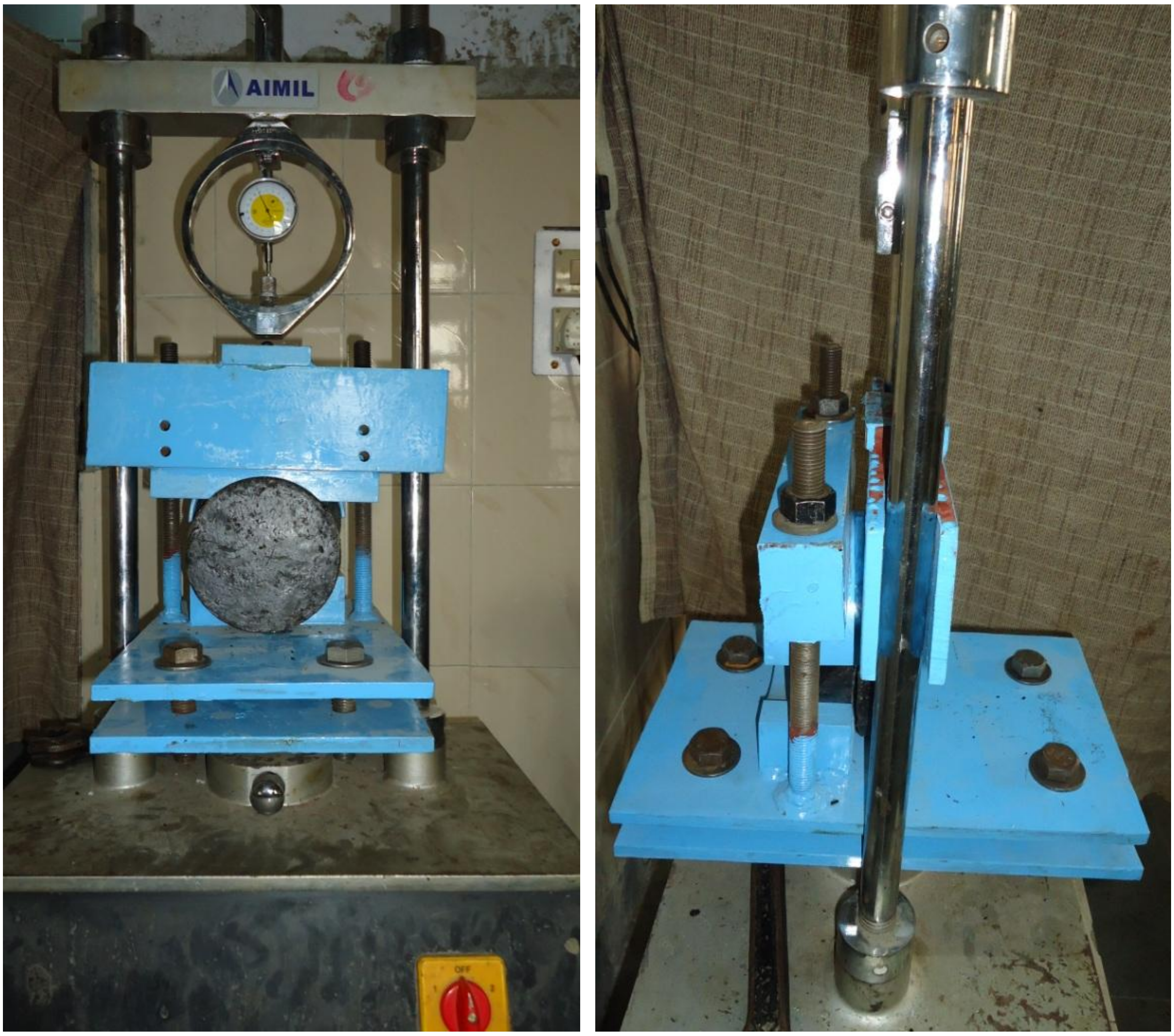
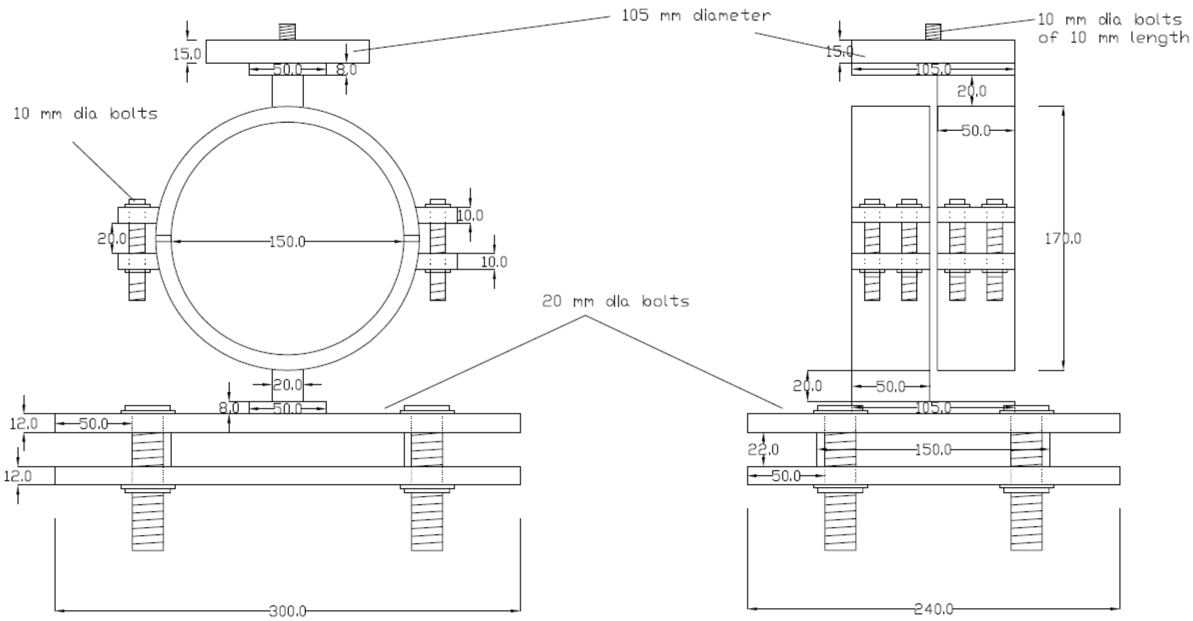


