MODELING OF INTERFACE BONDING OF BITUMINOUS PAVEMENT LAYERS FOR TROPICAL CLIMATE

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Thesis submitted in partial fulfillment of the requirements for the degree
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DECLARATION

"I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Abstract

The bonding strength of bituminous layers is an element of paramount consequence, as it defines the structural performance of flexible pavement layers. Failure to establish the required strength will lead to the occurrence of pavement distresses.

This study was conducted in pursuance of the aims of identifying and further analyzing the significant parameters affecting interface bonding strength. Type of tack coat, application rate and residual application rate of tack coat, curing time, and surface macro-texture were determined as the parameters, upon the examination of past studies. Another parameter which had not been subjected to prior examination- the absorbed emulsion content was also discovered. Furthering the research, correlations of these parameters were studied based on field data and laboratory data.

Field data were collected from in situ tests, namely the sand patch test and test methods which estimate rate of application, and the absorbed emulsion content test, conducted on actual road construction projects, while laboratory data comprised of interface shear strength of pavement core samples which were evaluated through the Moratuwa Interface Shear Strength Tester (MISST): a device that had been designed in line with the research especially for the purpose of evaluating interface shear strength of pavement core samples.

Established on the observations, a final model capable of evaluating interface shear strength of bituminous pavement layers was developed based on application rate determined by geotextile pads and corrected absorbed emulsion content computed through a past study: significant parameters affecting interface shear strength. It was thus observed that interface shear strength increases when the application rate estimated by the geotextile pads decreases, and when the corrected absorbed emulsion content increases.

Key words: Interface shear strength, Surface macro-texture, Absorbed emulsion content, Application rate

DEDICATION

I dedicate my thesis to my mother and father for nursing me with affection and love and their dedicated partnership for the success in my life

ACKNOWLEDGEMENT

First and foremost, I would like to express my cordial gratitude to my supervisor Prof.W.K.Mampearachchi for the continuous support, and motivation he readily gave me to accomplish this research on time. His patience in guiding me extremely well from the start to the very end of the days I worked on this thesis, are very much appreciated.

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I also express my sincere gratitude to the academic and nonacademic staff of Department of Civil Engineering, University of Moratuwa for the continuous support and guidance given throughout my undergraduate and postgraduate life. Furthermore, I thank my fellow research colleagues for the stimulating discussions, for all the support to successfully complete my experimental work and the help given to accomplish this research without any stress.

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LIST OF ABBREVIATIONS

AC-XX	Bitumen (Viscosity grade)
AEC	Absorbed emulsion content
ARG	Application rate by geotextile pad
ART	Application rate by tray test
CMS-2	Cationic medium-setting, high viscous bitumen
CRS-1	Cationic rapid-setting, low viscous bitumen
CRS-2	Cationic rapid-setting, high viscous bitumen
ISS	Interface Shear Strength
MC-XX	Medium Curing, XX-Kinematic viscosity at 60C in centistokes
MISST	Moratuwa Interface Shear Strength Tester
CAE	New absorbed emulsion content
PG XX-YY	Performance Grade (PG), XX - average seven day maximum pavement design temperature, YY - minimum pavement design temperature
RAR	Residual application rate
RC-XX	Rapid Curing, XX-Kinematic viscosity at 60C in centistokes
SBS	Styrene–Butadiene–Styrene
SC-XX	Slow Curing, XX-Kinematic viscosity at 60C in centistokes
SMT	Surface macro-texture
SS-1	Anionic slow-setting, low viscous bitumen

CHAPTER 01

1. INTRODUCTION

1.1 General

Bituminous pavement layers are the major and topmost layers of the flexible pavements which are used in roadway and airfield construction. They are also referred to as hot mix asphalt (HMA) layers. Generally, flexible pavements are constructed in two bituminous pavement layers, namely the existing layer and new layer. In most cases, the binder course is the existing layer. The new layer is the wearing course and is generally placed about one month after placing the binder course or the existing oxidized pavement layer. Bitumen content in the wearing course is normally higher than that of the binder course. Therefore, in the economical point of view, designing of flexible pavements as two layers is cost effective. Furthermore, in the construction point of view, placing and compaction of the thick bitumen layer with a thickness of about 100 mm is difficult. In addition to that, keeping a time gap of several weeks and allowing traffic on the binder course before placing wearing course will help to repair the cracks at an early stage.

However, above two bituminous layers should act as one layer in order to achieve the structural performance of flexible pavement layers. For that, bond at the interface of the two bituminous pavement layers should be strong enough. A poor bond at the interface of bituminous pavement layers causes various pavement distresses, such as delaminating, slippage cracking, top down cracking, potholes, and so on. Therefore, tack coat is usually applied in-between two layers to enhance the bonding characteristics at the interface as shown in Figure 1.

However, the amount of application of tack coat, and existing conditions of the existing pavement should be considered. An excessive amount of tack coat may cause shear slippage and even bleeding because it will penetrate in to the new layer and consequently, will reduce the air void content in the new bitumen layer.

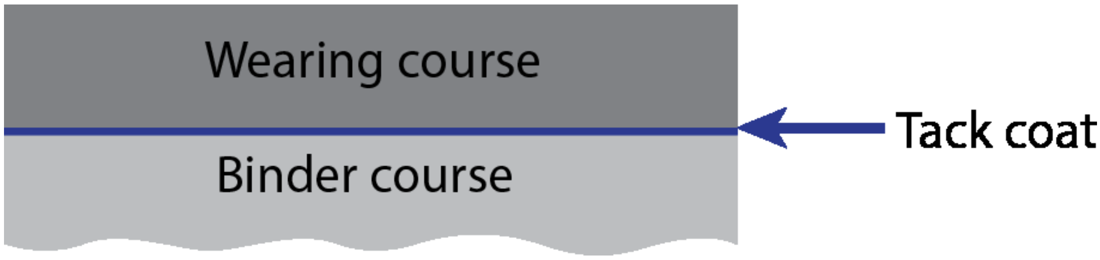


Figure 1. Typical pavement surface course

Therefore, it is important to study the interface bonding characteristics of bituminous pavement layers.

1.2 Objectives

The main objectives of the research,

- To evaluate the significant parameters affecting interface bonding
- To determine a correlation of effective parameters
- To develop an interface bond strength measuring device
- To develop a model to evaluate the bonding characteristics of the bituminous pavement layers

1.3 Scope of the research

In this study, first and foremost, an initial literature survey was conducted to identify significant parameters related to the interface bonding of bituminous pavement layers. In the meanwhile, a questionnaire survey was carried out to evaluate the common field practices, with the contribution of people in the executive level of the industry. Based on both past studies and the questionnaire survey results, a field data collection was conducted to collect information for the significant parameters identified. At the end of the field data collection, representative pavement core samples were gathered. Simultaneously, a test device was developed to estimate the interface bond strength, based on the past studies. Using that device, pavement core samples were tested in the laboratory. Based on laboratory and field test results, a final model was developed by regression analysis.

As well as, it should be noted that, the interface bonding characteristics between only the oxidized binder course which is also known as the old binder course, and the new wearing course were considered as bituminous pavement layers in this research.

1.4 Scope of thesis

Chapter 01 of this thesis provides an introduction to the study while Chapter 02 comprises of the findings of past studies. Chapter 03 explains the research methodology and Chapter 04 encompasses the results and discussion with the final model development. The final chapter, Chapter 05 concluded the research and provides recommendations for future studies.

CHAPTER 02

2. LITERATURE REVIEW

2.1 General

Several studies have been conducted in line of this research. Based on those studies, influence factors interacting with interface bond strength and methods of test, which had been used to measure the interface bond stress, are discussed in this chapter. However, it is important to note that most of the studies were conducted with controlled conditions in laboratories.

2.2 Type of tack coat materials

Type of tack coat material used in the field is one of the significant factors which affect proper interface bond strength between bituminous pavement layers. There are primarily three types of tack coat materials used in the road constructions, namely hot bitumen, cut back bitumen, and bitumen emulsions.

2.2.1 Hot bitumen

Hot bitumen is a bitumen binder which is heated to a particular temperature in order to spray on the existing layer. PG 58-28, PG 64-22, AC-20, AC-30, pen 60/70, and pen 85/100 are types of common hot bitumen which are used in the industry according to different specifications. Although any grade of hot bitumen can be used as the tack coat material, it is advantageous to use the same type of bitumen which is used in new bituminous pavement layer [1].

Hot bitumen needs to be heated before spraying. Therefore, it is commonly used under cool weather conditions or during the night. Hot bitumen does not require a 'curing time', thus construction time will be less. Zhang in 2017 has mentioned that Hot bitumen also had a higher bonding strength [2].

In addition, when geosynthetic pavement interlayer is placed, Hot bitumen is commonly used as the tack coat material [1]. However, it is not a popular and convenient tack coat material, because it needs more energy to be heated and is difficult to apply uniformly on the existing layer [3].

2.2.2 Cutback bitumen

Cutback bitumen is another type of tack coat material which is produced by combining bitumen and petroleum solvent. Cutback is an alternative material for hot bitumen as a tack coat material because it reduces the viscosity of bitumen at low temperatures. In addition to that, it is used as slurry seal [4]. There are mainly three types of cutback bitumen, namely rapid curing (RC), medium curing (MC), and slow curing (SC). Rapid curing cutback bitumen uses high volatile solvent such as naphtha or gasoline, medium curing uses intermediate volatile solvent such as kerosene or jet fuel and slow curing cutback uses oils of low volatility such as diesel oil [5]. Further, cutback bitumen cures after spraying, with the evaporation of the petroleum solvent. As a result of that, volatile components are released into the atmosphere, leading to environmental issues. Therefore, cutback bitumen is not widely used presently [4].

2.2.3 Bitumen emulsions

Bitumen emulsions are considered the most common type of tack coat material globally [3]. Emulsified bitumen are safer than cutback bitumen because they are devoid of harmful volatile components. Moreover, they are convenient to use and are energy saving as they can be applied without heating [6]. There are mainly three types of bitumen emulsions: slow-setting (SS), medium setting (MS) and rapid setting (RS). Bitumen emulsions or emulsified bitumen is a combination of bitumen, water and anionic or cationic emulsified agents. In addition to that, polymers or latex are added as additives [1]. When high application rates are used, polymer modified emulsion is used to seal the existing layer and keep a high binder content from the tack coat at the interface [4].

As well as, ICTAD specification has recommended Cationic Rapid Setting Emulsion (CRS) and Cationic Slow Setting Emulsion (CSS) as the tack coat material used for road construction in Sri Lanka [7].

A prevalent issue related to tack coat is the picking up of tack coat by the rubber tires of haul trucks as shown in Figure 2. In order to avoid these tracking problems, a new type of tack coat material has been introduced called ‘trackless tack coat’. Trackless tack coat is a polymer modified and a hard base bitumen thus is also capable of reducing the setting time of the tack coat [8]. Figure 3 demonstrates the performance of the trackless tack coat during road construction. However, Bae et al. (2010) has mentioned that trackless tack coat was brittle in low temperatures [9], thus not appropriate for cold environments.

Figure 2. Tack coat picked up by haul truck

Figure 3. Trackless Tack - no tack pick up on tires - Source [8]

2.3 Conditions of the existing layer

Before applying the tack coat, existing surface should be thoroughly cleaned in order to remove debris, clay and dust. In the construction field, the air compressor and broomer are used for this purpose. Further, the existing surface should be dried prior to the application of tack coat [7].

2.4 Surface macro-texture

Surface macro-texture is the large-scale smoothly rising and falling forms of pavement surface at a particular location. It arises due to the particle arrangement of aggregates in the bituminous mixture of existing pavement layer. It depends on the type of bituminous mixture used in the existing pavement surface, and the bituminous mixture depends on the size, shape, and gradation of the coarse aggregates [10].

There are several methods available to determine the surface macro-texture. Sand patch test is a simple and popular test method to estimate the surface macro-texture and a further explanation on the methodology of this test has been described in section 3.5.1. Surface macro-texture is indicated as the mean texture depth (MTD) by sand patch method and that test is carried out according to ASTM E965 [11].

Das et al. in 2014 [12] classified average MTD values of new bituminous surface and old bituminous surface as 0.91 and 0.97 respectively. Destreeet al. in 2016 has categorized the mean texture depth in four types as follows for the prepared test sections in the field [13].

- Very smooth (MTD ≤ 0.50 mm)
- Smooth (MTD > 0.70 mm)
- Fine texture (1.60 mm ≤ MTD ≤ 2.00 mm)
- Coarse texture (MTD ≥ 2.40 mm)

Based on ASTM E965, Raposeiras et al in 2013 has used optic filler with a particle size lower than 0.063 mm for their study on the "New procedure to control the tack coat applied between bituminous pavement layers" [14]. In this study, they have converted the macro-texture value from ophitic filler tests to standardized macro-texture which was measured by standardized river sand with a particle size ranging from 0.320 to 0.160 mm. The transformation model is shown in equation (1).

$$ST = (FT \times 1.271) + 0.041 \quad (1)$$

Where, *ST* is standardized macro-texture (mm) and *FT* is macro-texture from ophitic filler tests (mm).

In addition to that, laser-based devices such as, the circular texture meter (CT Meter) can be used to determine surface macro-texture as mean profile depth (MPD) according to ASTM E2157 [15]. Another device of quantifying mean profile depth is laser profilometer according to ASTM E1845 [16]. Mohammad et al in 2010 have measured the mean profile depth of different surfaces and according to that study, surface mean profile depth values were estimated as 1.05 mm and 0.63 mm for old bituminous surface and new bituminous surface respectively [17].

2.5 Methods of tack coat application

There are mainly two conventional methods of applying the tack coat in the construction field. One is the truck mounted application method while the other one is the manual application method which is also known as hand spraying. Figure 4 portrays the truck mounted application method while Figure 5 portrays the manual application method.

Figure 4. Truck mounted application

Figure 5. Manual application

In the truck mounted application method, there is a truck with a tank which can be heated to a desired temperature in order to store different types of tack coats at required working temperatures. There is a bar with nozzles at the rear side of the truck to distribute the tack coat evenly, and the height of the distributer bar is adjustable. Typical width of the distributer bar is 4.3 m in order to cover a single lane. The rate and coverage of tack coat application can be adjusted by changing the speed of the truck, nozzle type and size, and height of distributor bar [17].

In the manual application method, there is a spray bar connected to the truck with the tack coat tank, and the spraying process is done by a skilled laborer by shaking the spray bar while the truck is moving ahead. However, it is difficult to obtain a uniform surface coverage of tack coat application through this method. The rate and coverage of tack coat application depends on the experience of the operator.

Nevertheless, both methods mentioned above share a common issue: the tacked surface is tracked and partially removed due to movements of haul trucks and asphalt paver. Using trackless tack coat as mentioned in section 2.2.3 is one way to solve this issue. Another way is the utilization of a spray payer as shown in Figure 6. Spray paver is a special paver with tack coat distributor bars that can spray a tack coat just ahead of the screed of the bitumen concrete. Polymer modified tack coat materials are used with this spray paver in order to reduce the setting time. Consequently, this method is time saving, functionally effective and durable because tack coat forms a continuous film on the existing layer [3].

Figure 6. Spray paver Source [18]

2.6 Rate of application of tack coat

Tack coat application rate is the quantity of tack coat sprayed on a unit area of the existing surface, and it is the well-regulated factor related to tack coat application in the road construction field. There are few conventional methods and new methods to determine the tack coat application rate as described below.

2.6.1 Application rate

Application rate, rather direct application rate can be estimated by two methods. One method is tray test which is described in ICTAD specification – section 1802.5 [7]. Another way is the test method which is performed according to ASTM D2995 using geotextile pads the size of 300 mm by 300 mm [18]. These two test methods are further elaborated in section 3.5.2 and section 3.5.3.

Application rate will be differed based on the condition of the existing surface layer. Application rate for open textured, raveled, or milled surfaces were higher than for tight or dense surfaces. The optimum application rate will also differ based on the type of tack coat and the type of bituminous concrete mixture that was used as overlay.

Open-graded friction courses (OGFC) overlays will require more tack coat application than dense and gap-graded hot mix bitumen overlays [1].

Tack coat application rates recommended in different guidelines have been summarized in Table 1.

Table 1. Recommended application rates

Source	Existing surface type	Application Rate (l/m^2)	
		Minimum	**Maximum**
ICTAD Specification [7]	Not specified	0.25	0.55
FP-14 Specification [19]	Not specified	0.15	0.70
Tack Coat Guidelines [1]	New HMA	0.23	-
	Existing HMA	0.32	-

2.6.2 Residual application rate

The residual bitumen content is the tack coat layer that remains after the water evaporates from the emulsion. Hence, the residual application rate is more significant than the application rate, and is also varied based on the type of tack coat and conditions of the existing layer. Considering that fact, the application rate has been mentioned in some research based on the residual bitumen content. The residual application rate is measured using geotextile pads according to ASTM D2995 [18].

The minimum residue percentage after the distillation test of CRS-1, CRS-2, and CSS-1 are 60%, 65%, and 57 % respectively, according to ASTMD2397-05 [20]. Other requirements of cationic emulsified bitumen are attached in Appendix A.

2.6.3 Absorbed emulsion content

The absorbed emulsion content is the free bitumen content on the tacked surface, and is an alternative measurement for the application rate of the tack coat proposed by Raposeiras et al. in 2013. Raposeiras et al. [14] have mentioned that if the residual application rate is used as the application rate, there will be differences between the theoretical range of the applied emulsion dosage and its practical range. Therefore, when fast breaking cationic emulsions were used, the final amount of tack coat reduced because part of the emulsion had already evaporated as water by the time the geotextile pad was weighed [11].

Figure 7. Absorbed emulsion content test

To overcome those issues, this Spanish study proposed a new method to measure the application rate using a geotextile with a weight which will be placed on the tacked surface to obtain the absorbed bitumen content [14]. This new test is shown in Figure 7. For this test, bituminous concrete layers with different surface textures were prepared in the laboratory first. Six different tack coat dosages from 125 g/m^2 to 750 g/m^2 of residual bitumen were applied over the above layers. There were two types of tack coat materials used in this research, namely C60B4 ADH (conventional ECR-1) and C60B4 TER (anti-stick ECR- 1). Both materials were fast breaking cationic emulsions with 60 % of residual bitumen. After 5 min, a geotextile pad which was weighed before was placed on the tacked surface. A polyethylene foam layer of 10 mm followed by a steel plate of 250 mm by 250 mm were placed on top of that. A load of 20 kg was applied for a time period of 5 min. After the elapse of the designated time, the load was removed and geotextile was immediately weighed. Weighed difference divided by area of the geotextile pad was given the absorbed emulsion content in g/m^2 [14].

This test was performed at a temperature of 20 ^{0}C. Based on previous tests, waiting time period and loading time period were recommended. Raposeiras et al. [14] mentioned that waiting for a longer period would not aid the absorption of emulsion in to the geotextile because emulsion begins to break while the geotextile also does not absorb emulsion after 5 min of loading period.

In addition to that, Raposeiras et al. [14] developed a model related to this parameter based on the above test method. Equation 2 shows the linear regression model based on absorption data.

$$EA=0.065 \times ED-50.697 \times M+78.327 \quad (2)$$

Where, *EA* is emulsion absorbed percentage (%), *ED* is residual emulsion dosage (g/m^2), and *M* is standardized macro-texture and it is equivalent to surface macro texture.

2.7 Curing time

Curing time is the time gap in-between the spraying of the tack coat and the placing of the new layer. Especially for the bitumen emulsions, curing time has two parts: breaking time and setting time. During the breaking time, bitumen emulsions separate into water and bitumen while the colour changes from brown to black [3]. Woods in 2004 [21] conducted a research using SS-1 emulsion. That study discovered that there was a strong correlation between breaking time and application rate as shown in Figure 8.

Chen and Huang in 2010 [22] noted that the emulsion type and the atmospheric conditions affected the breaking time as well. Tashamn et al [23] indicated that minimum breaking time varied from 15 min to 1 hour. Furthermore, the time that takes for water to completely evaporate is considered as the setting time [3].