Figure 3.2.2: Photographs of the Shear-Testing model no. 2.

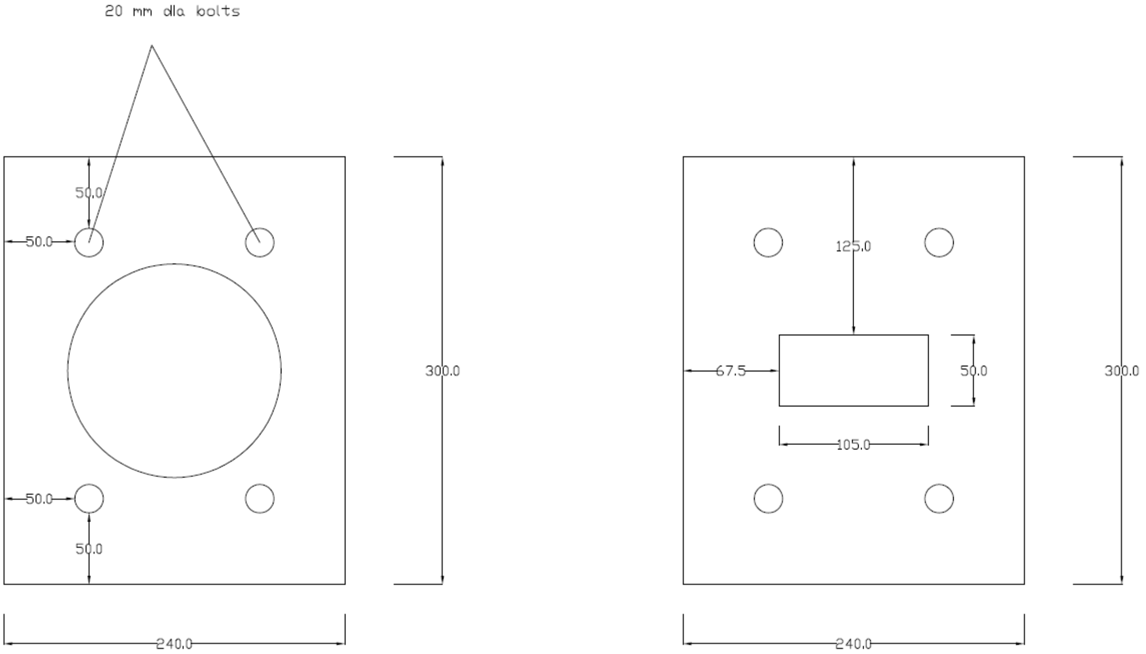
3.4.3 Model no. 3

This device consisted of two circular rings that could accommodate cylindrical specimen of 150 mm diameter and a gap of 5 mm was maintained in between the two rings in order to account for the irregular surface of the cored specimens. One of the rings was fixed at its bottom to a base plate and a concentric shear load was applied at a constant deformation rate of 50.8 mm/min on the top of other ring until failure occurred. The schematic view and photographic view of the model are shown in figures 3.3.1 and 3.3.2.