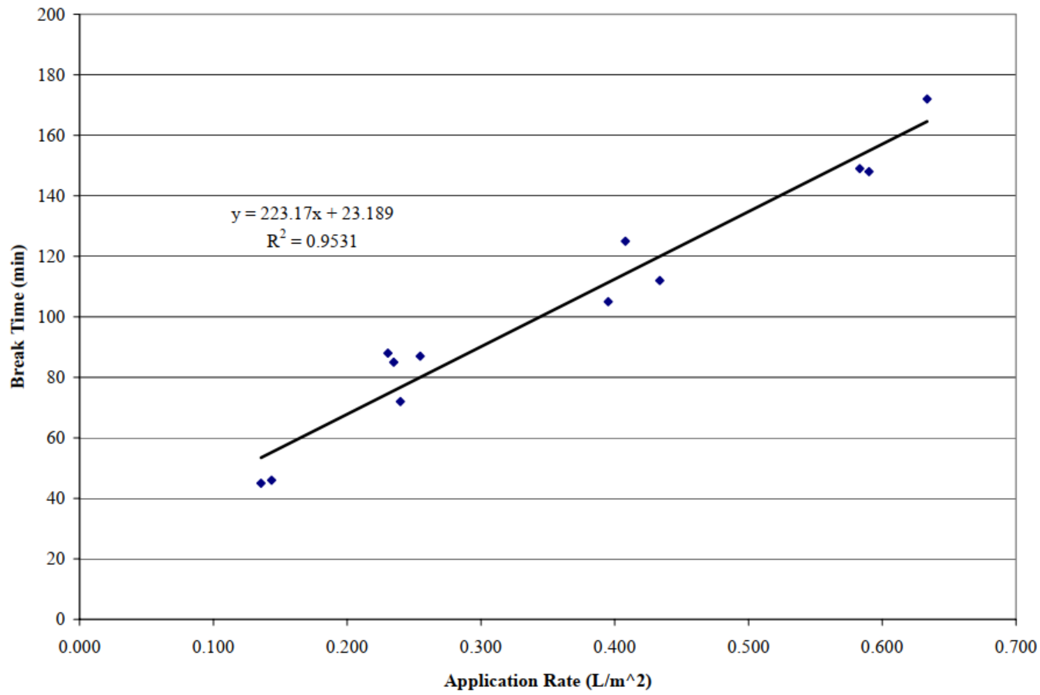


Figure 8. Emulsion breaking time versus application rate - Source [21]

2.8 Test methods

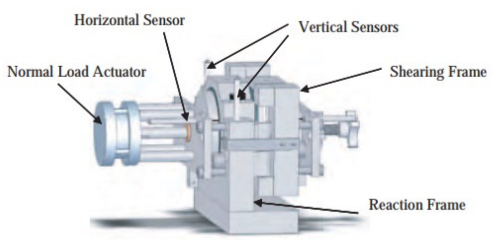
Different test methods were used in several studies to evaluate interlayer bonding properties of tack coat. There were mainly three modes of test groups, viz. shear, tensile, and torque. Among them, the most common mode of test is the shearing mode because it has a slippage failure behavior similar to actual interface between bituminous layers [4].

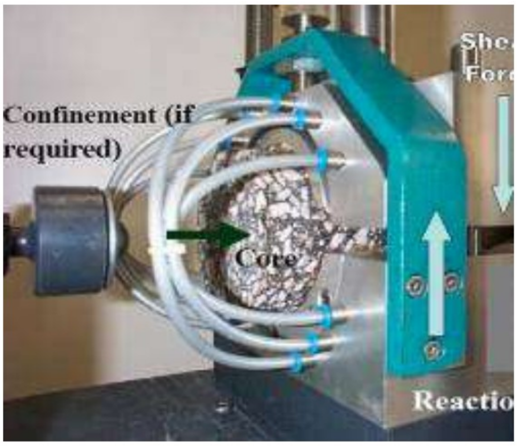
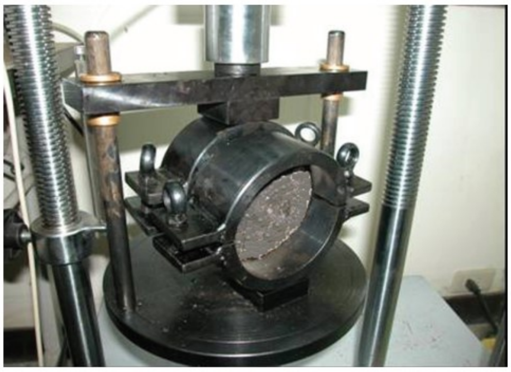
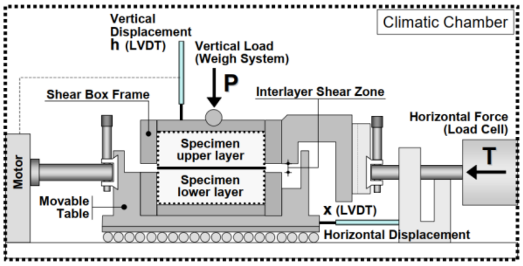
2.8.1 Shear tests

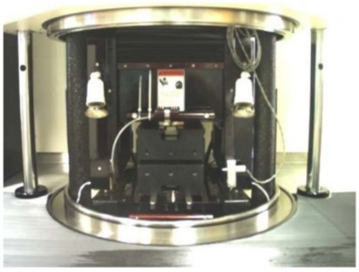
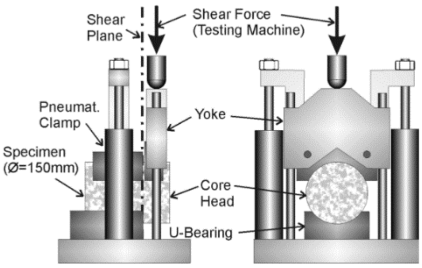
The first shear test device for evaluating interlayer boding properties was developed by Uzan et al. [24] in 1978 and a type of direct shear tests was used on a dual layer system in that study. Based on this study, several new shear test devices had been developed and Table 1 shows some of them.

When shear tests are considered, there is another fact that should be addressed. That is the normal load which is perpendicular to the shearing load. However, not all test devices considered the normal load. West et al. in 2005 [25] performed a study using National Center for Bitumen Technology (NCAT) bond strength device and they identified that the bond strength was not very sensitive to the normal load at the low and intermediate temperatures of 10 ^{0}C and 25 ^{0}C respectively. Mohammad et al. in 2012 [3] performed several studies for the optimization of tack coat based on Louisiana Interlayer Shear Strength Tester (LISST) device and concluded that a conservative estimate of interface shear strength values would be yielded by a specification developed based on testing condition without normal stress.

Table 2. Shear Tests

Apparatus	**Remarks**
Louisiana Interlayer Shear Strength Tester (LISST) [3] 	• Shearing Direction : Vertical • Normal Load : Considered, but optional • Control Mode : Strain • Loading Rate : 2.54 mm/min
National Center for Bitumen Technology (NCAT) shear test [25] 	• Shearing Direction : Vertical • Normal Load : Considered, but optional • Control Mode : Strain • Loading Rate : 50.8 mm/min

Leutner Shear Test[26] 	• Shearing Direction : Vertical • Normal Load : Not considered • Control Mode : Strain • Loading Rate : 50.8 mm/min
Simple Direct Shear Test (SDST) [27] 	• Shearing Direction : Vertical • Normal Load : Not considered • Control Mode : Strain • Loading Rate : 50.8 mm/min
Ancona Shear Testing Research and Analysis (ASTRA) Test [28] 	• Shearing Direction : Horizontal • Normal Load : Considered • Control Mode : Strain • Loading Rate : 2.5 mm/min

Louisiana Transportation Research Center (LTRC) Direct Shear Test [29] 	• Shearing Direction : Horizontal • Normal Load : Considered, but optional • Control Mode : Stress • Loading Rate : 50 lbs/min (0.22 kN/min)
Florida Direct Shear Test [30] 	• Shearing Direction : Vertical • Normal Load : Not considered • Control Mode : Strain • Loading Rate : 50.8 mm/min
Layer-Parallel Direct Shear (LPDS) Test [31]  	• Shearing Direction : Vertical • Normal Load : Not considered • Control Mode : Strain • Loading Rate : 50.8 mm/min

2.9 Interface bond strength

As discussed in section 2.8, there were several test methods and approaches to evaluate the interlayer shear strength. Nonetheless, there were mainly two types of methods of sample preparation, viz. laboratory prepared samples and field extracted pavement cores. The laboratory prepared samples were prepared under controlled conditions. Mohammad et al. [3] in 2012 conducted several samples prepared in the laboratory and core samples extracted from the prepared test sections. In that study, they mentioned that there was a large overestimation of laboratory prepared samples with a factor ranging from 2 to 10 compared with field extracted samples. Figure 9 depicts this difference.

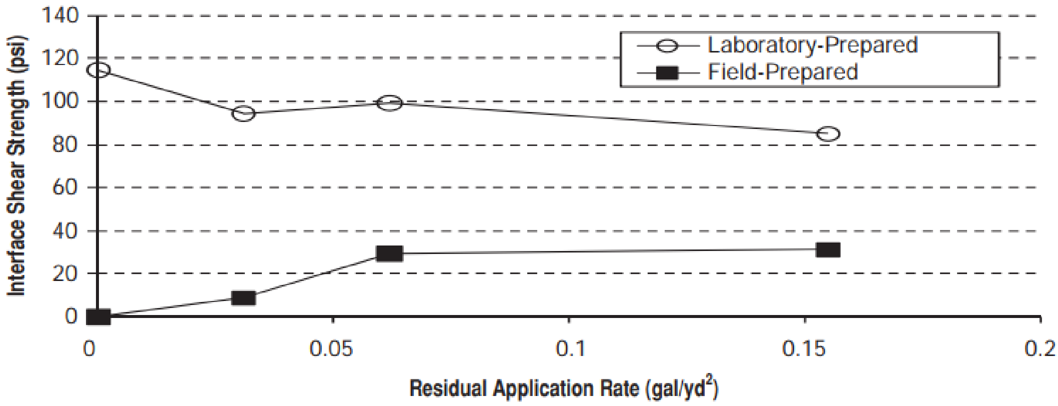


Figure 9. Effects of sample preparation methods - Source [3]

Another significant matter is the minimum interface shear strength of bituminous pavement layers. Mohammad et al. [3] conducted a finite element analysis for the laboratory prepared samples tested by the LISST device. Based on those results, they concluded that minimum interface shear strength for the acceptable performance was 275.79 kPa (40 psi). However, West et al. in 2005 conducted a study based on a laboratory prepared specimen and tested by NCAT shear tester. In that study, interface bond strength less than 345 kPa (50 psi) was considered inappropriate. A further description on this head is available in section 2.11.

2.10 Influence factors for interface bond strength

Several researches were conducted, exploring the parameters affecting interface bond strength of bituminous pavement layers. . In this section, tack coat type, application rate and residual application rate of tack coat, surface macro-texture, and curing time have been discussed as the significant parameters affecting interface bond strength.

2.10.1 Tack coat type

West et al. in 2005 [25], Mohammad et al. in 2012 [29], and Du in 2012 [27] mentioned that the tack coat type is a critical factor affecting interface bond strength. Mohammad et al. in 2012 [3] studied five tack coat types namely, SS-1h, SS-1, CRS-1, Trackless, and PG 64-22. Among them, trackless tack coat had a performance indicating the highest strength while CRS-1 showed lowest strength. Mohammad et al. in 2002 [14] stated that CRS-2P was superior to CSS-1 and SS-1, while CSS-1 and SS-1 were similar in interface bond strength at the test temperature of 25 ^{0}C.

West et al. in 2005 [25] have conducted a study using CRS-2, CSS-1, and PG 64-22 and have reported that CRS-2 had higher interface bond strength than CSS-1 while PG 64-22 showed the highest strength. Al-Qadi et al. in 2008 [32] have researched on SS-1h, SS-1hp, and RC-70 tack coat materials. In that study, RC-70, cutback bitumen showed lower bond strength than SS-1h and SS-1hp, while SS-1h and SS-1hp showed no significant difference. In the study conducted by Du in 2012 [27], CRS-1, RC-70, and MC-70 were used as tack coat materials. The results of that study showed CRS-1 had better interface bond strength than two cutback bitumen of RC-70 and MC-70. Bae et al. [9] in 2010 investigated emulsified tack coats using CRS-1, and trackless tack coat as tack coat materials. In that research, trackless tack coat has also shown higher interface shear strength than CRS-1.

Ghaly et al. in 2014, analyzing cutback bitumen and bitumen emulsion, discovered that emulsion with low viscosity performed with higher interface shear strength than that of high viscosity.

2.10.2 Application rate

Application rate is a parameter which is commonly considered during the spraying of the tack coat. The speed of the distributor truck and the height of the nozzles need to be controlled in order to control the application rate. Furthermore, Song et al. [33] reported that the application rate would be a critical factor affecting the shear strength of the interface bond for open graded friction course as the top layer at the intermediate temperature of 25 ^{0}C. Also, the interface shear strength decreases as a result of increasing the application rate from 0 to 0.5 l/m^2.

Various application rates have been recommended to get the proper interface bonding for different types of tack coats and different types of pavement surfaces. Du in 2012 [27] proposed that the optimum application rate was 0.18 l/m^2 for CRS-1 at the intermediate temperature of 25 ^{0}C. According to FP-14 specifications on Federal Highway Projects, application rate is 0.15-0.70 l/m^2 [19]. In Transportation Research Circular E-C102 [34], it was mentioned that application was 0.45 l/m^2 for slow-setting emulsions. In addition to that, West et al. [25] had found that a higher interface bonding strength can be obtained at lower application rates around 0.18 l/m^2 for the tack coat types of CRS-2 and CSS-1. Furthermore, in the ICTAD specification in Sri Lanka, the recommended application rate is 0.25-0.55 l/m^2 for CRS and CSS [7].

Mohammad et al. in 2002 [29] reported that at an application rate of 0.23 l/m^2, maximum interface shear strength of 272.6 kPa for CSS-1 was achieved, and that had decreased at higher application rates at the testing temperature of 25 ^{0}C. However, at higher testing temperature of 55 ^{0}C, the interface shear strength had not significantly changed with the application rate.

In addition to that, Mohammad et al. in 2012 [3] noted that, when excessive tack coat was available, during the compaction, the air void content of the overlay would decrease due to intrusion of the excessive tack coat. Chen and Huang in 2010 [22] also mentioned similar fact. They indicated that excessive tack coat would lead to a high risk of slippage and bleeding in surface treatment because of a thicker and more deformable tack coat film created by excessive tack coat. Raposeiras et al. in 2012 [35] also confirmed this situation.

2.10.3 Residual application rate

A past study has recommended different residual application rates ranging from 0.14 l/m^2 to 0.36 l/m^2 for different pavement conditions such as, new bituminous layers, oxidized bituminous layers, milled surfaces and Portland cement concrete [36]. Moreover, Mohammad et al. [3] has observed that, CRS-2P emulsion with a residual application rate of 0.09 l/m^2 has the highest interface bonding strength. In addition to that, they investigated that although the interface shear strength (ISS) of field extracted samples increased when increasing residual application rate, that of laboratory prepared samples decreased. Table 3 shows the recommended tack coat residual application rates.

Table 3. Recommended tack coat residual application rates

Existing surface type	Residual Application Rate (l/m^2)
New bituminous layers	0.16
Existing bituminous layers	0.25
Milled bituminous layers	0.25

However, Tashman et al. in 2007 [23] conducted a study using CSS-1 with residual application rate ranging from 0.08 to 0.32 l/m^2 and concluded that increasing the residual rate of tack coat did not significantly affect the interface shear strength. Nevertheless, the absence of the tack coat in non-milled sections severely decreases the interface shear strength.

2.10.4 Surface macro-texture

The surface macro-texture is also one of the significant parameters which affect the interface bonding stress. As well as, the application rate will also vary with the surface macro-texture, and if the application rate is insufficient for better interface bonding, the macro-texture will be the critical factor determining the interface bonding strength [13]. According to the findings of Mohammad et al. [3], the greatest interface shear strength will be provided by the milled surfaces. The findings of Tashman et al. [23] also confirmed those results. West et al. [25] conducted a study using two types of laboratory prepared bitumen mixtures: 19.0 mm coarse-graded mixture and 4.75 mm fine-graded mixture. According to that, specimens with a fine-graded mixture showed higher interface shear strength due to finer surface macro-texture. Further, Raposeiras et al. in 2012 [35] conducted a study using ECR-1 fast-break cationic emulsion, (described in section 2.6.3) and discovered that maximum interface shear strength could be gained under a surface texture of 0.17 mm and a residual application rate of 0.46 l/m^2.

However, Chen and Huang in 2010 [22] noted that, when increasing the mean texture depth (MTD), the contact area between existing and new layers would decrease. It causes the reduction of interface shear strength.

2.10.5 Curing time

Some studies also considered the effect of curing time for interface shear strength. Notwithstanding, as described in section 2.7, the curing time depends on several factors, such as the type of emulsion used, application rate, and atmospheric conditions. Tashman et al. in 2008 [23] and Chen and Huang in 2010 [22] investigated that the effect of curing time on the interface shear strength was not considerable.

2.11 Summary

According to past studies, the most popular type of tack coat material was bitumen emulsions because there were specific environmental issues and practical issues related to the application of cutback bitumen and hot bitumen. Polymer modified tack coat emulsions such as the trackless tack coat provided better interface bond strength while reducing tracking problems.

Tack coat should be applied on a dry and thoroughly cleaned surface. Surface macro-texture was one of the significant parameters affecting the interface shear strength and could be estimated either as the mean texture depth (MTD) or mean profile depth (MPD). Truck mounted application method and manual application method are two conventional methods of applying the tack coat. However, new equipment was introduced, as a spray paver, in order to mitigate the issues arising in the conventional application method.

Rate of application of the tack coat could be estimated in four ways, namely application rate by tray test, application rate by geotextile pads, residual application rate, and absorbed emulsion content. Absorbed emulsion content was not a typical method, but was introduced in a past study.

Curing time depended on the application rate, atmospheric conditions, and type of tack coat material. The fast breaking emulsions needed a minimal curing time. There were several test methods to estimate the interface bond strength. Among them, shear tests were the most common test method. At intermediate temperatures (25 ^{0}C) normal stress was not essential to estimate the interface shear strength. However, there was a difference of interface shear strength results between laboratory prepared specimens and core samples collected from the field. The summary of interface shear strength (ISS) results from past studies which was conducted related bitumen emulsions is shown in Table 4.

Table 4. Interface shear strength (ISS) values

Source	**Sample type**	**Normal Stress (kPa)**	**App. rate (l/m^2)**	**Residual App.rate (l/m^2)**	**Type of Tack Coat**	**ISS (kPa)**
Mohammad et al (2012)[3]	Field	0	-	0.28	CRS-1	130
					SS-1h	139
					Trackless	263
					PG 64-22	154
Bae et al (2010)[9]	Field	0	-	0.28	CRS-1	319
					Trackless	702
Tashman et al (2008)[23]	Field	0	-	0.22	CSS-1	450
West et al. (2005)[25]	Laboratory	0	0.18	-	CRS-2	2138
					CSS-1	1817
					PG 64-22	2808
Du (2012)[27]	Laboratory	0	0.18	-	CRS-1	1613
			0.17		RC-70	918
			0.09		MC-70	654
Chen & Huang (2010)[22]	Laboratory	552	-	0.12	CRS	840

Mohammad et al (2002)[29]	Laboratory	0	0.23	-	SS-1h	235
					CSS-1	273
					SS-1	263
			0.09		CRS-2P	351
Ghaly et al (2014)[6]	Laboratory	0	0.25	-	Emulsion	1240
Canestrari & Santagata (2005)[28]	Laboratory	0	0.55	-	Emulsion	590
					Emulsion	190
Clark et al. (2010)[8]	Laboratory	0	-	0.19	CRS-1	282
					CRS-2	285
					Trackless	339

CHAPTER 03

3. METHODOLOGY

3.1 General

The overview of the research methodology is outlined in Figure 10. Data collection of this research had been conducted in two stages, namely field data collection and laboratory data collection. The field data collection was carried out in actual road development projects in Sri Lanka.

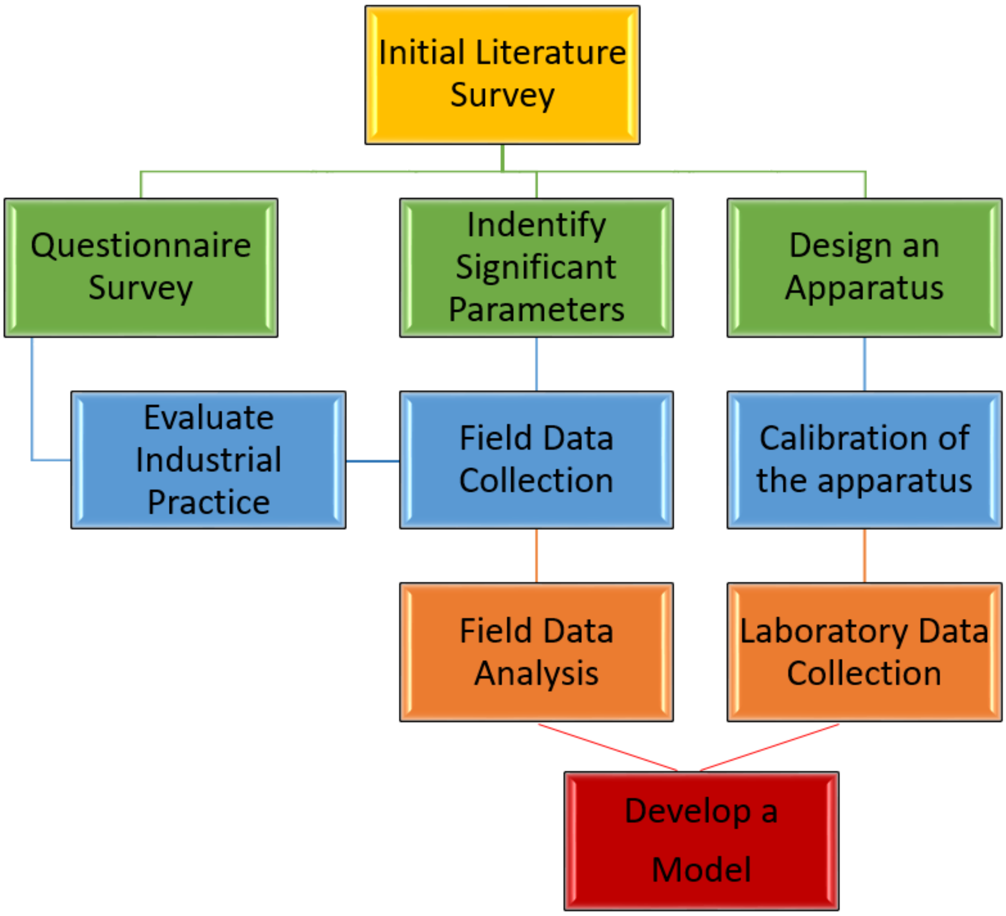


Figure 10. Research Methodology

3.2 Initial literature survey

First and foremost, the past studies relevant to this research were investigated to establish the fundamental concepts of this research and ascertain the research gap. Literature review of this study is presented in section 2. Identifying significant parameters affecting interface bond strength, designing an apparatus to determine the interface bond strength and carrying out a questionnaire survey were done based on that knowledge.