Side view

Front view



Lower Base Plate 12.0 mm thick

Upper Base Plate 12.0 mm thick

Figure 3.3.1: Schematic diagrams of the Shear-Testing model no. 3.

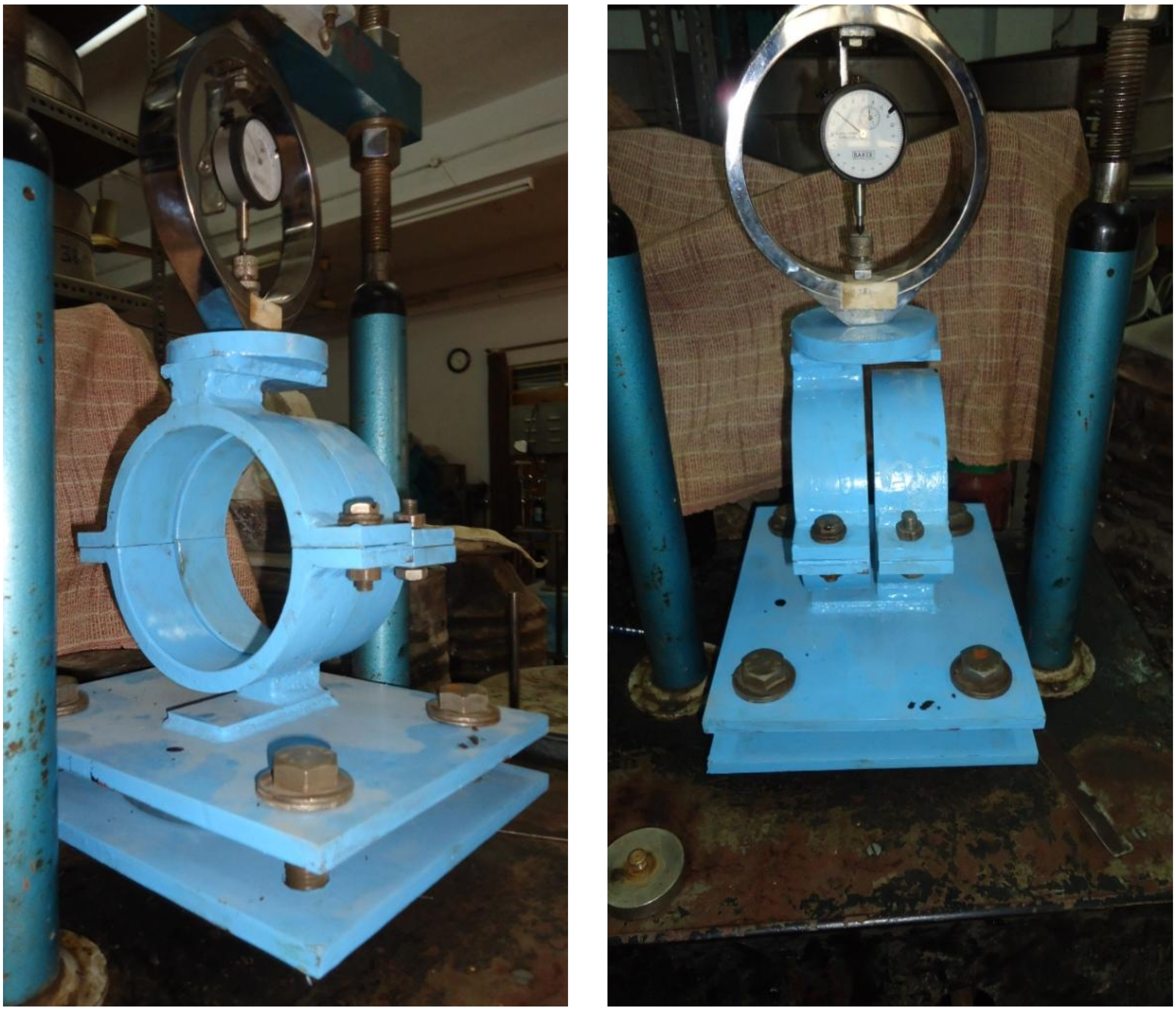


Figure 3.3.2: Photographs of the Shear-Testing model no. 3.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents results and discussion on the findings of the experimental investigations carried out on the cylindrical laboratory prepared specimens which were tested on special fabricated attachments fitted on the Marshall Loading Frame.

The interface bond strength results obtained from the three shear test models conducted at a temperature of 25^0C on 100 mm and 150 mm diameter specimens with CMS-2 and CRS-1 as tack coats at application rate varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2.