3.3 Questionnaire survey

A questionnaire survey was conducted on the “Application of Tack Coat”, targeting professional and experienced people in the road construction field. The main purpose of the questionnaire survey was to evaluate the industrial practice on the usage of tack coat in Sri Lanka. The form of the questionnaire survey and its results are illustrated in Appendix B and Appendix C respectively. Tack coat type, application rate, curing time, tack coat spraying method and other relevant information were gathered from this questionnaire survey. 84 respondents shared their experiences.

3.4 Identification of significant parameters

Based on the initial literature survey, significant parameters which affect the interface shear strength were identified in the initial stage of the research. Surface macro-texture, application rate, absorbed emulsion content and residual application rate were considered as the variables.

According to the results of the questionnaire survey which are presented in section 4.2, the most popular tack coat type was found to be CRS-1 and the curing time was discovered to be commonly less than 30 min. In consequence, when carrying out the research tack coat type and curing time were not altered in order to minimize the disturbances to actual road development projects.

3.5 Field data collection

Surface macro-texture of the existing bituminous layer, application rate of tack coat, absorbed emulsion content, and residual application rate were collected as field data. These field data were collected from five actual road development projects around Sri

Lanka. The details of the road development projects from which the field data were collected are presented in Table 5.

Table 5. Locations of field data collected

Name of Road Development Project	**Project Number**
B216 - Kesbewa – Polgasowita Road Development Project	P-1
B622 - Agunukolapelessa – Wetiya Juction Road Development Project	P-2
B204 - Katubedda Junction to Piliyandala Road Development Project	P-3
B112 - Elahera–Giritale Road Development Project	P-4
E01 - Extension of Southern Expressway Project (ESEP) - Section 4	P-5

As previously mentioned, there are two different methods of tack coat application: manual application (hand spraying), automated application (vehicle mounted spraying). Automated application method was used in project P-2, P-4, and P-5 while manual application method was used in project P-1 and P-3.

However, it is noted that the tack coat application was not uniform in the manual application method. Figure 11 and Figure 12 show the tacked surfaces of automated application and manual application respectively.

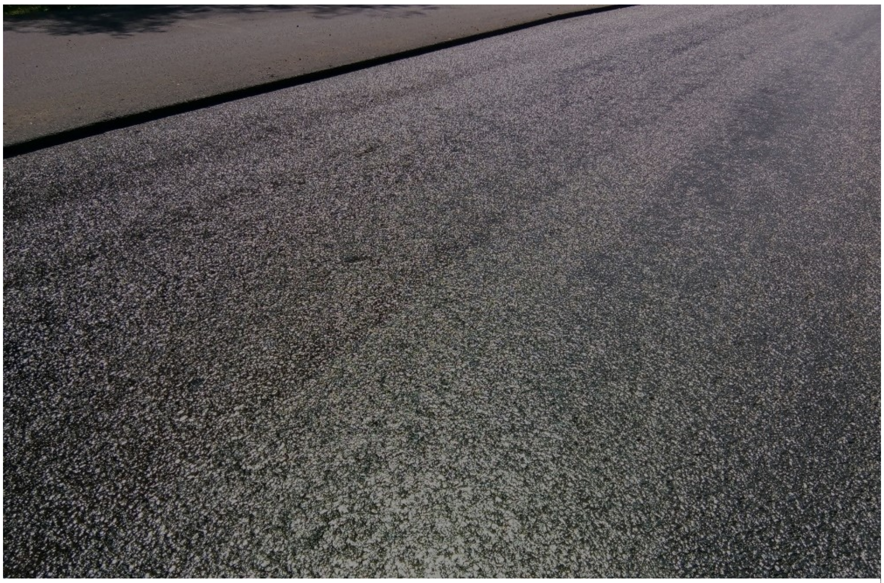


Figure 11. Tacked surface of automated application

Figure 12. Tacked surface of manual application

Five tests were carried out on the same location before placing the new bituminous layer as described in the sections from 3.5.1 to 3.5.5.

3.5.1 Sand patch test

This test was performed to evaluate the surface macro-texture (mean texture depth (MTD) of the existing pavement layer. This test was carried out according to ASTM E965 [11] “Standard test method for measuring pavement macrotexture depth using a

Figure 13. Solid glass spheres

volumetric technique". Moreover, this test was carried out before spraying the tack coat. Material and apparatus of this test are shown below.

- Solid glass spheres (passing No.60 sieve and retaining on a No. 80 sieve) (Figure 13)
- Measuring cylinder (volume of 200 cm^3)
- Spreader tool (wooded hard disk approximately of 25 mm thickness and 100 mm in diameter, with the bottom face covered by a 2 mm thick hard rubber material) (Figure 14)
- Ruler (at least 400 mm long)
- Brush (to clean) & dust pan (to collect the glass spheres used)

Figure 14. Spreader tool

The procedure of the test is as follows.

- The test was conducted after cleaning the existing pavement using a water and air compressor. Furthermore, the test was performed for a dry and nearly homogenous location.
- Selected location was thoroughly cleaned by a brush again.
- 50 cm^3 of glass spheres were measured in to the measuring cylinder.

- The measured volume of glass spheres was carefully poured on to the existing surface and was spread into a circular patch by the spreader tool to fill the voids in-between aggregate particle tips.
- Four diameters were recorded as shown in Figure 15 and the average of them was computed.
- The tested location was cleaned again using the brush and dust pan to remove the glass spheres from the existing pavement surface.

Figure 15. Sand patch test

The calculation of the test is given in equation 3.

$$SMT = \frac{4V}{\pi D^2} \tag{3}$$

Where:

SMT = Surface macro-texture (mm)

V = Sample volume (50000 mm^3)

D = Average diameter of the area covered by the glass spheres (mm)

3.5.2 Application rate by metal tray

This test method is commonly called as the “Tray Test” and was performed according to the ICTAD specification – section 1802.5: “Rate of spread of binders” [7]. This test is carried out during the spraying of the tack coat. Apparatus of this test are shown below.

- Light metal tray (area of 300 mm × 300 mm and 10 mm in depth) (Figure 16)
- Balance (0.5 g sensitivity)

Figure 16. Light metal tray

The procedure of the test is as follows.

- A cleaned metal tray was weighed prior to the test.
- It was kept on the required location as shown in Figure 16 before the spraying of the tack coat.
- Immediately after spraying the tack coat, the tray was weighed again and the weight difference was calculated.

The calculation of the test is given in equation 4.

$$Application\ rate\ , l/m^2 = \frac{W}{G \times A} \times 0.001 \qquad (4)$$

Where,

W = weight difference (g)

G = density of tack coat, vary from 0.909 to 1.009 g/cm^3

A = area of the metal tray, 0.09 m^2

3.5.3 Application rate by geotextile pad

This test was conducted according to ASTM D2995 [18] "Standard Practice for Estimating Application Rate and Residual Application Rate of Bituminous Distributors". It was performed during the spraying of the tack coat similar to tray test. Material and apparatus of this test are shown below.

- Non-woven geotextile pad (area of 300 mm × 300 mm) (Figure 17)
- Zip-lock bag
- Balance (0.5 g sensitivity)

Figure 17. Geotextile pad

The procedure of the test is as follows.

- The geotextile pad was put into the zip-lock bag as indicated in Figure 18 and was weighed. (Zip –lock bag was used in order to minimize the mass loss of the tack coat material)
- The geotextile pad was taken out of the zip-lock bag and was placed on the required location of the existing pavement just before spraying the tack coat.
- Just after spraying tack coat the geotextile pad was removed, was put into the zip-lock bag and weighed again. The weight difference is obtained, considering the amount of tack coat material collected to the geotextile pad.

Figure 18. Geotextile pad in zip-lock bag

The calculation of the test is identical to that of equation 5.

$$Application\ rate\ , l/m^2 = \frac{W}{G \times A'} \times 0.001 \qquad (5)$$

Where,

W = weight difference (g)

G = density of tack coat, vary from 0.909 to 1.009 g/cm^3

A' = area of the geotextile pad, 0.09 m^2

3.5.4 Residual application rate

This test was also conducted according to ASTM D2995 [18]. The geotextile pad which was used for the test of "application rate by geotextile pad" described in section 3.5.3, was kept in an oven maintained at 110 ± 5 ^{0}C for 24 hrs. The dried geotextile pad was put into a zip-lock bag and was weighed again. The weight difference is determined by the residual amount of tack coat material accumulated on to the geotextile pad. The calculation of the test is similar to that of equation 5.

3.5.5 Absorbed emulsion content test

This test was conducted according to the past study described in section 2.6.3, and was performed for the tacked surface. The material and apparatus of the test is shown below.

- Geotextile pad (non-woven polypropylene geotextile, area of 250 mm × 250 mm)
- Polyethylene foam layer (10 mm thick) (Figure 19)
- Steel plate (area of 250 mm × 250 mm)(Figure 20)
- Cylindrical load (20 kg) (Figure 21)

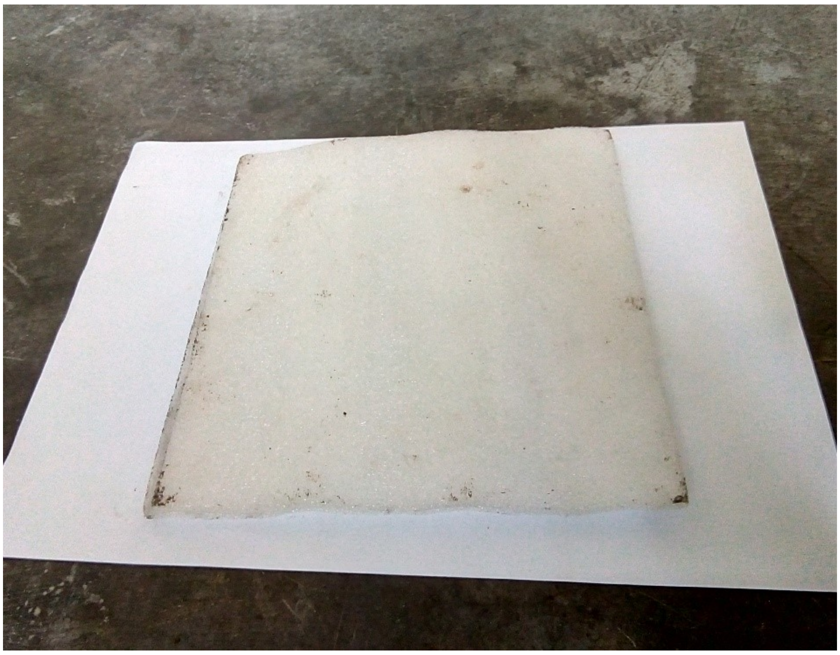


Figure 19. Polyethylene foam layer

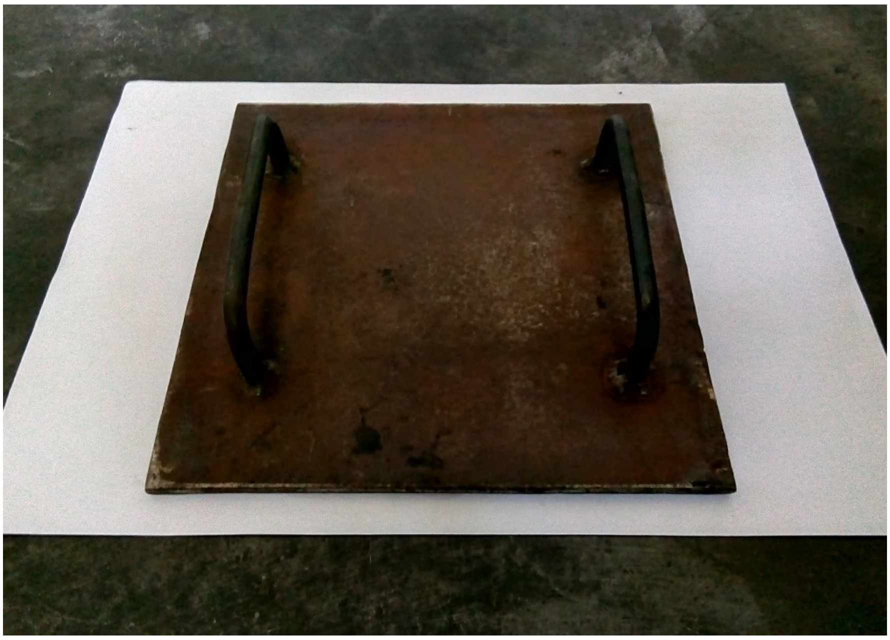


Figure 20. Steel plate

Figure 21. Cylindrical load

The procedure of the test is as follows.

- A geotextile pad was weighed before the test.
- 5 min after spraying tack coat, a geotextile pad was laid on the tacked surface at the required location.
- As depicted in Figure 22, the polyethylene foam layer, steel plate and cylindrical load were kept on the geotextile pad respectively.
- After 5 min, the geotextile was removed from the tacked surface and weighed.
- The weighed difference indicates the amount of emulsion absorbed into the geotextile pad.

Figure 22. Absorbed emulsion content test

The calculation of the test is given in equation 6.

$$\text{Absorbed Emulsion Content (AEC), } g/m^2 = W/A \quad (6)$$

Where,

W = weight difference (g)

A = area of the geotextile pad, 0.0625 m^2

3.5.6 Collecting pavement cores

The following day after laying the new bitumen layer, and before allowing traffic, the representative pavement core samples including both wearing course and binder course were collected from the locations where the above tests were conducted. Figure 23 shows the coring process in project P-5 and Figure 24 shows a pavement core sample extracted from project P-1.

Table 6 shows the number of core samples collected from each project, and all together 59 core samples were collected.

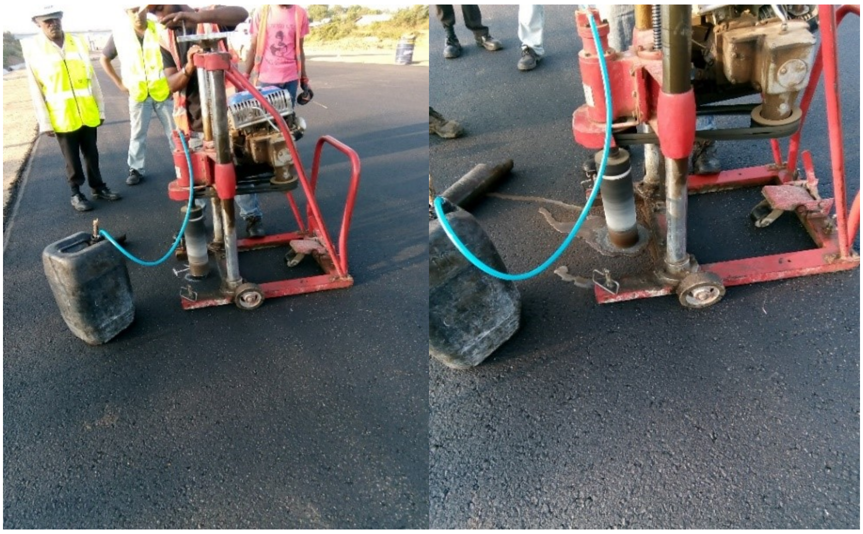


Figure 23. Coring process

Figure 24. Pavement core sample

Table 6. Amount of core samples

Project Number	Number of core samples collected
P-1	9
P-2	10
P-3	12
P-4	20
P-5	13

3.6 Field data analysis

All field test data are available in Appendix D. An initial analysis for the collected field data was conducted for each project. In this initial analysis, ranges of the data collected for each parameter were evaluated. Further, the relationships between the methods of estimating the dosage of the application of tack coat, such as the application rate, residual application rate, and absorbed emulsion content were analyzed. In addition to that, the characteristics of application methods and features of core samples were evaluated.

As well as, performance of absorbed emulsion content with other parameters was analyzed by MATLAB software at initial stage.

3.7 Moratuwa Interface Shear Strength Test (MISST) device

Based on the past studies, a new test device named "Moratuwa Interface Shear Strength Tester (MISST)" device was designed and built to evaluate the interface shear strength (ISS) of the collected pavement core samples. MISST device is shown in Figure 25.

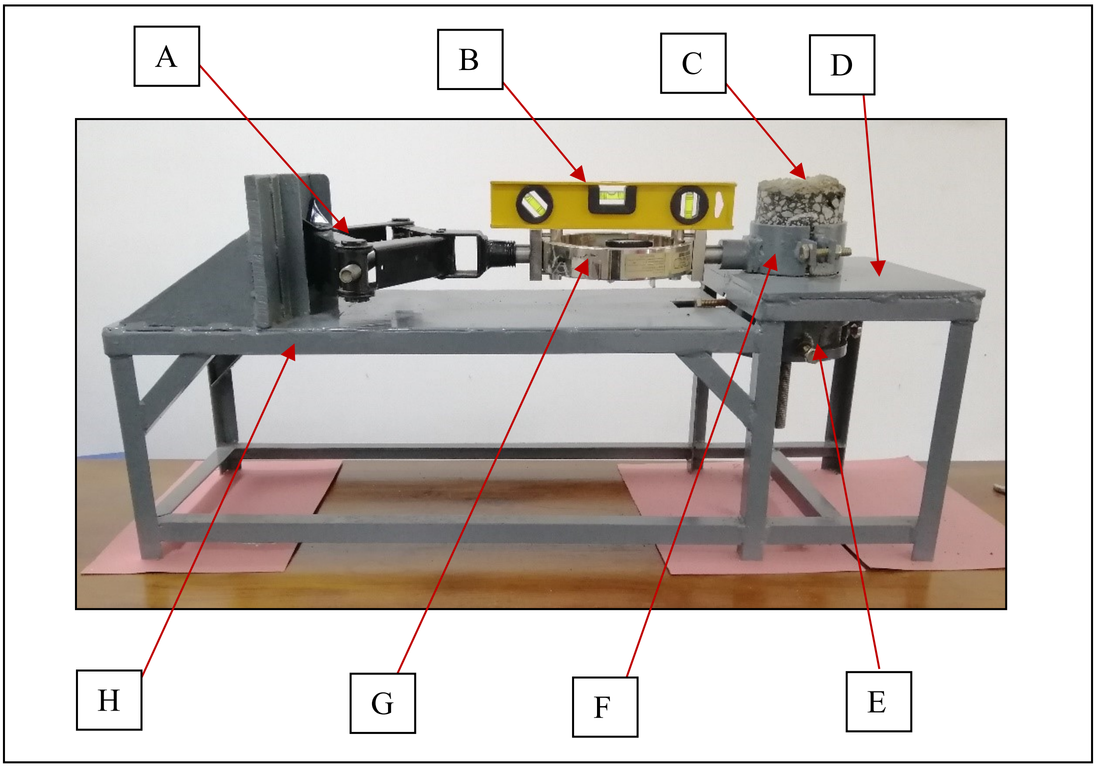


Figure 25. Moratuwa Interface Shear Strength Tester (MISST) Device

A: Screw jack

B: Spirit level

C: Pavement core sample

D: Upper bed of the frame

D: Bottom holder

E: Top collar

F: Proving ring

G: Lower bed of the frame

3.7.1 Performance of MISST device

Further illustrations of MISST device are shown in Figure 26 and 27.