The interface shear strength, ISS, was computed as follows:

$ISS = F_{max} / A$

Where,

ISS = Interface Shear Strength (kPa),

F_{max} = Ultimate load applied to specimen (kN), and

A = Cross-sectional area of test specimen (m^2)

$= \Pi \times R^2$

R = Radius of the specimen (m)

4.2 Shear testing model no. 1

The test was conducted on 100 mm diameter cylindrical specimens with CRS-1 and CMS-2 as tack coats applied at application rate varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 at a temperature of 25^{0}C. As seen in table 4.1 and figure 4.1 the specimen with CRS-1 as tack coat exhibited higher shear strength as compared to CMS-2 for all application rates.

Table 4.1 Results of the shear strength of 100 mm diameter specimens using Shear testing model no. 1 at 25^{0}C

Tack Coat Type	Application rate (kg/m^2)	Load (kN)	Shear Strength (kPa)	Average Shear Strength (kPa)
CMS-2	0.20	3.228	411.001	429.590
CMS-2	0.20	3.374	429.590	
CMS-2	0.20	3.52	448.179	
CMS-2	0.25	4.397	559.842	572.277
CMS-2	0.25	4.397	559.842	
CMS-2	0.25	4.690	597.148	
CMS-2	0.30	4.032	513.369	538.155
CMS-2	0.30	4.251	541.253	
CMS-2	0.30	4.397	559.842	
CRS-1	0.20	3.812	485.358	460.615
CRS-1	0.20	3.667	466.896	
CRS-1	0.20	3.374	429.590	
CRS-1	0.25	4.543	578.431	597.106
CRS-1	0.25	4.69	597.148	
CRS-1	0.25	4.836	615.737	
CRS-1	0.30	4.543	578.431	575.376
CRS-1	0.30	4.397	559.842	
CRS-1	0.30	4.617	587.853	

As shown in figure 4.1, the optimum rate of application was found to be 0.25 kg/m^2 for both CMS-2 and CRS-1 as tack coat.

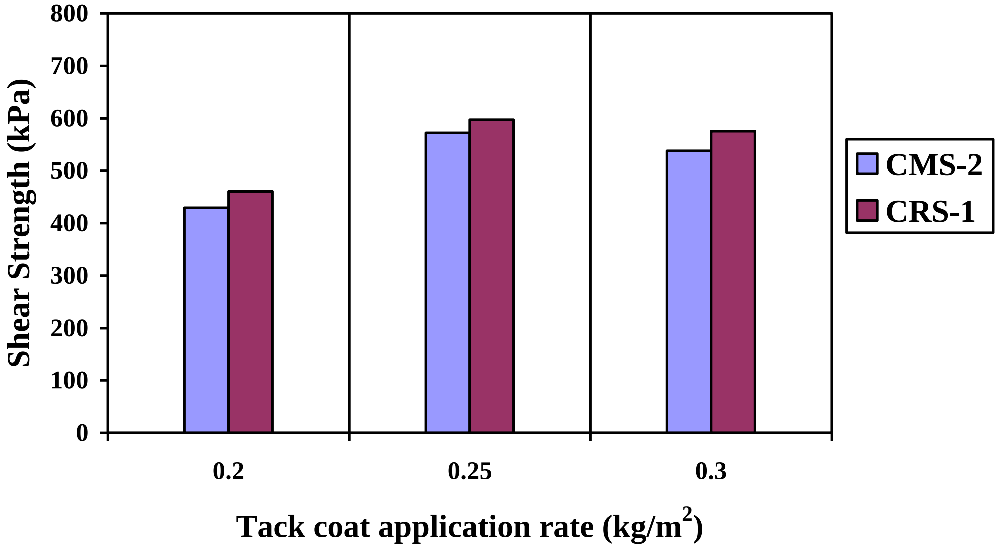


Figure 4.1: Plot of Shear Strength v/s Tack Coat application rates for 100 mm diameter specimens using Shear testing model no. 1.

4.3 Shear testing model no. 2

The test was conducted on 150 mm diameter cylindrical specimens with CRS-1 and CMS-2 as tack coats applied at application rate varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 at a temperature of 25^{0}C. As seen in table 4.2 and figure 4.2 the specimen with CRS-1 as tack coat exhibited slightly higher shear strength than CMS-2 for all tack coat application rates.