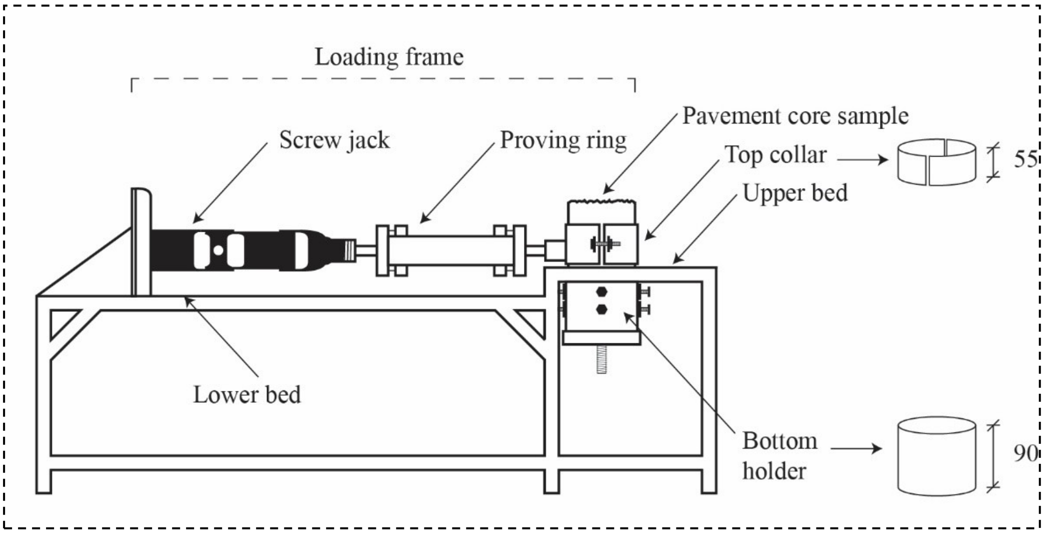


Figure 26. Illustration of MISST device

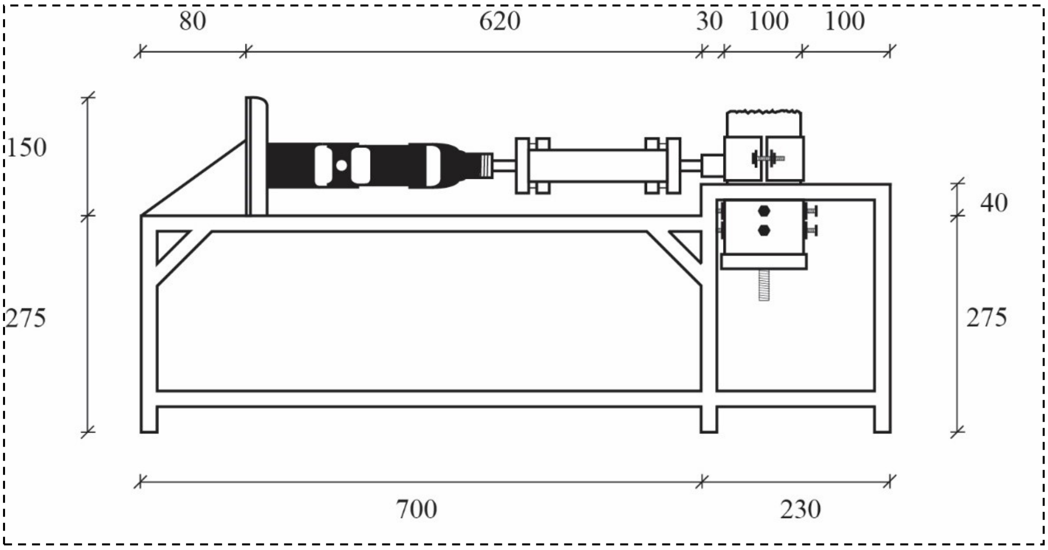


Figure 27. Dimensions of MISST device

Functions and specifications of main part of the device is presented below.

- Screw jack (Figure 28)
  - In this part, a screw thread is rotated to produce horizontal load.
  - Maximum loading capacity of this device is 13 kN.

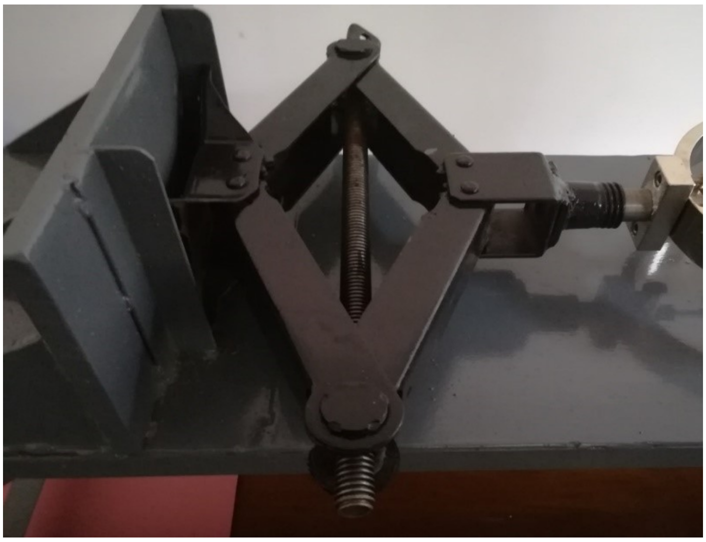


Figure 28. Screw jack

- Proving ring (Figure 29)
  - This is a S370-05 type proving ring with a load capacity of 10 kN.
  - Function of this is to record the amount of load being applied.

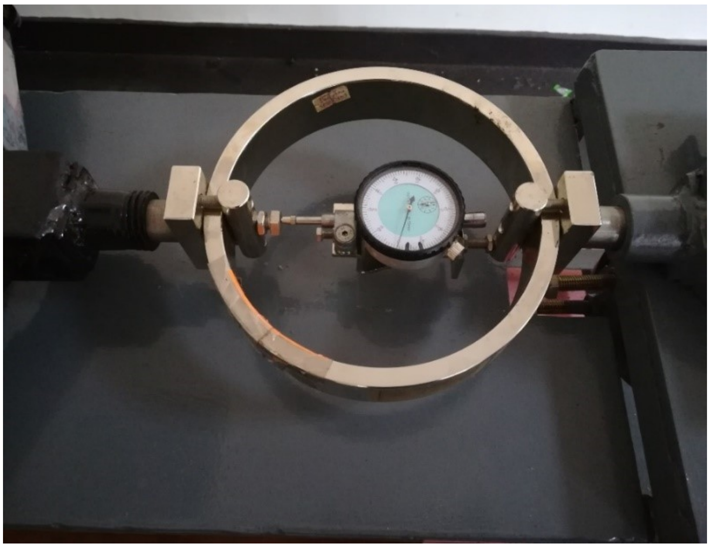


Figure 29. Proving ring

- Pavement core sample (Figure 30)
    - Pavement core samples 100 mm in diameter collected under field data collection are tested here.
    - It is noted that, the core sample should be placed up and down because the new layer has a nearly flat surface.

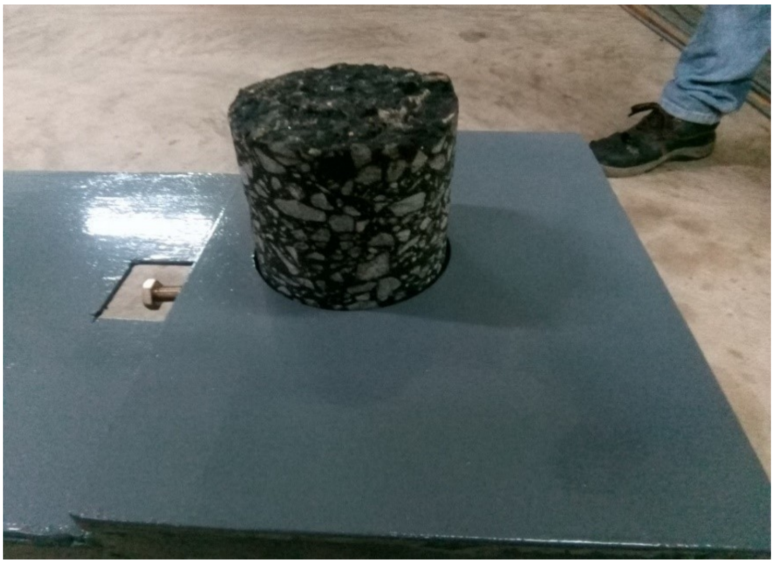


Figure 30. Pavement core samples on MISST device

- Bottom holder (Figure 31)
    - Main purpose of this part is to thoroughly hold the bottom part of the core sample, and this is attached to the upper bed of the frame.

Figure 31. Bottom holder

- There is a 15 mm screw thread attached to a 10 mm thick circular steel plate to adjust the elevation of the pavement core sample.
- There is also a splitting steel cylinder of 10 mm thickness which is capable of holding the core sample thoroughly this collar is covered by another steel cylinder with a 5 mm thickness.
- There are 8 nuts and bolts attached to this holder to clamp the steel collar comprehensively in order to avoid any movements.

- Top collar
  - This is a splitting steel cylinder with a 5mm thickness with two couplings.
  - The function of this part is to transfer the load to the pavement core sample evenly.

Figure 32. Top collar

- Spirit level
  - A spirit level was used to keep the loading frame (screw jack and proving ring) horizontally.

3.7.2 Calibration of MISST device

Before testing the pavement core samples, the MISST device was calibrated. For that, models made by wooden cylindrical samples 100 mm in diameter, as shown in Figure 33 were used.

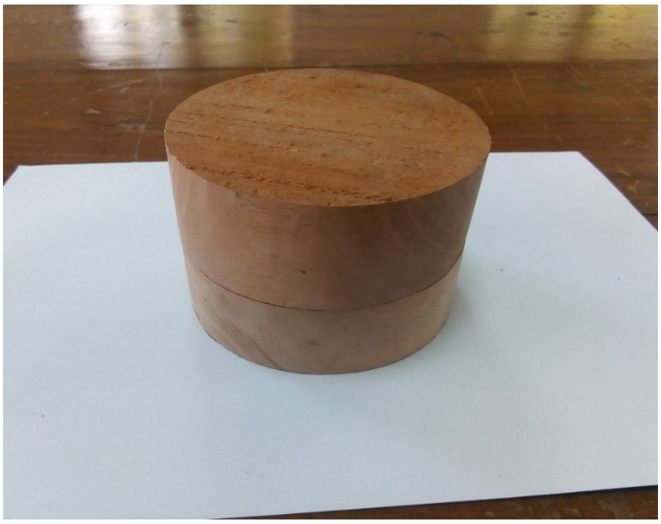


Figure 33. Wooden cylindrical samples

First, both the top and bottom sides of each wooden cylindrical sample were polished using P120 sand paper in order to obtain an even surface texture. Then, two segments were bound employing different bond conditions as described in Table 7. Twelve samples were tested using MISST device. Figure 34 shows wooden samples bounded by bitumen 60/70.

Figure 34. Wooden samples bounded by bitumen 60/70

Table 7. Calibrating details of MISST device

Sample Number	Bonding Agent	Amount (g)	Remarks	Failure Load (kN)	Standard deviation of load (kN)
W1	Bitumen 60/70	8	Use Hot bitumen to bind and allow to dry 24 hrs before the test	0.32	0.05
W2		8		0.43	
W3		8		0.38	
W4	Multibond–364	0.60	Apply bonding agent on both surface and allow 3 days to dry before test	2.65	0.1
W5		0.62		2.76	
W6		0.54		2.65	
W7	Multibond–364	1.55	Apply bonding agent on both surfaces and allow 1 day to dry before test	1.19	0.1
W8		1.42		1.30	
W9		1.36		1.35	
W10	Chemifix	4.44	Apply bonding agent on both surfaces and allow 1 day to dry before test	>8.1281	0
W11		4.76		>8.1281	
W12		4.61		>8.1281	

According to the details presented in Table 1, it can be observed that there are some minor differences among results because of the slight differences in amount of bonding agent. Although this device is not much sensitive to small loads, it is sensitive enough for the larger loads.

3.8 Laboratory data collection

The test procedure is described below.

- First and foremost, the line of bond between two layers of the core sample is carefully marked by white chalk.
- Next, the core sample is placed through the bottom collar and the elevation is adjusted so that the bond line is 2 mm above the top surface of the upper bed of the frame.
- Then, the pavement core sample is clamped tightly using nuts and bolts of the bottom holder.
- Top part of the pavement core sample is clamped using the top collar.
- Then, top clap and screw jack are connected utilizing the proving ring.
- The loading frame is leveled horizontally using the spirit level. With these preparations being complete the test device is ready for testing.
- A constant load of 0.22 kN/s is manually applied by the screw jack until failure (Figure 35). A failed core sample is shown in Figure 36.
- 55 pavement core samples were tested as above.

Figure 35. Core sample at the failed moment

Figure 36. Failed core sample

3.9 Final analysis

The final analysis was conducted using the field laboratory data collected as interface shear strength of pavement (ISS) core samples, which were evaluated by the MISST device. Correlations of each parameter, with the interface shear strength, were analyzed by the MATLAB software and Minitab software. A final model was developed using significant parameters affecting interface shear strength. Results of 32 pavement core samples were utilized to develop the final model, while results of 10 pavement core samples were utilized to validate the final model. Appendix F and Appendix G are inclusive of all the information used for the final analysis.

Validation of the regression model was conducted by method of Root Mean Square Error (RMSE) as presented in equation 7.

$$RMSE = \sqrt{\frac{\sum(P_i - O_i)^2}{n}} \tag{7}$$

Where,

P_i= Predicted value by final model

O_i = Observed value by laboratory test data

n = number of core samples used for validation

RMSE values were calculated for both the trained data set and validation data set and were compared.

CHAPTER 04

4. RESULTS AND DISCUSSION

4.1 General

The salient findings of this research are encompassed within this chapter. It includes the results of the questionnaire survey, distribution of the data collected from the field, relationships between each parameter, comparison between former studies and this research, results of the calibration of MISST device, and development of the final model.

4.2 Questionnaire survey results

All questionnaire survey results are included in Appendix C. Some of critical results were discussed in this section.

4.2.1 Type of tack coat material

Figure 37 shows types of tack coat material are typically applied on existing pavement surfaces. According to the results, it is clearly observed that CRS-1 is the most common type of tack coat material used in the field.

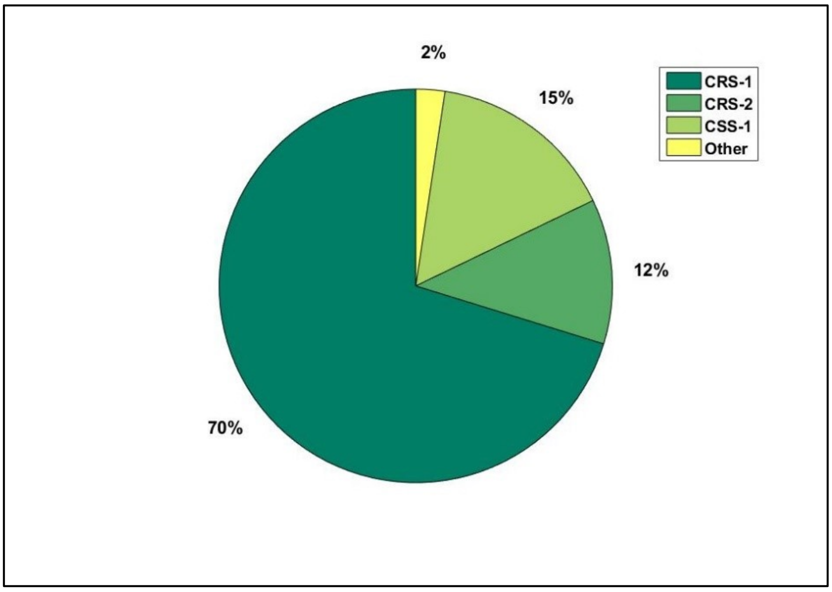


Figure 37. Types of tack coat material

4.2.2 Curing time

Figure 38 shows the common time gap in between the spreading of the tack coat and placing of the wearing course in the field. Because the type of tack coat is CRS-1, it can be observed that the common curing time was also less than 30 min.

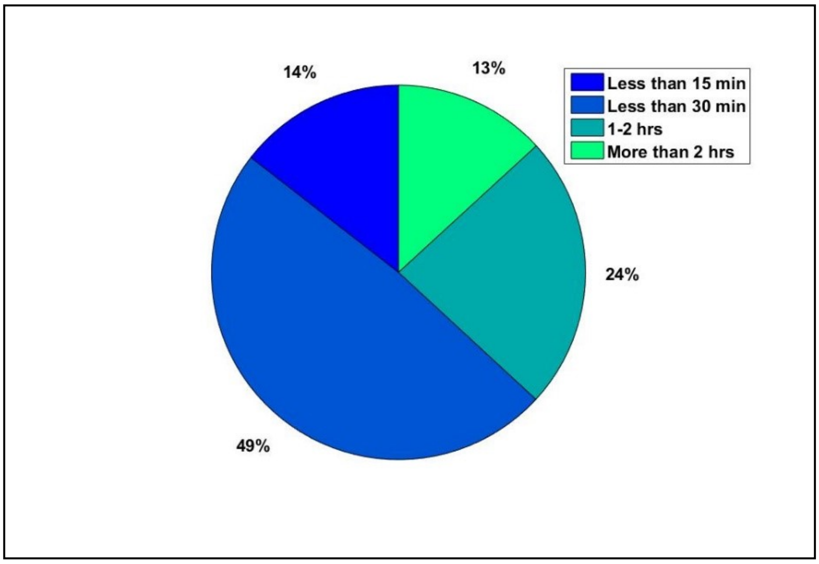


Figure 38. Curing time

In the construction point of view, using CRS-1 is more convenient than using CSS-1. Because CSS-1 needs more curing time than CRS-1. In addition to that, CSS-1 tends to drain off from the existing pavement surface due to the camber of the pavement.

4.2.3 Application rate

Table 8 shows the application rate for different existing pavements as the average values of the results. The results indicate that a high application rate is needed for milled surfaces while the lowest application rate is needed for fresh pavement surfaces. As well as, it is noted that the application rate for every pavement type is within the range between 0.25 and 0.55 l/m^2, as recommended in the ICTAD specification [7].

Table 8. Average application rates

Existing Pavement (Binder Course) Type	Application Rate *(l/m²)*
Old / Oxidized HMA layer	0.35
New / Fresh HMA Layer	0.29
Portland Cement Concrete (PCC) layer	0.44
Milled HMA Surface	0.47
Milled PCC Surface	0.50

4.2.4 Application method

According to the questionnaire results, both conventional methods were used in the field, although the hand spraying method was more popular than the truck mounted application method, as shown in Figure 39.

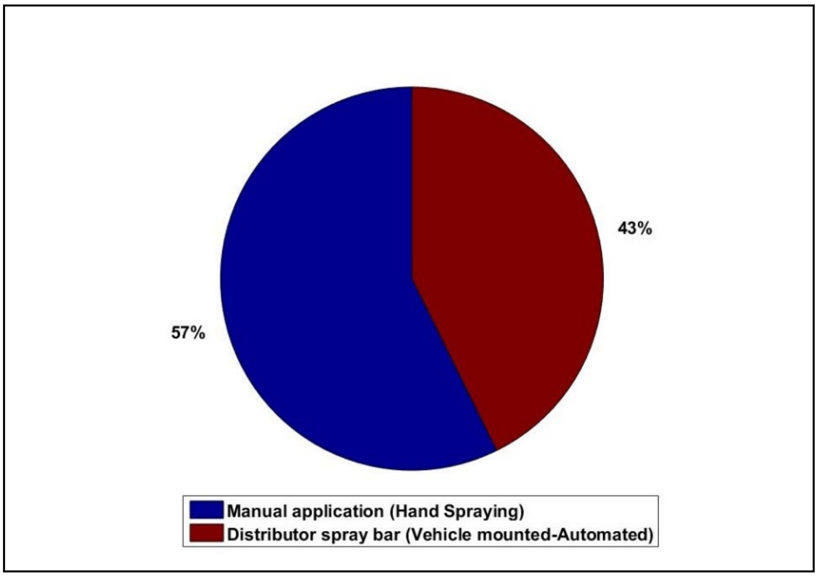


Figure 39. Application methods

4.3 Distribution of field data

This section demonstrates the ranges of variables that were considered for this study. All field data collected is presented in Appendix A. Table 9 shows the ranges of surface macro-texture (SMT) and application rate by tray test (ART) of each project. Further,

Table 10 shows the ranges of the application rate by geotextile (ARG) and residual application rate (RAR) while Table 11 shows the ranges of absorbed emulsion content (AEC).

Table 9. Surface macro-texture and application rate by tray test

Project Number	Surface macro-texture (mm)		Application rate by tray test (l/m^2)	
	Minimum	Maximum	Minimum	Maximum
P-1	0.45	1.03	0.11	0.54
P-2	0.56	2.44	0.17	0.45
P-3	0.41	2.37	0.12	0.85
P-4	0.60	1.27	0.19	0.59
P-5	0.48	0.79	0.15	0.43

Table 10. Application rate by geotextile and residual application rate

Project Number	Application rate by geotextile (l/m^2)		Residual application rate (l/m^2)	
	Minimum	Maximum	Minimum	Maximum
P-1	0.15	0.68	0.07	0.32
P-2	0.22	0.56	0.10	0.22
P-3	0.14	1.04	0.06	0.43
P-4	0.30	0.87	0.12	0.34
P-5	0.17	0.42	0.13	0.28

Table 11. Absorbed emulsion content

Project Number	Absorbed Emulsion Content (g/m^2)	
	Minimum	Maximum
P-1	3.0	58.7
P-2	12.9	197.5
P-3	5.0	376.0
P-4	8.0	328.0
P-5	16.0	61.0

Figure 40 shows the distribution of all the data concerning the surface macro-texture (SMT). However, surface macro-texture for location number 15, 18, 22, and 35 exhibit unusual values. A segregation of the bitumen on the existing pavement layer could be observed at those locations as shown in Figure 41. Therefore, those four locations were considered as outliers and were removed from the analysis. Consequently, summary of the entire set of data used in the initial analysis are presented in Table 12 and further elaborated in Appendix B.