Table 4.2 Results of the shear strength of 150 mm diameter specimens using Shear testing model no. 2 at 25^{0}C

Tack Coat Type	Application rate (kg/m^2)	Load (kN)	Shear Strength (kPa)	Average Shear Strength (kPa)
CMS-2	0.20	7.417	419.715	419.583
CMS-2	0.20	7.117	402.739	
CMS-2	0.20	7.710	436.296	
CMS-2	0.25	9.193	520.216	531.421
CMS-2	0.25	9.490	537.023	
CMS-2	0.25	9.490	537.023	
CMS-2	0.30	9.193	520.216	503.428
CMS-2	0.30	8.896	503.409	
CMS-2	0.30	8.600	486.659	
CRS-1	0.20	8.007	453.102	453.084
CRS-1	0.20	7.710	436.296	
CRS-1	0.20	8.303	469.853	
CRS-1	0.25	9.490	537.023	553.735
CRS-1	0.25	10.080	570.410	
CRS-1	0.25	9.786	553.773	
CRS-1	0.30	9.638	545.398	535.193
CRS-1	0.30	9.341	528.591	
CRS-1	0.30	9.394	531.590	

As shown in figure 4.2, the optimum rate of application was found to be 0.25 kg/m^2 for both CMS-2 and CRS-1 as tack coat.

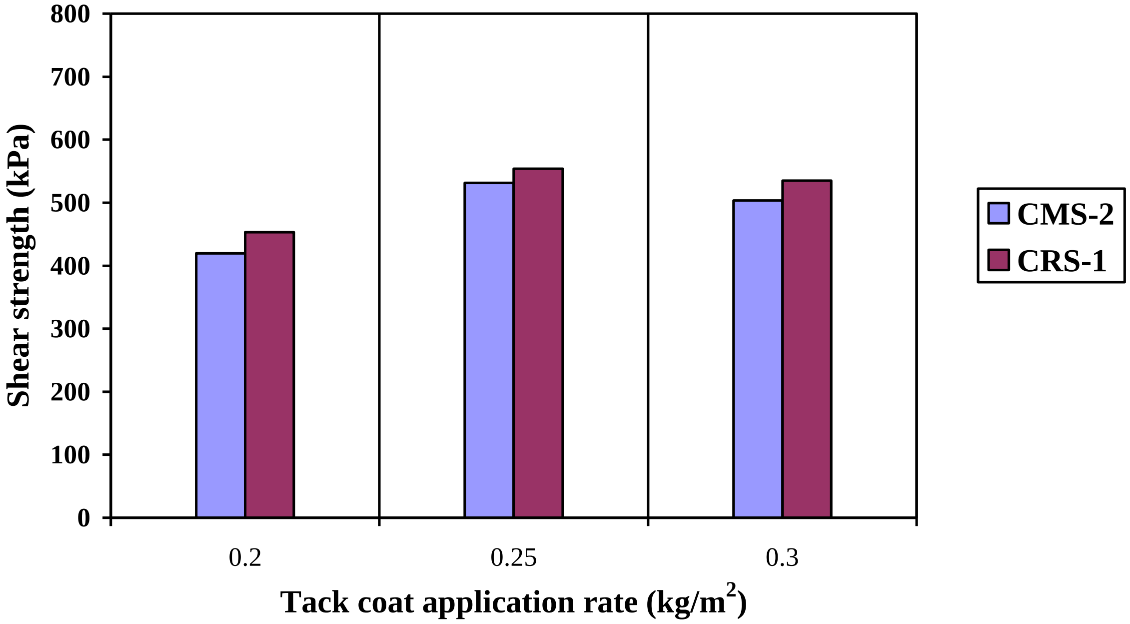


Figure 4.2: Plot of Shear Strength v/s Tack Coat application rates for 150 mm diameter specimens using Shear testing model no. 2.

4.4 Shear testing model no. 3

The test was conducted on 150 mm diameter cylindrical specimens with CRS-1 and CMS-2 as tack coats applied at application rate varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 at a temperature of 25^{0}C. As seen in table 4.3 and figure 4.3 the specimen with CRS-1 as tack coat exhibited slightly higher shear strength than CMS-2 at an application rate.

Table 4.3 Results of the shear strength of 150 mm diameter specimens using Shear testing model no. 3 at 25^{0}C

Tack Coat Type	Application rate (kg/m^2)	Load (kN)	Shear Strength (kPa)	Average Shear Strength (kPa)
CMS-2	0.20	9.193	520.216	537.004
CMS-2	0.20	9.786	553.773	
CMS-2	0.20	9.490	537.023	
CMS-2	0.25	11.560	654.161	676.607
CMS-2	0.25	12.450	704.524	
CMS-2	0.25	11.860	671.137	
CMS-2	0.30	11.414	645.899	634.732
CMS-2	0.30	10.970	620.774	
CMS-2	0.30	11.266	637.524	
CRS-1	0.20	9.786	553.773	570.523
CRS-1	0.20	10.082	570.523	
CRS-1	0.20	10.378	587.273	
CRS-1	0.25	12.450	704.524	704.430
CRS-1	0.25	12.150	687.548	
CRS-1	0.25	12.745	721.218	
CRS-1	0.30	11.710	662.649	668.195
CRS-1	0.30	11.857	670.967	
CRS-1	0.30	11.857	670.967	

As shown in figure 4.3, the optimum rate of application was found to be 0.25 kg/m^2 for both CMS-2 and CRS-1 as tack coat.