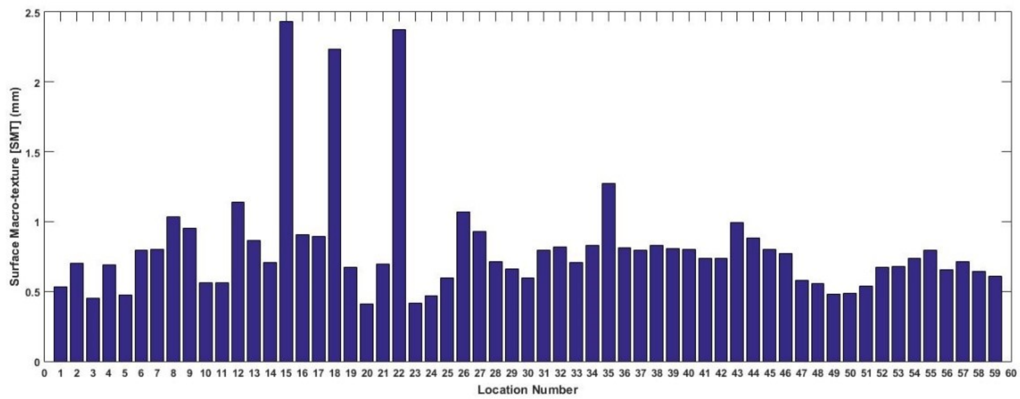


Figure 40. Distribution of surface macro-texture data

Figure 41. Segregated pavement surface

Table 12. Summary of data set of initial analysis

Parameter	Minimum	Maximum	Average	Standard Deviation
Surface macro-texture [SMT] *(mm)*	0.41	1.14	0.72	0.17
Application rate by tray test [ART] *(l/m²)*	0.11	0.83	0.31	0.14
Application rate by geotextile [ARG] *(l/m²)*	0.14	1.02	0.39	0.19
Residual application rate [RAR] *(l/m²)*	0.06	0.39	0.20	0.07
Absorbed Emulsion Content [AEC] *(g/m²)*	3	376	74	68.47

4.4 Relationships of parameters

The correlations of mutual parameters are discussed in this section.

4.4.1 Relationship between ART and ARG

The relationship between the application rate by tray test (ART) and application rate by geotextile (ARG), is shown in Figure 42.

R-squared value of this graph is 81.51 %. Accordingly, there is a good correlation between the two test methods of application rate.

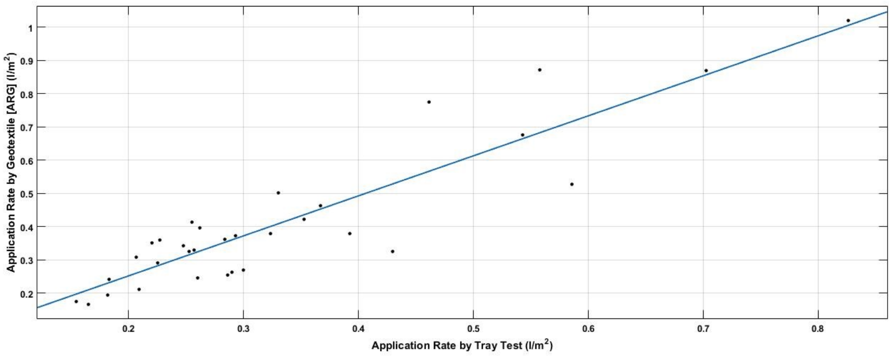


Figure 42. ARG vs ART

4.4.2 Relationship between ART and RAR

The relationship between the application rate by tray test (ART) and residual application rate (RAR), is shown in Figure 43. R-squared value of the graph is 73.34 %. Therefore, there is a good correlation between ART and RAR.

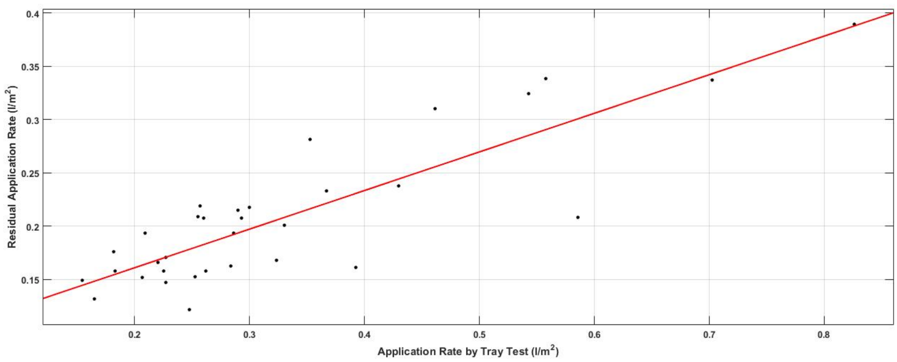


Figure 43. RAR vs ART

4.4.3 Relationship between ARG and RAR

The relationship between the application rate by tray test (ART) and residual application rate (RAR), is shown in Figure 44. R-squared value of this graph is 72.72 %.Therefore, there is a good correlation between ARG and RAR.

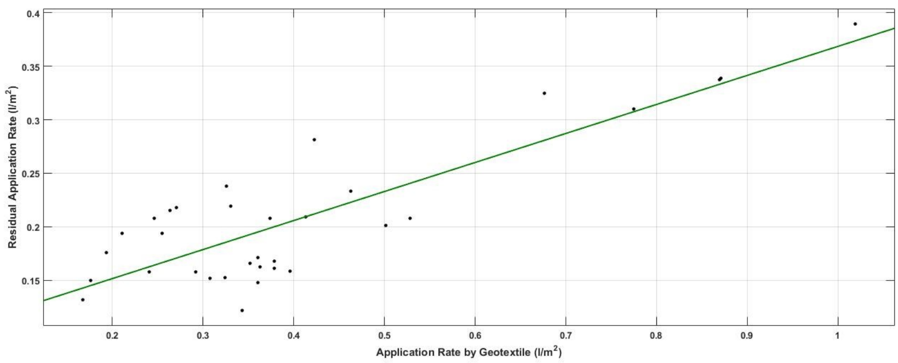


Figure 44. RAR vs ARG

However, according to the section from 4.4.1 to 4.4.3, there was not a very strong goodness of fit (R-squared ~ 1.00) among ART, ARG, and RAR. The average residual bitumen content was 54.6 % although the minimum requirement of ASTM is 60%. In addition to that, there may be some errors in estimating the application rate by field tests. Those may be causes for being unable to obtain very strong goodness of fitness in this study.

4.5 Relationships with absorbed emulsion content (AEC)

Correlations between the absorbed emulsion content (AEC) and other parameters are discussed in this section because the absorbed emulsion content was introduced as a new parameter in a study by Raposeiras et al. [14] using laboratory prepared samples.

Prior to delineating the analysis, the distribution of absorbed emulsion content is shown in Figure 45. Accordingly, location number 10 was an outlier and therefore, was removed from the analysis for absorbed emulsion content.

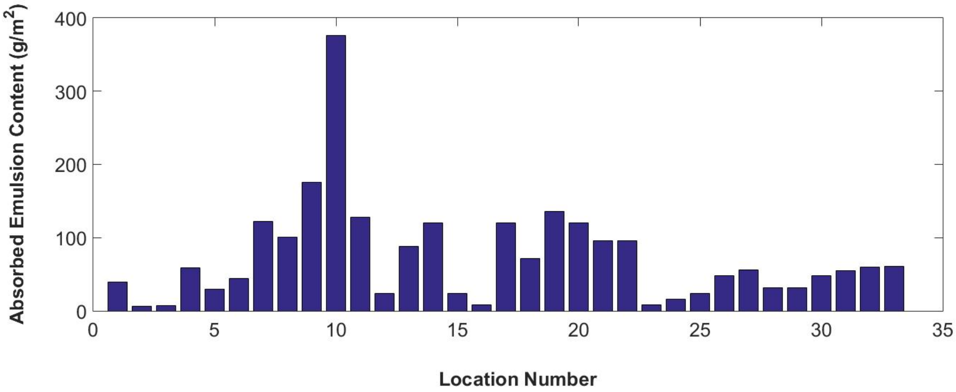


Figure 45. Distribution of absorbed emulsion content data

4.5.1 Relationship between AEC and SMT

The relationship between absorbed emulsion content (AEC) and surface macro-texture (SMT), is shown in Figure 46. R-squared value of this relationship is 4.84 %. Thus, itis observed that the absorbed emulsion content does not depend exclusively on the surface macro-texture.

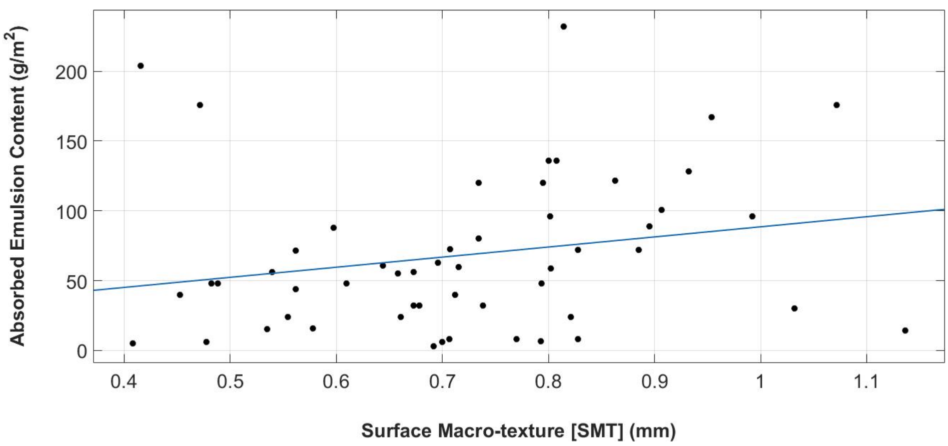


Figure 46. AEC vs SMT

4.5.2 Relationship between AEC and ART

The relationship between absorbed emulsion content (AEC) and application rate by tray test (ART), is shown in Figure 47. R-squared value of this relationship is 42.80 %, and it is a weak relationship.

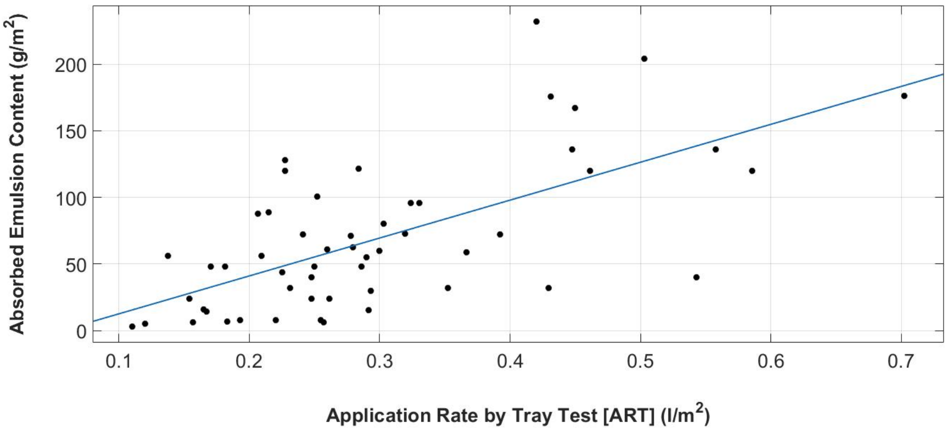


Figure 47. AEC vs ART

4.5.3 Relationship between AEC and ARG

The relationship between absorbed emulsion content (AEC) and application rate by tray test (ART), is shown in Figure 48. R-squared value of this relationship is 42.80 % and this is also a weak relationship like section 0.

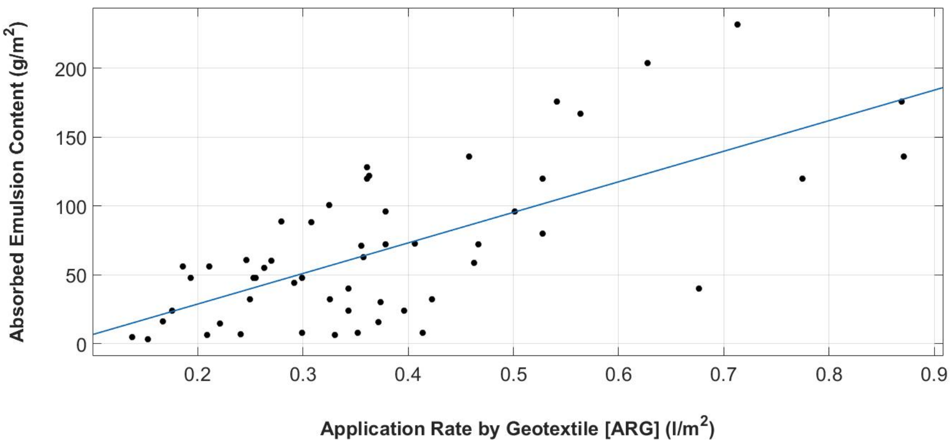


Figure 48. AEC vs ARG

4.5.4 Relationship between AEC and RAR

The relationship between absorbed emulsion content (AEC) and residual application rate (RAR), is shown in Figure 49. R-squared value of this relationship is 25.99 %, and correlation of this is very weak.

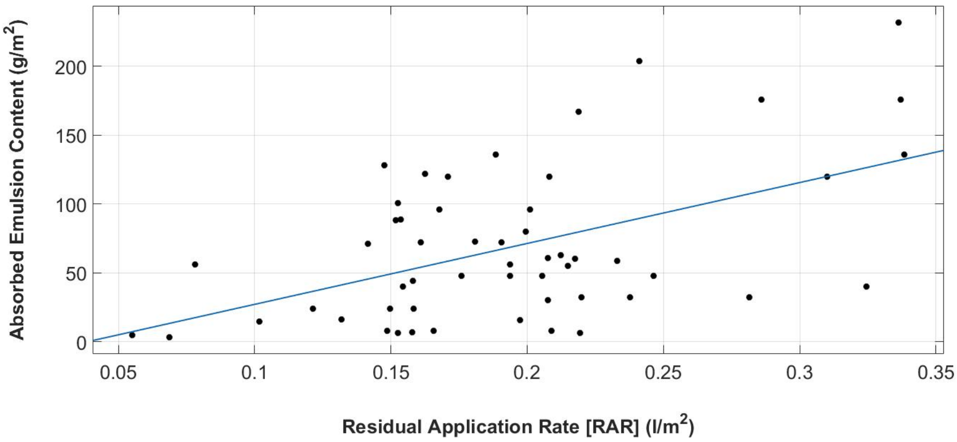


Figure 49. AEC vs RAR

4.5.5 Relationship among AEC, SMT and ART

The relationship among absorbed emulsion content (AEC), application rate by tray test (ART) and surface macro-texture (SMT), is shown in Figure 50. R-squared value of this relationship is 46.55 %.P-values of ART and SMT are 0.000 and 0.065 respectively. Although ART is significant in this relationship, SMT is not significant.

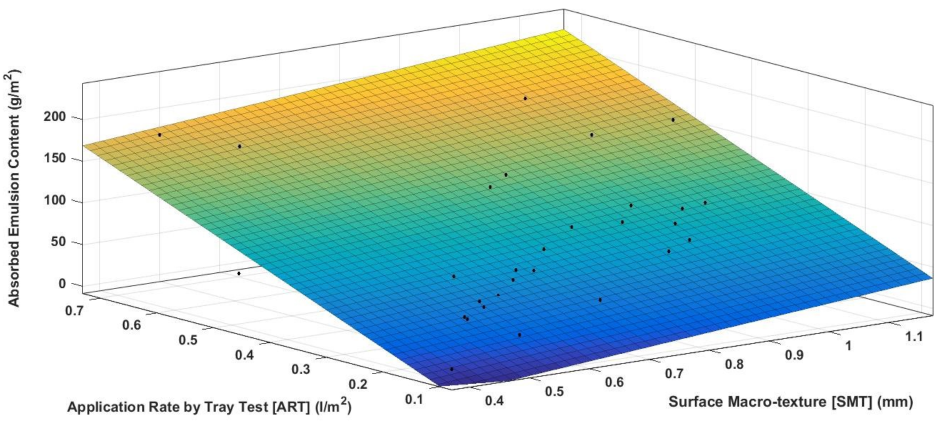


Figure 50. AEC vs ART, SMT

4.5.6 Relationship among AEC, SMT and ARG

The relationship among absorbed emulsion content (AEC), surface macro-texture (SMT) and application rate by geotextile (ARG), is shown in Figure 51. R-squared value of this graph is 49.57 %.P-values of ARG and SMT are 0.000 and 0.183 respectively. Although ARG is significant in this relationship, SMT is not significant, similar to that of section 4.5.5.

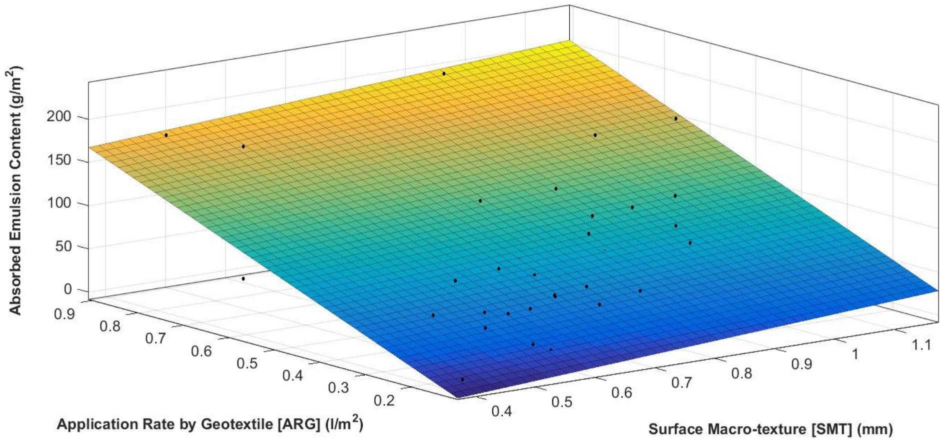


Figure 51. AEC vs ARG, SMT

4.5.7 Relationship among AEC, SMT and RAR

The relationship among absorbed emulsion content (AEC), surface macro-texture (SMT) and residual application rate (RAR), is shown in Figure 52. R-squared value of

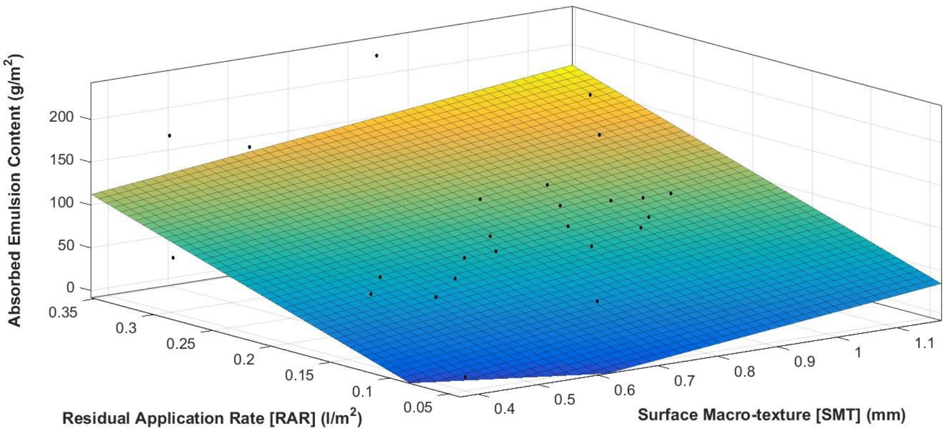


Figure 52. AEC vs RAR, SMT

this graph is 31.69 %. P-values of RAR and SMT are 0.000 and 0.045 respectively. Accordingly, both RAR and SMT are significant to AEC but, the coefficient of determination (R-squared) is low.

4.5.8 Summary AEC analysis

In a research conducted by Raposeiras et al. [14], a model for absorbed emulsion content had been developed using the standardized macro texture and residual bitumen dosage as shown in equation 8 and R-squared this model was 73.6%.

$$EA=0.065 \times ED-50.697 \times M+78.327 \tag{8}$$

Where, *EA* is the percentage of absorbed emulsion of the residual bitumen content (%), *ED* is the residual emulsion dosage (g/m^2), and *M* is the standardized macro-texture (mm). It is noted that the standardized macro-texture (M) is equivalent to surface macro-texture (SMT) collected in the field of the new study.

Considering surface macro-texture and residual application of the new analysis, the regression equation for the field data collection as described in section 4.5.7is shown in equation 9.

$$AEC = 449.4\times RAR+78.19\times SMT-74.94 \tag{9}$$

Where, *AEC* is absorbed emulsion content (g/m^2), *RAR* is the residual application rate (g/m^2), and S*MT* is surface macro-texture.

The coefficient of determination (R-squared) is low in this relationship while residual application rate and surface macro-texture are significant. It indicates that the surface macro-texture and residual application rate are correlated with the absorbed emulsion content. Yet the variability in the absorbed emulsion content is not subjected to a satisfactory explanation. The reasons of such a variation may be because data was collected at various temperatures and environmental conditions, emulsions were supplied by various manufactures and their breaking time may not be within 5 min, as considered in the past study. Residual bitumen content also deviated from the ASTM minimum requirement and could also be considered a valid reason.

Therefore, the values for absorbed emulsion content corrected by the equation 8 were used for further analysis. Calculated values for corrected absorbed emulsion content (CAE) is also presented as a percentage in Appendix E.

4.6 Summary of field data analysis

Table 13 shows the summary of pair wise comparison of all parameters using the field data collection, and values shown in the table are R-squared values. Accordingly, the bolded values show a strong correlation with each other. Therefore, those pairs of parameters should not be included together in the final model.

Table 13. Summary of field data analysis

	SMT (mm)	ART (l/m^2)	ARG (l/m^2)	RAR (l/m^2)	AEC (g/m^2)	CAE (%)
SMT (mm)	-	0.17	0.32	3.7	1.04	**76.87**
ART (l/m^2)	0.17	-	**79.96**	**65.07**	**52.18**	18.27
ARG (l/m^2)	0.32	**79.96**	**-**	**68.27**	**56.1**	13.02
RAR (l/m^2)	3.7	**65.07**	**68.27**	-	37.03	45.31
AEC (g/m^2)	1.04	**52.18**	**56.1**	37.03	-	4.78
CAE (%)	**76.87**	18.27	13.02	45.31	4.78	-

4.7 Laboratory test results

Although, 59 core samples were collected, 4 of them were separated at the interface during the coring. Such a core sample is shown in Figure 54. Field data of these core samples are depicted in Appendix I. It is clearly observed that the application rate in both methods at such locations was comparably low.