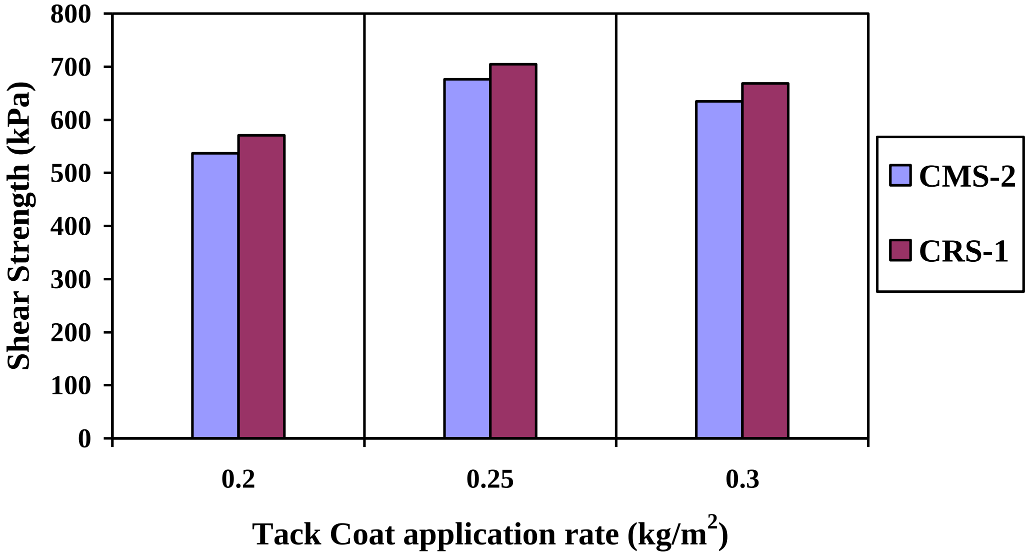


Figure 4.3: Plot of Shear Strength v/s Tack Coat application rates for 150 mm diameter specimens using Shear testing model no. 3.

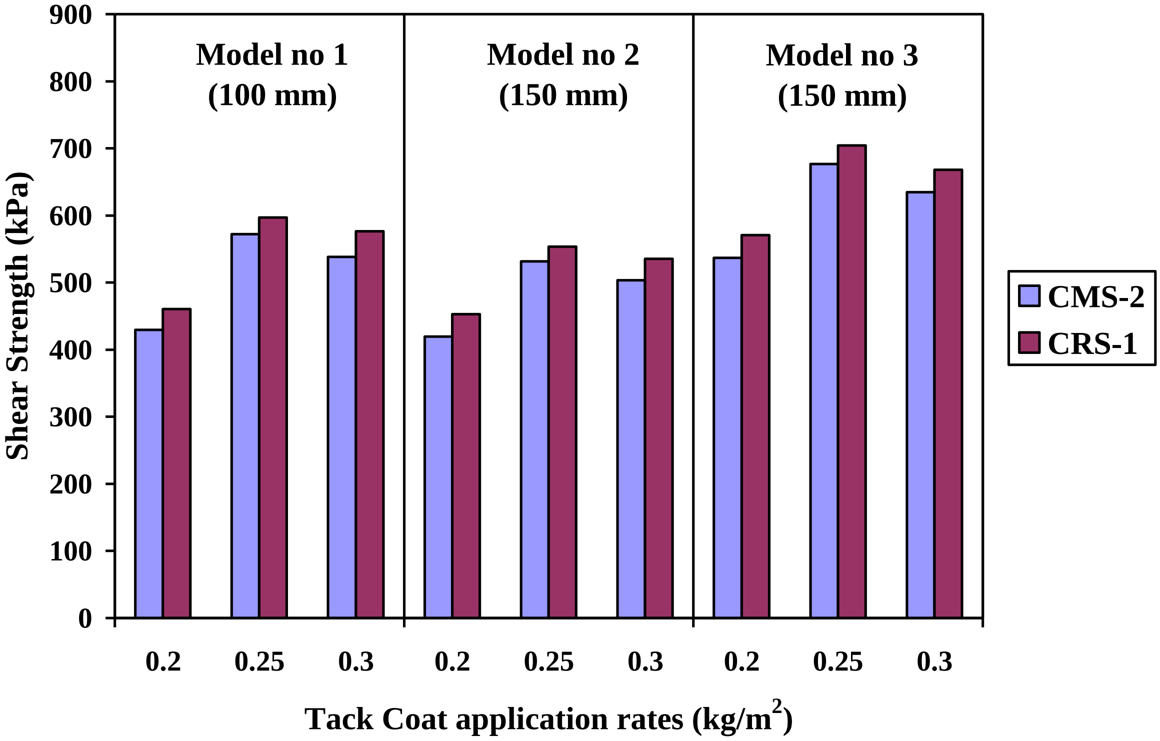


Figure 4.4: Comparison of Shear Strength v/s Application rates for the three models.

Analyzing the results graphically as shown in figure 4.4, it can be concluded that specimen with CRS-1 as tack coat exhibited higher shear strength values compared to CMS-2 as tack coat at all application rates varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 for all three types of shear testing devices. Also the optimum application rate was found to be 0.25 kg/m^2 for the all three models.

4.5 Overall Performance of tack coat

The average shear strength of the specimens with both types of emulsions, namely CMS-2 and CRS-1 as tack coat at application rates varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 considering all three models together, are calculated as shown in tables 4.4 and 4.5.

Table 4.4: Results of the average shear strength using CMS-2 as tack coat for all three models at 25^{0}C

Model No	Rate of Application (kg/m^2)	Specimen no	Shear Strength (kPa)	Average Shear Strength (kPa)
1	0.20	1	411.001	462.059
	0.20	2	429.590	
	0.20	3	448.179	
2	0.20	1	419.715	
	0.20	2	402.739	
	0.20	3	436.296	
3	0.20	1	520.216	
	0.20	2	553.773	
	0.20	3	537.023	
1	0.25	1	559.842	593.435
	0.25	2	559.842	
	0.25	3	597.148	
2	0.25	1	520.216	
	0.25	2	537.023	
	0.25	3	537.023	
3	0.25	1	654.161	
	0.25	2	704.524	
	0.25	3	671.137	
1	0.30	1	513.369	558.772
	0.30	2	541.253	
	0.30	3	559.842	
2	0.30	1	520.216	
	0.30	2	503.409	
	0.30	3	486.659	
3	0.30	1	645.899	
	0.30	2	620.774	
	0.30	3	637.524	

Table 4.5: Results of the average shear strength using CRS-1 as tack coat for all three models at 25^{0}C

Model No	Rate of Application (kg/m^2)	Specimen no	Shear Strength (kPa)	Average Shear Strength (kPa)
1	0.20	1	485.358	494.740
	0.20	2	466.896	
	0.20	3	429.590	
2	0.20	1	453.102	
	0.20	2	436.296	
	0.20	3	469.853	
3	0.20	1	553.773	
	0.20	2	570.523	
	0.20	3	587.273	
1	0.25	1	578.431	618.424
	0.25	2	597.148	
	0.25	3	615.737	
2	0.25	1	537.023	
	0.25	2	570.410	
	0.25	3	553.773	
3	0.25	1	704.524	
	0.25	2	687.548	
	0.25	3	721.218	
1	0.30	1	578.431	592.921
	0.30	2	559.842	
	0.30	3	587.853	
2	0.30	1	545.398	
	0.30	2	528.591	
	0.30	3	531.590	
3	0.30	1	662.649	
	0.30	2	670.967	
	0.30	3	670.967	