During the testing of the pavement core samples by the MISST device, 44 pavement core samples exactly separated at the interface. However, 10 pavement core samples did not precisely separate at the interface, failing through the new bitumen layer. Figure 53 shows a core sample which had failed at the interface. Figure 55 shows a core sample that had not failed at the interface. The failure plane of such core samples in the wearing course was also clearly observed as shown in Figure 56. Furthermore, it was noted that there were larger aggregates in the wearing course accumulated much closer to the interface. It might have been a reason for such behavior. In addition to that, the plane of interface not being exactly horizontal might also be a cause for that.

Figure 54. Split core sample during coring

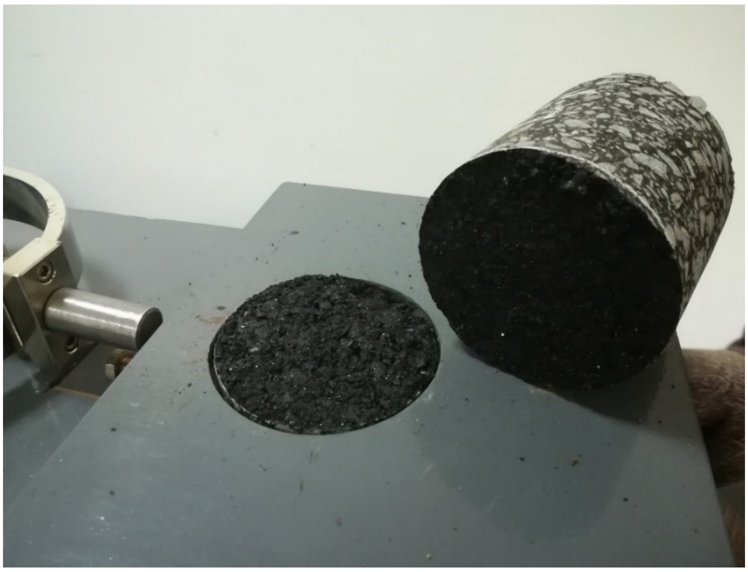


Figure 53. Core sample, failed at bond

Figure 55. Core sample, not failed at bond

Figure 56. Failure plane of the core sample (a) above the interface (b) below the interface

4.8 Final Model development

The behavior of the interface shear strength values of pavement core samples which were estimated by the MISST device was discussed in this section. Final model was developed by test results related to 32 pavement core samples and all information is presented in Appendix F.

4.8.1 Relationship between ISS and SMT

The relationship between interface shear strength (ISS) and surface macro-texture (SMT) is shown in Figure 57. R-squared value of this relationship is 28.51%, and it is a negative correlation.

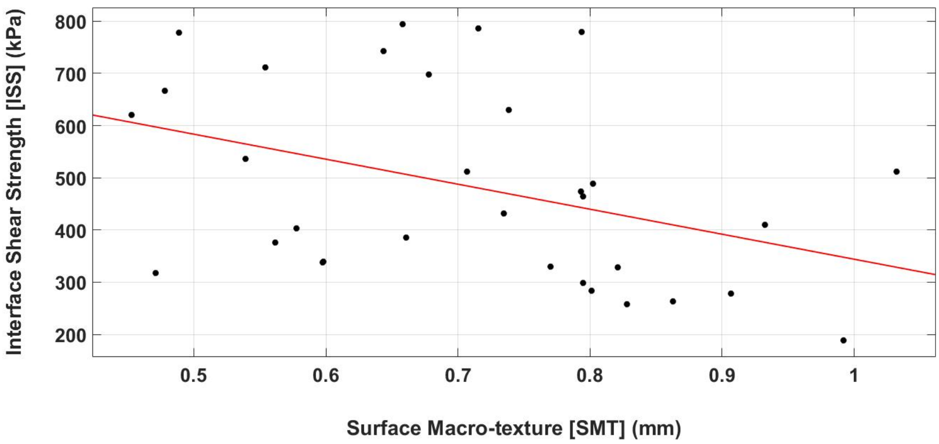


Figure 57. ISS vs SMT

4.8.2 Relationship between ISS and ART

The relationship between interface shear strength (ISS) and application rate by tray test (ART) is shown in Figure 58. R-squared value of this relationship is 7.49 %, and it is a negative correlation.

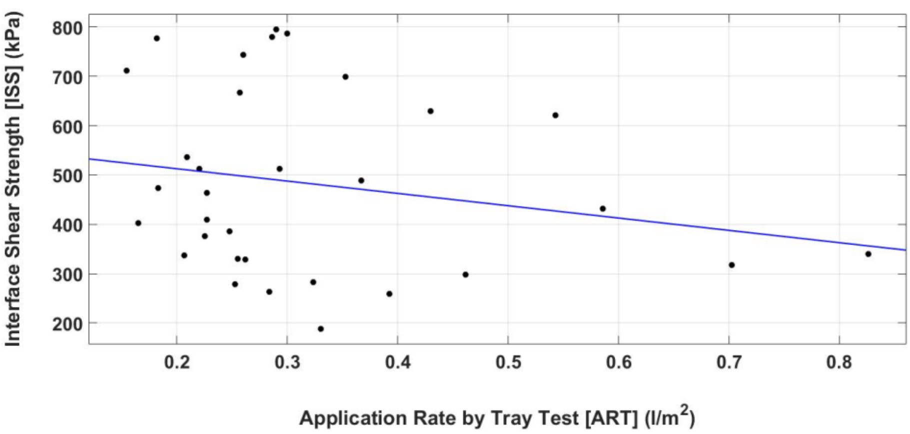


Figure 58. ISS vs ART

4.8.3 Relationship between ISS and ARG

The relationship between interface shear strength (ISS) and application rate by geotextile (ARG), is shown in Figure 59. R-squared value of this relationship is 21.58 %, and it is a negative correlation.

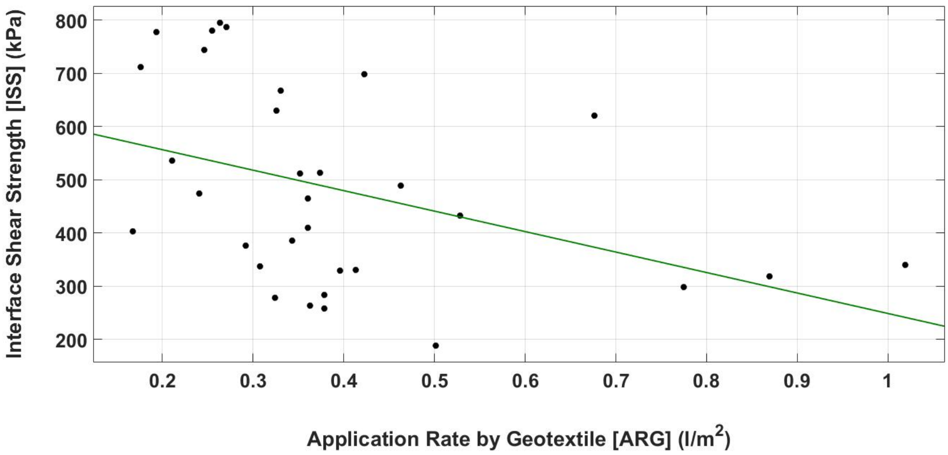


Figure 59. ISS vs ARG

4.8.4 Relationship between ISS and RAR

The relationship between interface shear strength (ISS) and residual application rate (RAR), is shown in Figure 60. R-squared value of this relationship is 0.03 %, and it is a positive correlation.

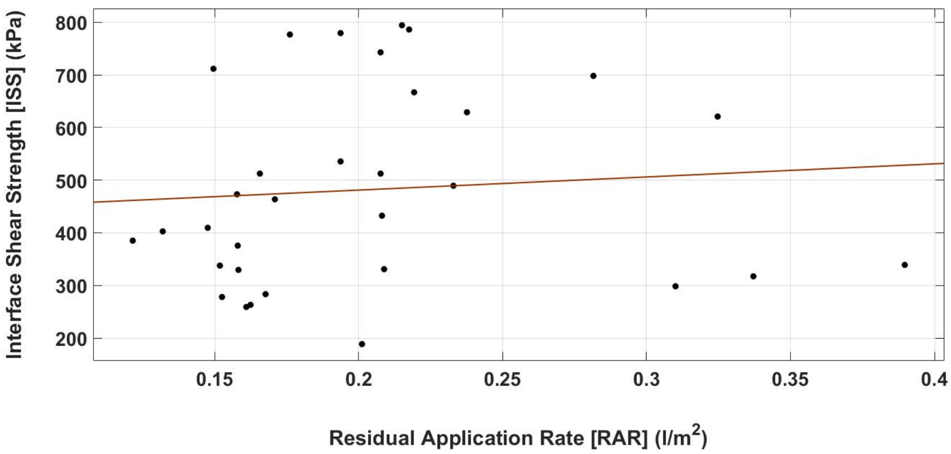


Figure 60. ISS vs RAR

4.8.5 Relationship between ISS and AEC

The relationship between the interface shear strength (ISS) and absorbed emulsion content (AEC) is shown in Figure 61. R-squared value of this relationship is 16.44 %, and it is a negative correlation.

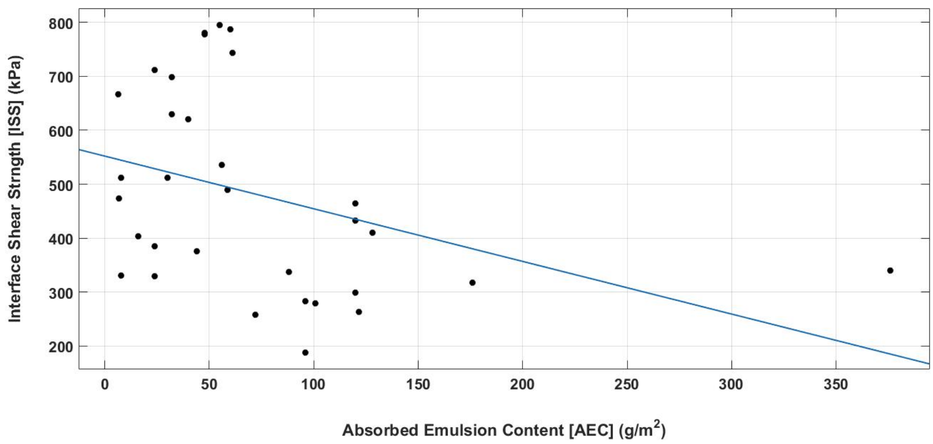


Figure 61. ISS vs AEC

4.8.6 Relationship between ISS and CAE

The relationship between interface shear strength (ISS) and corrected absorbed emulsion content (CAE), is shown in Figure 62.R-squared value of this relationship is 17.70 %, and it is a positive correlation.

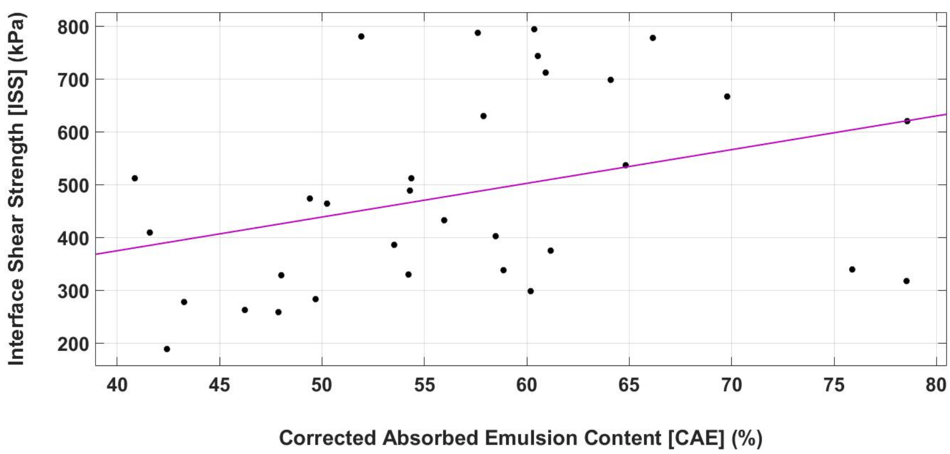


Figure 62. ISS vs CAE

Coefficient of determination (R-squared) values and type of the correlation of each parameter with Interface shear strength (ISS) is shown in Table 14. Accordingly every parameter has a weak correlation with ISS. Therefore, the model should be developed with multi variables.

Table 14. Summary of correlations of ISS with other parameters

Parameter	R-squared	Correlation type
SMT(mm)	28.51%	Negative
ART (l/m^2)	7.49 %	Negative
ARG (l/m^2)	21.58 %	Negative
RAR (l/m^2)	0.03 %	Positive
AEC (g/m^2)	16.44 %	Negative
CAE (%)	17.70 %	Positive

4.8.7 Relationship among ISS, SMT and ART

The relationship among interface shear strength (ISS), surface macro-texture (SMT) and application rate by tray test (ART), is shown in Figure 63. R-squared value of this

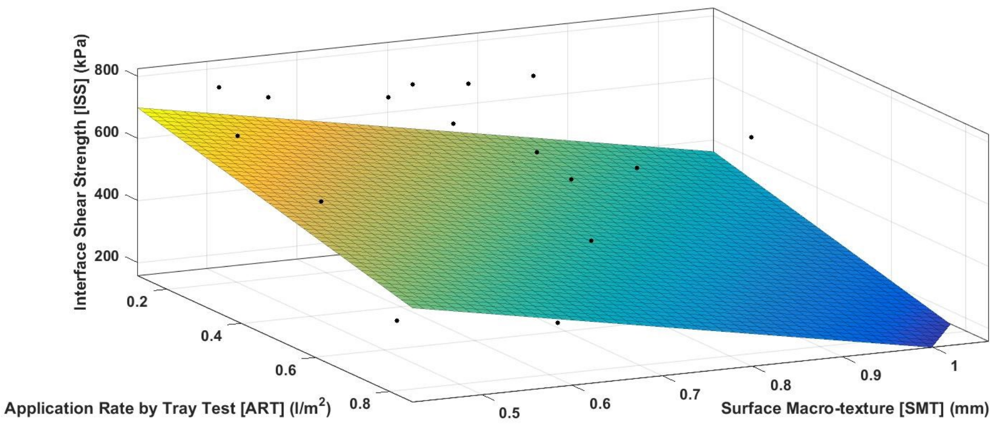


Figure 63. ISS vs ART, SMT

relationship is 40.89 %.P-values of ART and SMT are 0.020 and 0.000 respectively. Therefore, goodness of fit is weak, although parameters are significant.

4.8.8 Relationship among ISS, SMT and ARG

The relationship among interface shear strength (ISS), surface macro-texture (SMT) and application rate by geotextile (ARG), is shown in Figure 64. R-squared value of this relationship is 42.92 %.P-values of ARG and SMT are 0.001 and 0.000 respectively. Therefore, goodness of fit is low even though ARG and SMT are significant.

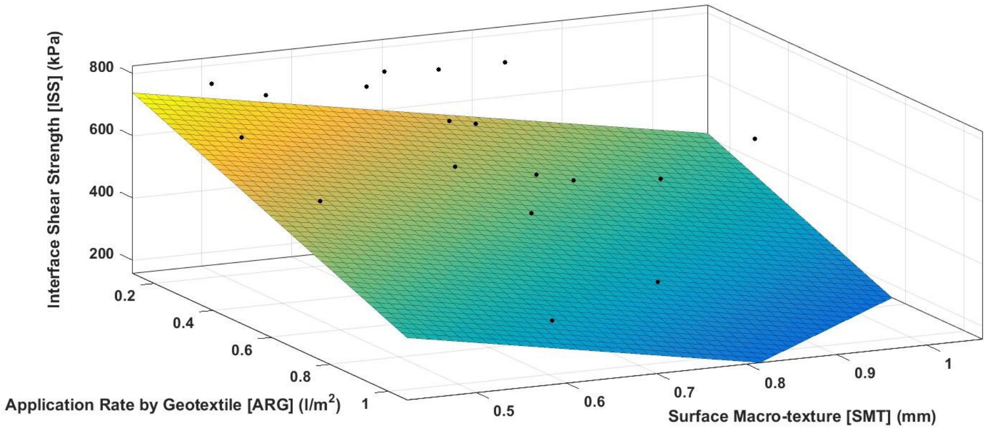


Figure 64. ISS vs ARG, SMT

4.8.9 Relationship among ISS, SMT and RAR

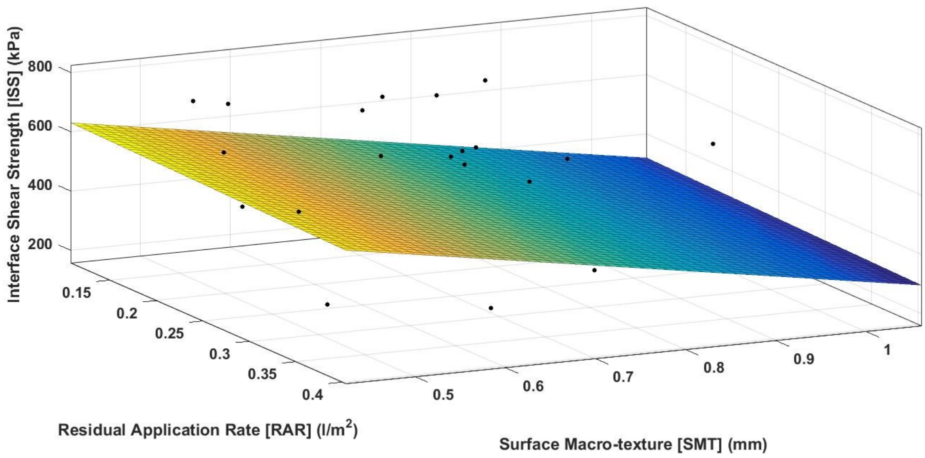


Figure 65. ISS vs RAR, SMT

The relationship among interface shear strength (ISS), surface macro-texture (SMT) and residual application rate (RAR), is shown in Figure 65. R-squared value of this relationship is 30.52 %.P-values of RAR and SMT are 0.367 and 0.001 respectively. Therefore, goodness of fit is very low and RAR is also not significant.

4.8.10 Relationship among ISS, SMT and AEC

The relationship among interface shear strength (ISS), surface macro-texture (SMT) and absorbed emulsion content (AEC), is shown in Figure 66. R-squared value of this relationship is 44.07 %. P-values of AEC and SMT are 0.008 and 0.001 respectively. Therefore, goodness of fit is low although AEC and SMT are significant.

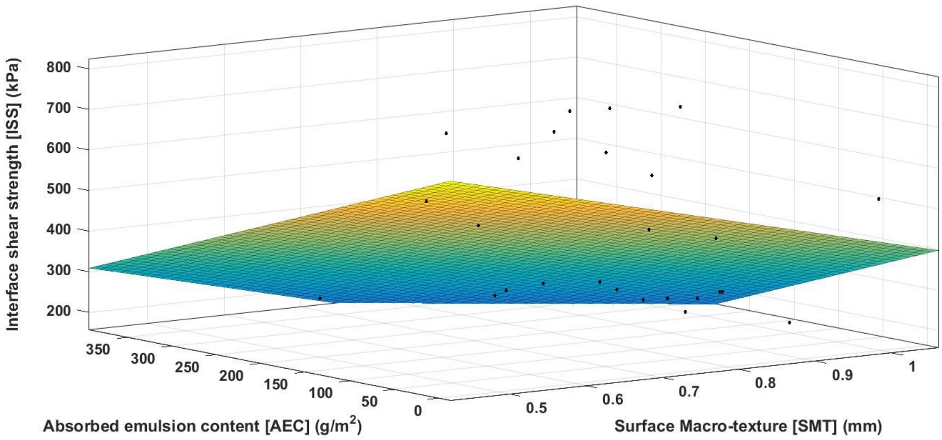


Figure 66. ISS vs SMT, AEC

4.8.11 Relationship among ISS, ART and CAE

The relationship among interface shear strength (ISS), application rate by tray test (ART) and corrected absorbed emulsion content (CAE), is shown in Figure 67. R-squared value of this relationship is 47.85%. Both P-values of CAE and ART are 0.000. However, goodness of fit is weak.

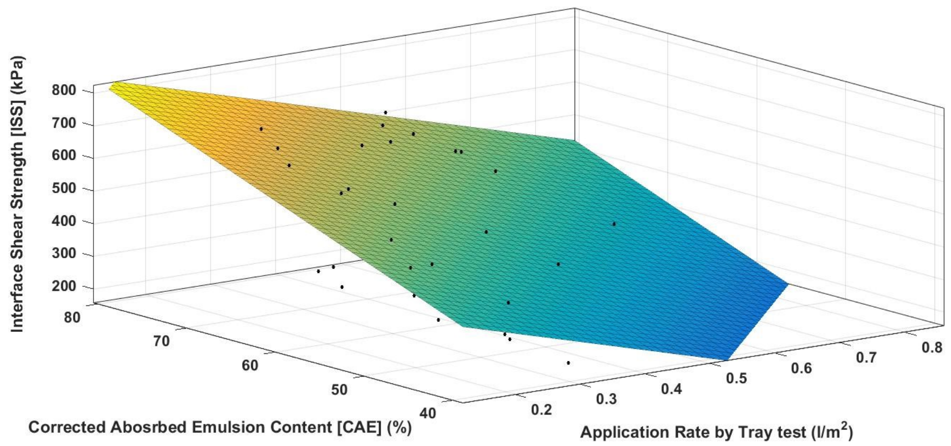


Figure 67. ISS vs ART, CAE

4.8.12 Relationship among ISS, ARG and CAE

The relationship among interface shear strength (ISS), application rate by geotextile pad (ARG) and corrected absorbed emulsion content (CAE), is shown in Figure 66. R-squared value of this relationship is 67.07 %. Both P-values of CAE and ARG are 0.000. As well as, there is a strong goodness of fit.

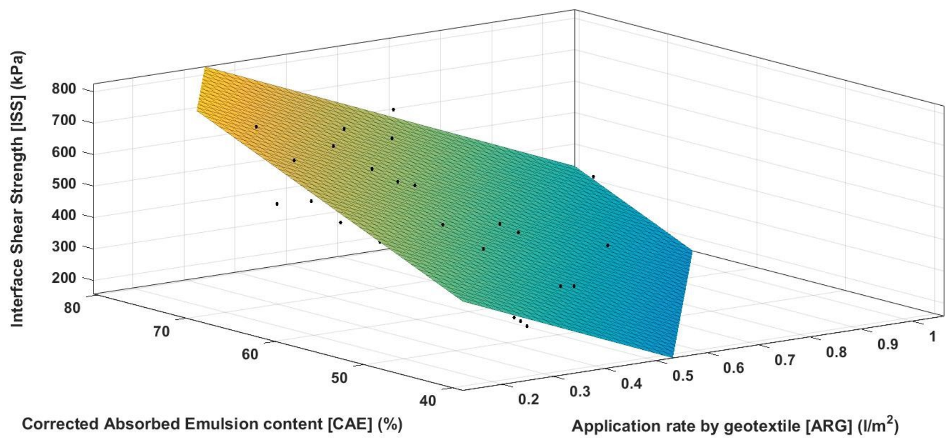


Figure 68. ISS vs ARG, CAE

4.8.13 Final model

Considering the individual relationships of interface shear strength with each parameter, it was observed that the surface macro-texture, application rate by geotextile, new absorbed emulsion content, have a comparably high coefficient of determination. It indicates that those relationships have a comparably good fit for the data. Therefore, relationship among interface shear strength and those three parameters was analyzed as the next relationship, by the Minitab software. The summary of the results is shown in Table 15and the comprehensive set of results given by the software is illustrated in Appendix H. R-squared value of this relationship is 67.07%.

Table 15. Summary of coefficient of final model

Term	Coefficient	P-value
Constant	24	0.827
ARG	-689	0.000
CAE	12.88	0.000

According to Table 15, it can be seen that the constant term is not significant. Therefore, the final model has been developed excluding the constant term, and R-squared value of the model is 96.32 %.

Consequently, the regression equation of the final model is shown in equation 9.

$$ISS = 13.3 \times CAE - 691 \times ARG \quad (9)$$

Where,

ISS = Interface Shear Strength (kPa)

ARG = Application Rate by Geotextile pad (l/m^2)

CAE = Corrected absorbed emulsion content (%) calculated by equation 10

$$CAE = 0.065 \times RAD - 50.697 \times SMT + 78.327 \quad (10)$$

Where,

RAD = Residual Application Dosage (g/m^2), *SMT* = Surface Macro-texture (mm)

According to this relationship, both parameters have a significant effect on the interface shear strength with a higher goodness of fit. It is noted that the interface shear strength will decrease when the application rate by geotextile pads increases. The main cause for this type of behavior will be the excess of diluted emulsion remaining at the interface, reducing the adhesion of the interface bond.

As well as, the corrected absorbed emulsion content ultimately indicates the amount of free bitumen dosage which remains on the existing surface. Consequently, when the corrected absorbed emulsion content is increased, interface shear strength will increase as well. Furthermore, the corrected absorbed emulsion content will increase while decreasing the surface macro-texture according to equation 10. As a result of that, interface shear strength will increase as well. The reason for that is the reduction of the surface macro-texture may increase the contact area between the new layer and existing layer. However, reducing the surface macro-texture of the existing surface is a difficult process.

Therefore, residual application dosage should be increased in order to increase the corrected absorbed emulsion content. However, the residual application dosage in g/m^2 rather the residual application rate in l/m^2 had a strong positive correlation with the application rate estimated by the geotextile pad. Therefore, the residual application rate shall not be increased directly by increasing the application rate because increasing application rate estimated by geotextile pad will decrease the interface shear strength as mentioned earlier. Nevertheless, actual requirement of the tack coat may be indicated by the residual application rate. Therefore, it can be increased by using high viscous or high residue emulsions, such as CRS-2, CMS-2, and styrene–butadiene–styrene (SBS)-modified bitumen emulsion.

4.8.14 Validation of final model

The data set used for the validation of the model is presented in Appendix G. Root Mean Square Error (RMSE) calculation for the validating data set is shown in Table 16.

Table 16. Calculation for validation

ISS [O_i] (kPa)	**ISS – Predicted [P_i] (kPa)**	$(P_i - O_i)^2$
655	698	1841.64
505	610	11055.22
489	549	3604.04
572	583	110.09
330	497	27731.89
668	522	21385.36
291	438	21882.17
495	529	1151.55
670	830	25832.48
623	638	240.45
588	654	4354.42
Calculation:	$\sum(P_i - O_i)^2$	119189.31
	$\sum(P_i - O_i)^2/n$	10835.39
	$\sqrt{\sum(P_i - O_i)^2/n}$	104.09

RMSE value of validating data set is, $RMSE_{validating} = 104.09$

RMSE value of training data set is, $RMSE_{training} = 98.59$

Accordingly,

$RMSE_{validating} \approx RMSE_{training}$

Therefore, it is confirmed that new model developed is accurate under following ranges:

Application rate by geotextile pad (ARG): 0.17 – 1.00 l/m^2

Surface macro-texture (SMT): 0.45 – 1.00 mm

Residual application rate (RAR): 0.12 – 0.39 l/m^2

CHAPTER 05

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The foremost objective of this study was to evaluate the significant parameters affecting the interface bonding of bituminous pavement layers. To accomplish that a literature survey was conducted based on past studies. Type of tack coat, application rate and residual application rate of tack coat, curing time, and surface macro-texture were identified as significant parameters which affect interface bond strength. As well as, a new parameter called the absorbed emulsion content was identified as a variable which is related to the tack coat.

This research was conducted based on the pavement core samples which were collected from actual road development projects in Sri Lanka. A questionnaire survey was implemented to evaluate the common industrial practices related to the application of the tack coat. Based on that information a field data collection process was implemented. Therefore, the low viscous cationic rapid setting emulsion (CRS-1) was selected as the tack coat type. Moreover, curing time was not considered as a variable and was calculated to be less than 30 min.

Field data collection was administered in five road construction projects. Four tests were conducted to collect information for the effective parameters before the laying of the new bitumen layer. Sand patch test was conducted to estimate the surface macro-texture of the existing pavement layer, while the tray test was conducted to estimate the application rate of the tack coat. The test method described in ASTM 2995 was carried out to estimate the application rate by a geotextile pad and residual application rate. Absorbed emulsion content test was also conducted. Representative pavement core samples were collected from relevant locations where the above tests were administered.

Based on the field data collected, correlations of effective parameters were analyzed. Consequently, a correlation for absorbed emulsion content was determined. However, there was a great disparity between the new relationship based on field data and a model that had been developed in a past study. As well as, the new relationship had a low coefficient of determination. Therefore, absorbed emulsion content which was calculated by the past model was used for the final model development.

Moratuwa Interface Shear Strength Tester (MISST) device was designed to estimate the interface shear strength of the pavement core samples. Laboratory tests were carried out by MISST device.

The final model was developed to evaluate the interface shear strength of bituminous pavement layers based on the application rate estimated by geotextile pads, and the corrected absorbed emulsion content calculated, utilizing the past model. According to this model, increase of the corrected absorbed emulsion content takes place when surface macro-texture decreases. Nevertheless, facilitating the decrease of surface macro-texture is arduous, thus increasing the residual application rate is the most desirable alternative. Though it can be amplified through the means of increasing the application rate, that method cannot be utilized, as the direct increase of application rate is a determinant of lowering interface shear strength, as mentioned previously. As a consequence, resorting to the means of amplifying the residual application dosage through using high viscous or high residue emulsions, such as CRS-2, CMS-2, and SBS-modified bitumen emulsion is the most desirable alternative.

5.2 Recommendations

This study was focused on the surface macro-texture within the range of 0.45 mm to 1.00 mm because it might be the typical surface macro-texture of the existing pavement layer. Therefore, it would be beneficial to conduct a finite element analysis for surface macro texture less than 0.45 mm. As well as, a study on milling surfaces to analyze the effect of surface macro-texture more than 1.00 mm can also be recommended as a commendable study that could be conducted parallel to this research.

Furthermore, due to the presence of a substantial difference in the estimation of the absorbed emulsion content by the past study based on laboratory prepared samples and this study based on field data, it is constructive to conduct further studies to make appropriate adjustments to evaluate the absorbed emulsion content for field conditions.

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APPENDIX A: STANDARD SPECIFICATION FOR CATIONIC EMULSIFIED BITUMEN

TABLE 1 Requirements for Cationic Emulsified Asphalt

NOTE 1—CQS–1H emulsions shall meet the requirements outlined in Practices D 3910.
NOTE 2—CQS-1h is used for Quick Set Slurry Seal systems.

Type	Rapid-Setting				Medium-Setting				Slow-Setting				Quick Setting	
Grade	CRS-1		CRS-2		CMS-2		CMS-2h		CSS-1		CSS-1h		CQS-1H	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Test on emulsions:														
Viscosity, Saybolt Furol at 25°C (77°F) SFS									20	100	20	100	20	100
Viscosity, Saybolt Furol at 50°C (122°F) SFS	20	100	100	400	50	450	50	450						
Storage stability test, 24-h, %[A]		1		1		1		1		1		1		
Demulsibility, 35 mL, 0.8 % dioctyl sodium sulfosuccinate, %	40	...	40	...										
Coating ability and water resistance:														
Coating, dry aggregate					good		good							
Coating, after spraying					fair		fair							
Coating, wet aggregate					fair		fair							
Coating, after spraying					fair		fair							
Particle charge test	positive		positive		positive		positive		positive		positive		positive	
Sieve test, %[A]		0.10		0.10		0.10		0.10		0.10		0.10		0.10
Cement mixing test, %										2.0		2.0		N/A
Distillation:														
Oil distillate, by volume of emulsion, %		3		3		12		12						
Residue, %	60		65		65		65		57		57		57	
Tests on residue from distillation test:														
Penetration, 25°C (77°F), 100 g, 5 s	100	250	100	250	100	250	40	90	100	250	40	90	40	90
Ductility, 25°C (77°F), 5 cm/min, cm	40		40		40		40		40		40		40	
Solubility in trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5		97.5	

[A] This test requirement on representative samples is waived if successful application of the material has been achieved in the field.

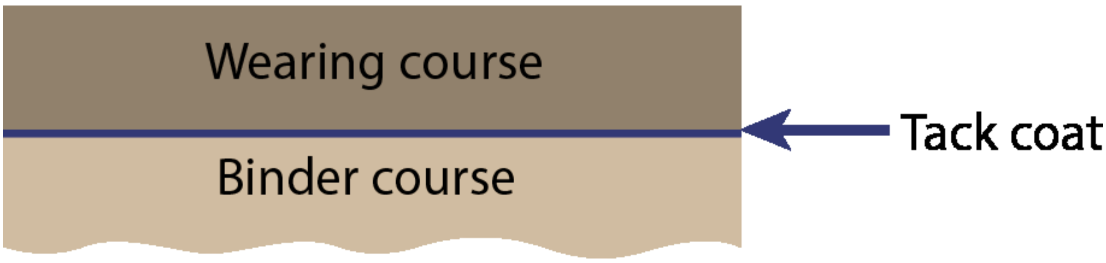
APPENDIX B: SAMPLE QUESTIONNAIRE SURVEY FORM

QUESTIONNAIRE SUREVEY

"Application of Tack Coat"

Note: The Department of Civil Engineering guarantees that these data will be used only for research purposes and only for internal evaluation
The following image shows a typical cross section of Bituminous Pavement Surface. There are two layers namely "Existing Layer" (usually Binder Course) and "New Layer" (Wearing Course)

Bituminous Pavement Layers



Personal Information

I. Your Designation :
II. Experience in Road Rector:
   a. Less than 2 years
   b. 2-5 years
   c. 5-10 years
   d. More than 10 years

QUESTIONNAIRE

1. What type(s) of **tack coat** material is (are) typically applied to each of the following existing pavement surfaces?

CRS-1 (Cationic rapid-setting emulsion, low viscous bitumen)	
CRS-2 (Cationic rapid-setting emulsion, high viscous bitumen)	
CSS-1(Cationic slow-setting emulsion, low viscous bitumen)	
Other	

2. In your experience, what is the application rate of tack coat in the field for following conditions

Existing Pavement (Binder Course) Type	**Application Rate (liter/m^2)**
Old / Oxidized HMA Layer	
New / Fresh HMA Layer	
Portland Cement Concrete (PCC) Layer	
Milled HMA Surface	
Milled PCC Surface	

3. What is the common time gap in between spreading tack coat and placing wearing course in field?

Less than 15 min	
Less than 30 min	
1-2 hrs	
More than 2 hrs	
Other	

4. What is the required curing time for tack coat according to your understanding?

Less than 15 min	
Less than 30 min	
1-2 hrs	
More than 2 hrs	

5. What is the reason for application of tack coat just before the wearing course?

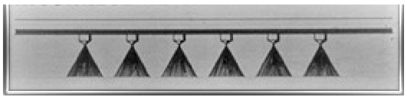
To save tack coat from debris	
To get fresh tack coat layer (in liquid form) for better bonding	
To prevent disturbances from traffic	
Other (please mention)	

6. What is the common method of application of tack in field?

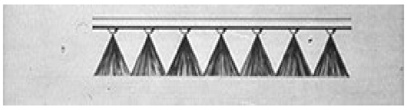
Manual application (Hand Spraying)	
Distributor spray bar (vehicle mounted/Automated)	
Other	

7. If distributor spray bar is used, what are the best arrangements of nozzles to apply tack coat among figures shown below.

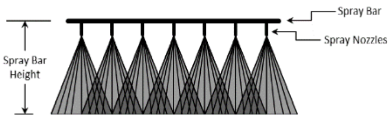
A



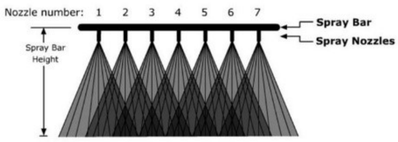
B



C



D



8. Do you carry out laboratory or field test methodsto determine the **interface bond strength** between bituminous layers?

Yes	
No	

9. If your answer 'Yes' for above question, please mention the test.

10. Do you think that Tack Coat is essential for better bonding between bituminous pavement layers?

Yes	
No	

11. If your answer is 'No', what are the situations of application of wearing course without tack coat?

Over fresh binder course	
On shoulders, bus bays or cycle lanes	
Roads with heavy traffic (Allocated construction time is limited)	
On washed or cleaned existing surfaces	
Other	

12. If it rains after spraying Tack Coat and before placing bitumen, what should be done practically?

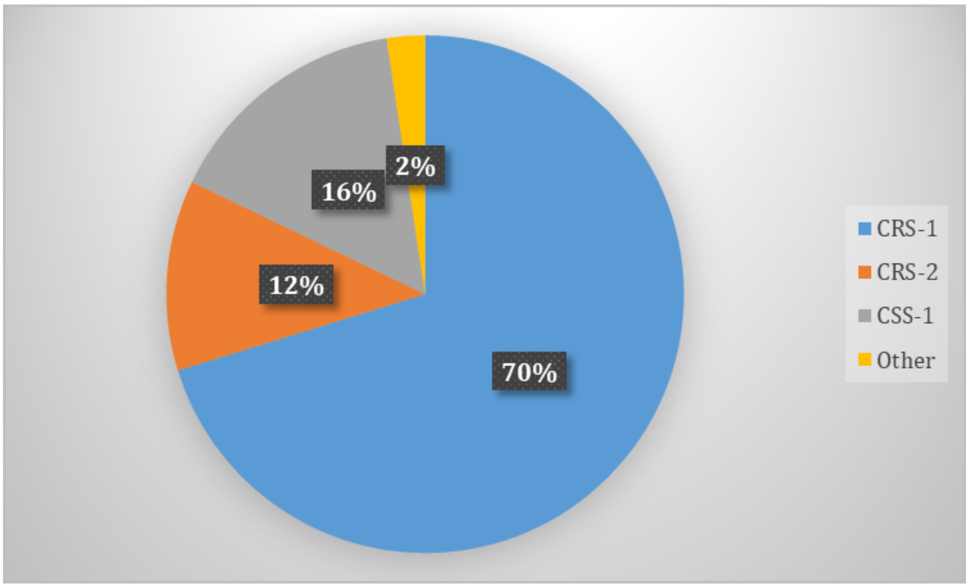
Do nothing , continue placing bitumen	
Use compressor to dry the surface and then continue placing bitumen	
Use compressor to dry the surface, spray Tack Coat again and then continue placing bitumen	
Other	

13. In your experience, what type of pavement failure is related to improper application of tack coat? (Check all that apply)

Slippage of the surface course layer on top of the underlying layer	
Delaminating of the surface course layer from the underlying layer	
Fatigue cracking of the pavement structure	
Top-down cracking	
Rutting of the pavement surface	
Other distress	
Do not know	

APPENDIX C: RESULTS OF QUESTIONNAIRE SURVEY

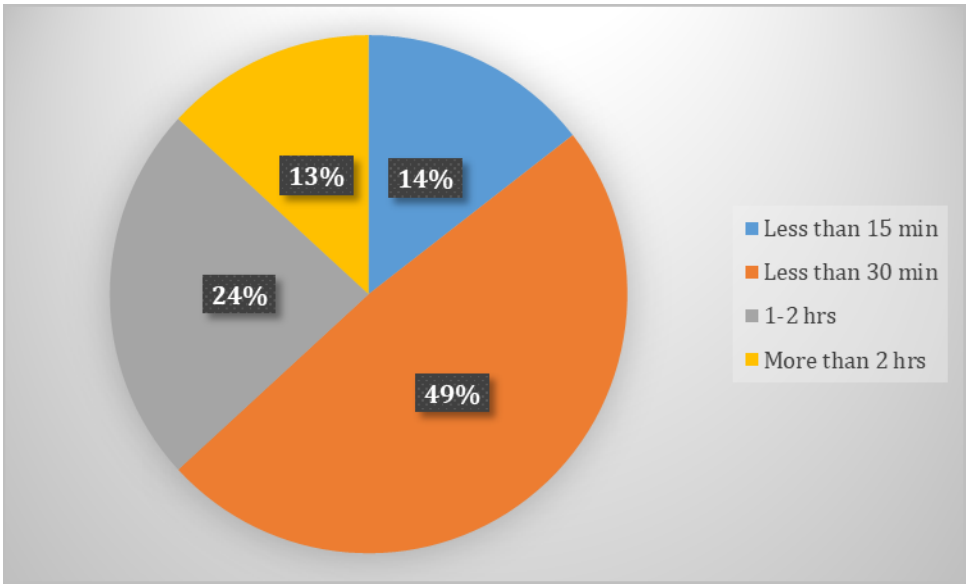
1. What type(s) of **tack coat** material is (are) typically applied to each of the following existing pavement surfaces?