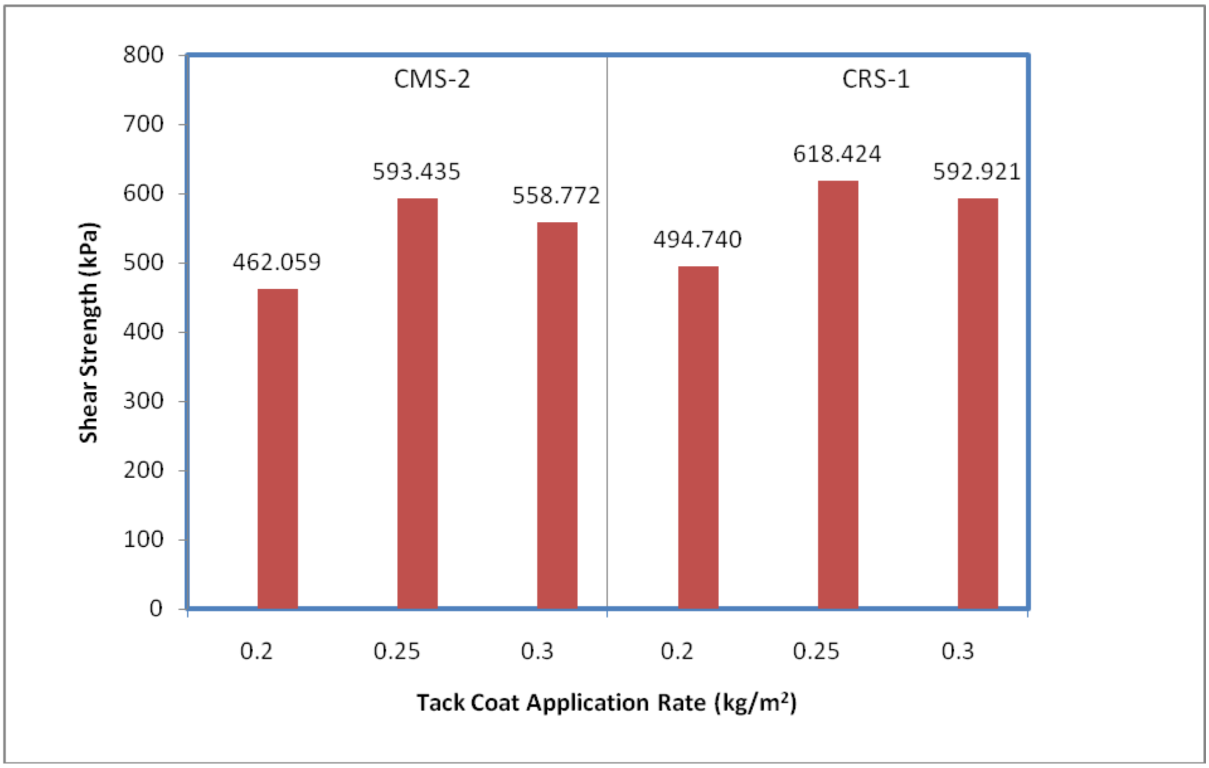


Figure 4.5: Average Shear Strength v/s Application rates for the three models.

The average maximum shear strength was observed on specimens with CRS-1 as tack coat at an application rate of 0.25 kg/m^2 while the specimens with CMS-2 at an application rate of 0.20 kg/m^2 showed the average minimum shear strength as shown in figure 4.5. Using CMS-2 as tack coat the average shear strength values were obtained as 462.059, 593.435 and 558.772 kPa at application rates of 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 respectively. Similarly using CRS-1 as tack coat at application rates of 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 the average shear strength values obtained were 494.740, 618.424 and 592.921 kPa respectively.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

4.1 Introduction

This chapter summarizes the findings of the laboratory study to evaluate the bond strength between pavement layers. The scopes for the future research work are also recommended in this chapter.

4.2 Conclusions

A laboratory study was conducted to evaluate the bond strength between the Bituminous Concrete (BC) and Dense Bituminous Macadam (DBM) layers with tack coat sprayed at the interface. For this purpose three simple shear testing models were fabricated and experiments were conducted using the same in a Marshall Stability Apparatus. For shear testing model no 1, laboratory tests were conducted on 100 mm diameter cylindrical specimens at a temperature of 25^0 C by applying a shear force of constant deformation rate of 50.8 mm/min. While the shear testing model no. 2 and 3 were fabricated to evaluate the bond strength of 150 mm diameter cylindrical specimens. The samples were prepared in laboratory by applying CMS-2 and CRS-1 as tack coat at interface at application rates varying at 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2.

The following are specific observations drawn from the test results.

- The test results concluded the application rate of 0.25 kg/m^2 as the optimum one for all the tack coats.
- Generally, CRS-1 as tack coat provided the highest shear strength at all application rates, 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 as compared to CMS-2.

- The shear strength values obtained from shear testing model no. 3 were higher than those obtained from model no.1 and 2 for all types of tack coat at all application rates. This might be due to eccentricity as the shear load was applied near the interface therefore; the shear strength values obtained were lower than those obtained from model no. 3 where a concentric shear load was applied.
- Considering all models together, average shear strength values were found to be as 462.059, 593.435 and 558.772 kPa using CMS-2 as tack coat at application rates of 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 respectively while using CRS-1 as tack coat at application rates of 0.20 kg/m^2, 0.25 kg/m^2 and 0.30 kg/m^2 the average shear strength values obtained were 494.740, 618.424 and 592.921 kPa respectively.

4.3 Future research recommendations

The following recommendations are provided as a part of future work based on the observations drawn from this study.

- It is recommended to compare the results obtained from the laboratory specimens with the results obtained from field core specimens. This will assist in getting a correlation between the laboratory test results and the field observations.
- Further research is recommended to examine the variation of interface bond strength at varying tack coat material types, temperatures and normal pressure.
- Theoretical models are to be developed to validate the experimental results and decide the best model to be adopted.

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