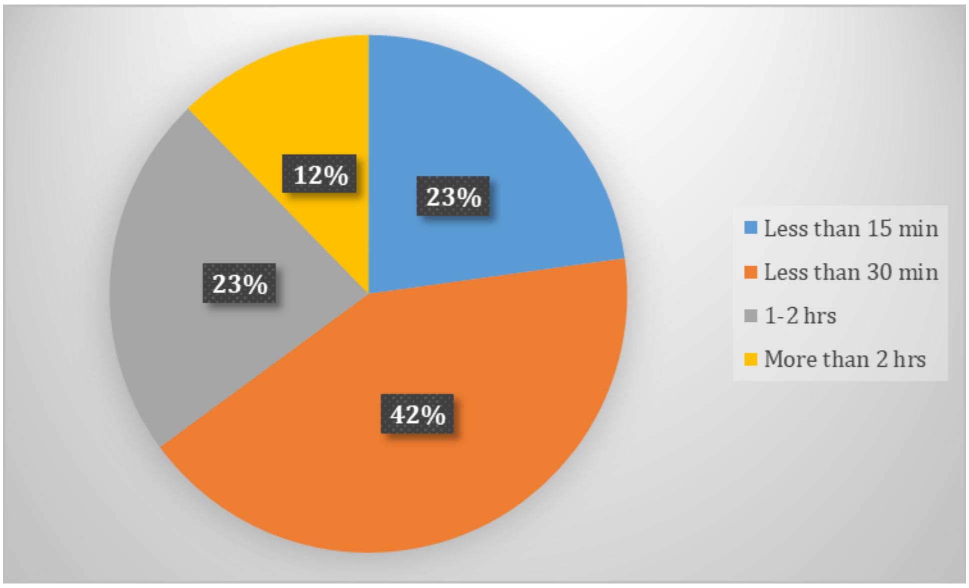
2. In your experience, what is the application rate of tack coat in the field for following conditions

Existing Pavement (Binder Course) Type	**Average Application Rate (liter/m^2)**
Old / Oxidized HMA Layer	0.35
New / Fresh HMA Layer	0.29
Portland Cement Concrete (PCC) Layer	0.44
Milled HMA Surface	0.47
Milled PCC Surface	0.50

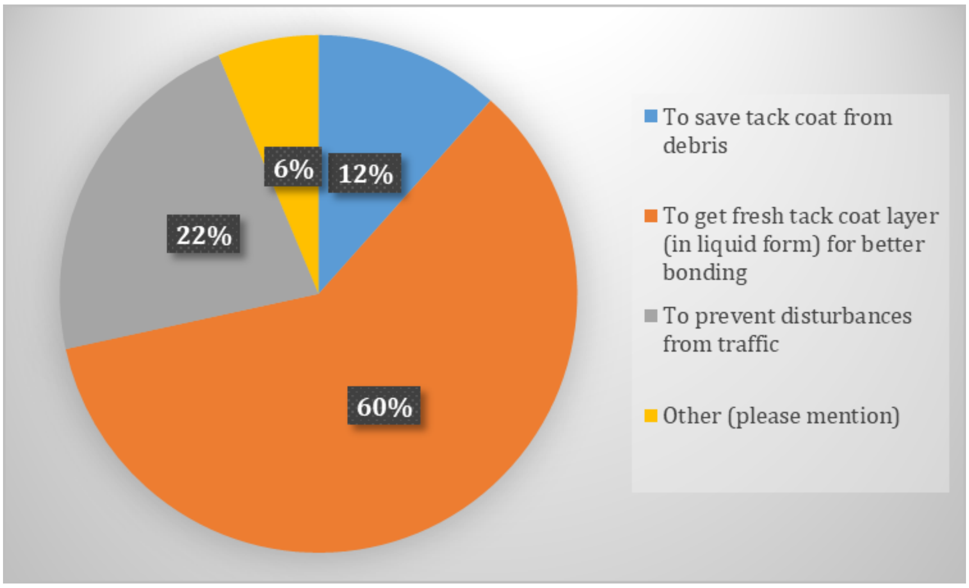
3. What is the common time gap in between spreading tack coat and placing wearing course in field?



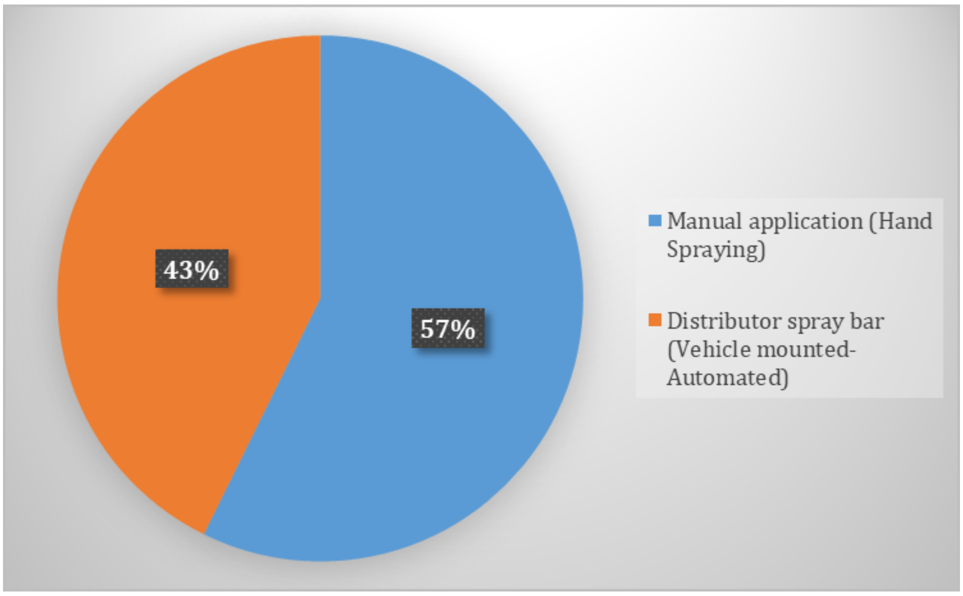
4. What is the required curing time for tack coat according to your understanding?



5. What is the reason for application of tack coat just before the wearing course?

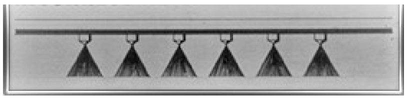


6. What is the common method of application of tack in field?

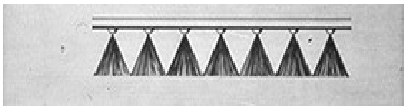


7. If distributor spray bar is used, what are the best arrangements of nozzles to apply tack coat among figures shown below.

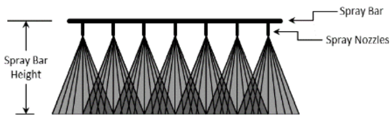
A



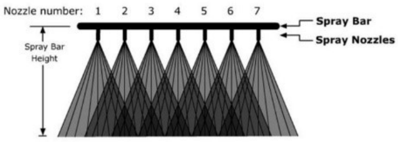
B

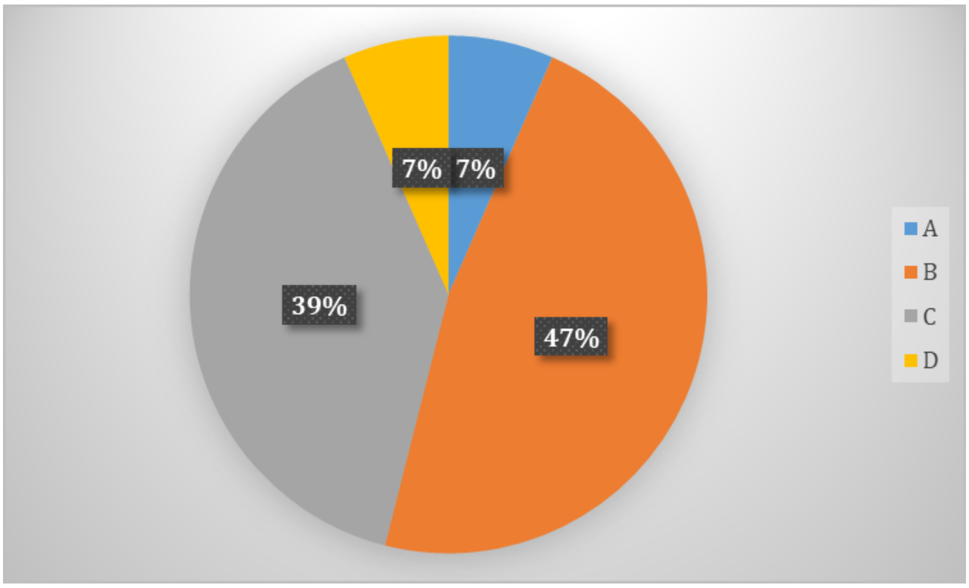


C

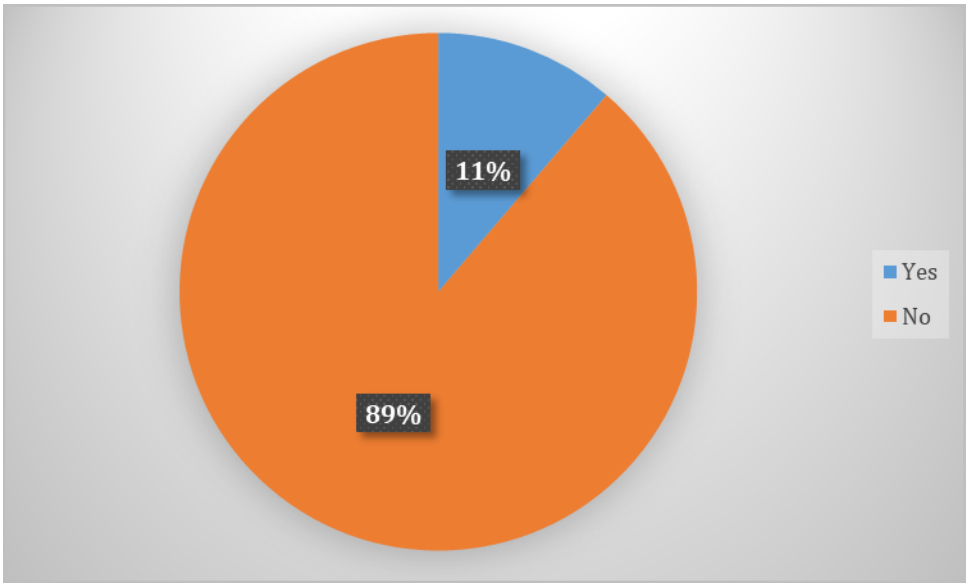


D



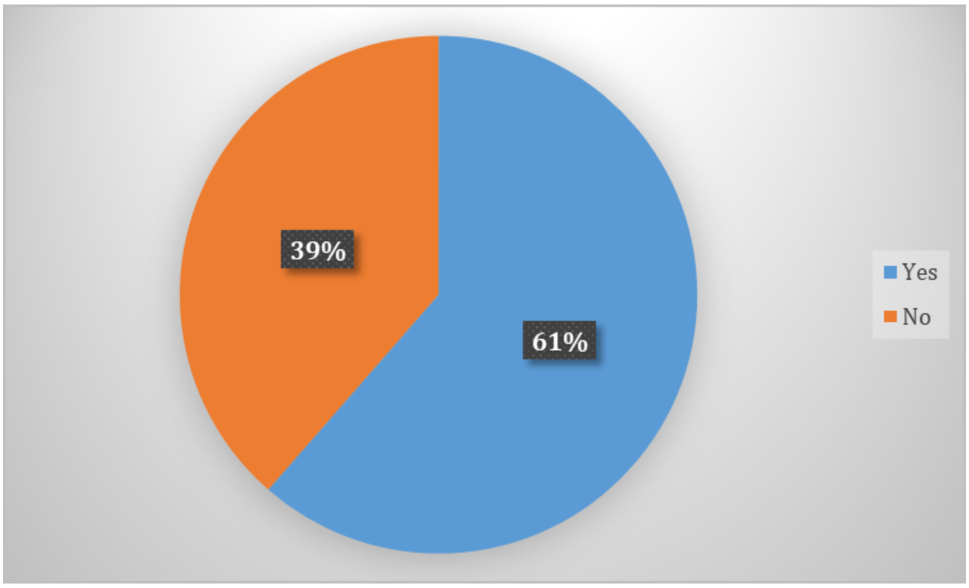


8. Do you carry out laboratory or field test methods to determine the **interface bond strength** between bituminous layers?

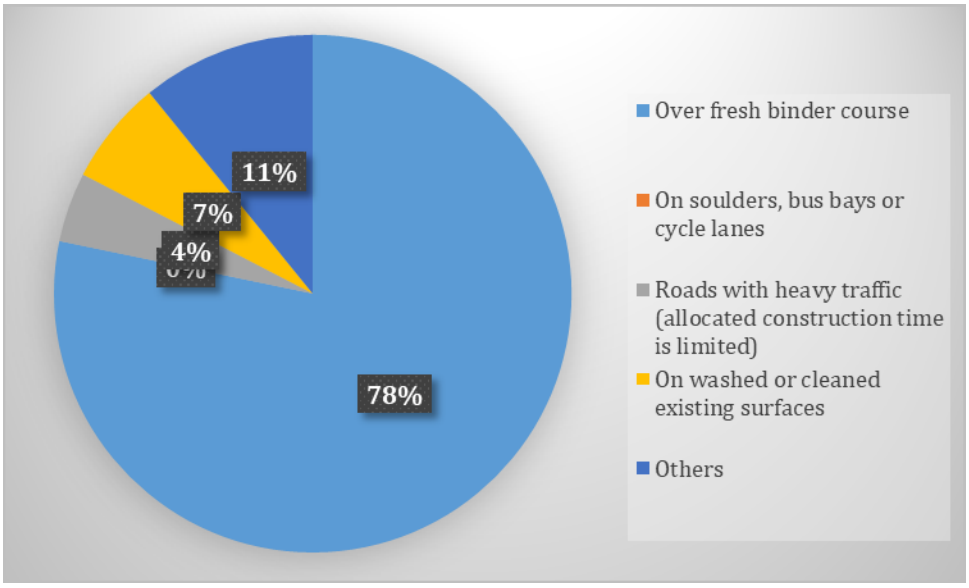


9. If your answer 'Yes' for above question, please mention the test.
   (There were not appropriate answers)

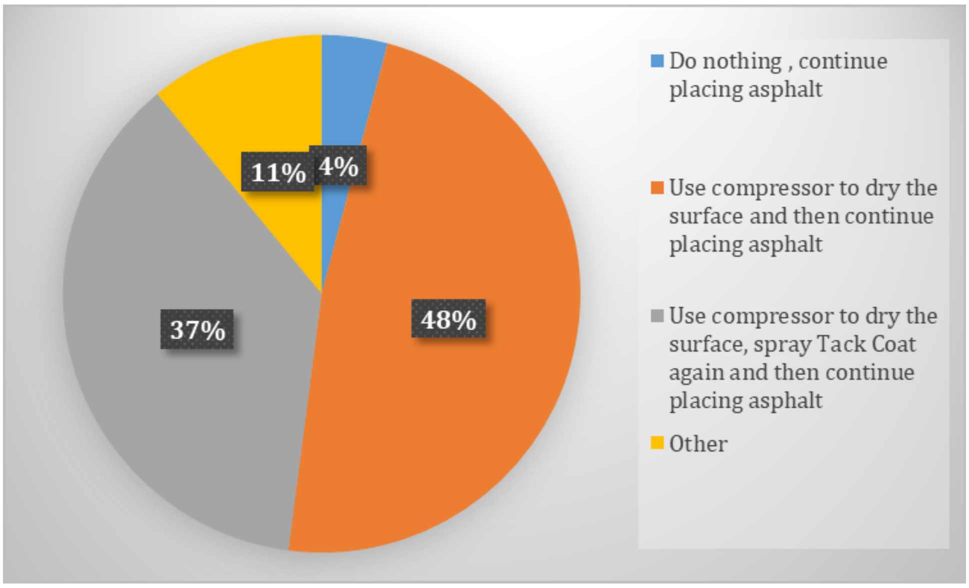
10. Do you think that Tack Coat is essential for better bonding between bituminous pavement layers?



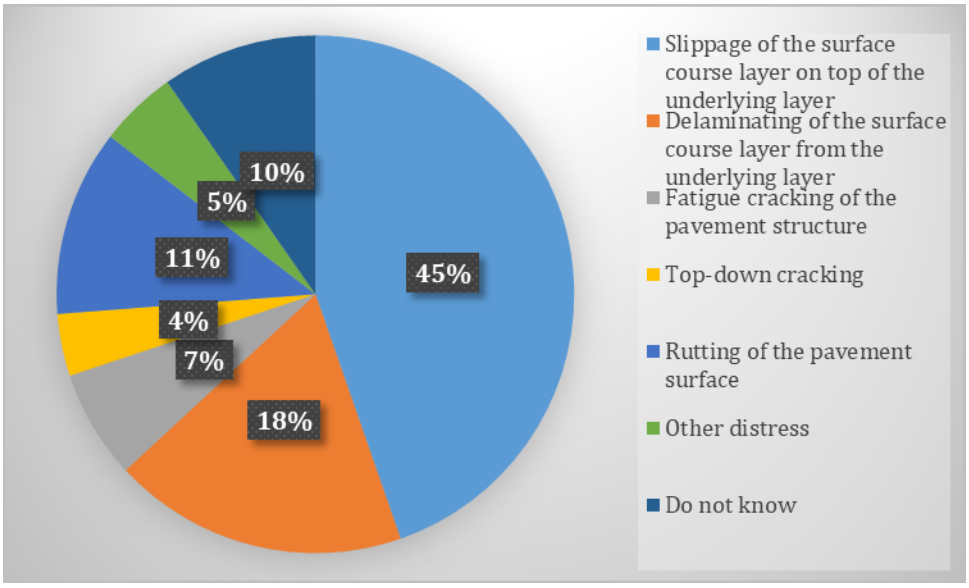
11. If your answer is 'No', what are the situations of application of wearing course without tack coat?



12. If it rains after spraying Tack Coat and before placing bitumen, what should be done practically?



13. In your experience, what type of pavement failure is related to improper application of tack coat?



APPENDIXD: ALL DATA COLLECTED FROM FIELD TESTS

Project P-1: Kesbewa – Polgasowita Road Development Project

Location Number	Core Sample No.	SMT *(mm)*	ART *(l/m^2)*	ARG *(l/m^2)*	RAR *(l/m^2)*	AEC *(g/m^2)*
1	**A1**	0.53	0.29	0.37	0.20	15.6
2	**A2**	0.70	0.16	0.21	0.15	6.3
3	**A3**	0.45	0.54	0.68	0.32	39.8
4	**A4**	0.69	0.11	0.15	0.07	3.0
5	**A5**	0.48	0.26	0.33	0.22	6.4
6	**A6**	0.79	0.18	0.24	0.16	6.8
7	**A7**	0.80	0.37	0.46	0.23	58.7
8	**A8**	1.03	0.29	0.37	0.21	30.1

Project P-2: Agunukolapelessa – Wetiya Juction Road Development Project

Location Number	Core Sample No.	SMT *(mm)*	ART *(l/m^2)*	ARG *(l/m^2)*	RAR *(l/m^2)*	AEC *(g/m^2)*
9	**B1**	0.95	0.45	0.56	0.219	167
10	**B2**	0.56	0.23	0.29	0.158	44
11	**B3**	0.56	0.28	0.36	0.142	71
12	**B4**	1.14	0.17	0.22	0.102	14.4
13	**B5**	0.86	0.28	0.36	0.163	121.76
14	**B6**	0.71	0.32	0.41	0.181	72.69
15	**B7**	*2.44*	0.23	0.30	0.208	451.42
16	**B8**	0.91	0.25	0.32	0.153	100.8
17	**B9**	0.90	0.22	0.28	0.154	89

Project P-3: Katubedda Junction to Piliyandala Road Development Project

Location Number	**Core Sample No.**	**SMT** *(mm)*	**ART** *(l/m²)*	**ARG** *(l/m²)*	**RAR** *(l/m²)*	**AEC** *(g/m²)*
18	**C1**	2.24	0.28	0.35	0.146	104
19	**C2**	0.67	0.14	0.19	0.078	56
20	**C3**	0.41	0.12	0.14	0.055	5
21	**C4**	0.70	0.28	0.36	0.212	62.81
22	**C5**	2.37	0.85	1.04	0.429	240
23	**C6**	0.42	0.50	0.63	0.241	204
24	**C7**	0.47	0.70	0.87	0.337	176
25	**C8**	0.60	0.83	1.02	0.390	376
26	**C9**	1.07	0.43	0.54	0.286	176

Project P-4: Elahera–Giritale Road Development Project

Location Number	**Core Sample No.**	**SMT** *(mm)*	**ART** *(l/m²)*	**ARG** *(l/m²)*	**RAR** *(l/m²)*	**AEC** *(g/m²)*
27	**D1**	0.93	0.23	0.36	0.148	128
28	**D2**	0.71	0.25	0.34	0.154	40
29	**D3**	0.66	0.25	0.34	0.121	24
30	**D4**	0.60	0.21	0.31	0.152	88
31	**D5**	0.79	0.23	0.36	0.171	120
32	**D6**	0.82	0.26	0.40	0.158	24
33	**D7**	0.71	0.22	0.35	0.166	8
34	**D8**	0.83	0.19	0.30	0.149	8
35	**D9**	1.27	0.44	0.31	0.134	328
36	**D10**	0.81	0.42	0.71	0.336	232
37	**D11**	0.79	0.46	0.77	0.310	120
38	**D12**	0.83	0.39	0.38	0.161	72

39	**D13**	0.81	0.45	0.46	0.189	136
40	**D14**	0.80	0.56	0.87	0.338	136
41	**D15**	0.73	0.59	0.53	0.208	120
42	**D16**	0.73	0.30	0.53	0.199	80
43	**D17**	0.99	0.33	0.50	0.201	96
44	**D18**	0.89	0.24	0.47	0.190	72
45	**D19**	0.80	0.32	0.38	0.168	96
46	**D20**	0.77	0.25	0.41	0.209	8

Project P-5: Extension of Southern Expressway Project (ESEP) - Section 4

Location Number	**Core Sample No.**	**SMT** ***(mm)***	**ART** ***(l/m^2)***	**ARG** ***(l/m^2)***	**RAR** ***(l/m^2)***	**AEC** ***(g/m^2)***
47	**E1**	0.58	0.17	0.17	0.132	16
48	**E2**	0.55	0.15	0.18	0.150	24
49	**E3**	0.48	0.17	0.30	0.246	48
50	**E4**	0.49	0.18	0.19	0.176	48
51	**E5**	0.54	0.21	0.21	0.194	56
52	**E6**	0.67	0.23	0.25	0.220	32
53	**E7**	0.68	0.35	0.42	0.282	32
54	**E8**	0.74	0.43	0.33	0.238	32
55	**E9**	0.79	0.29	0.26	0.194	48
56	**E10**	0.66	0.29	0.26	0.215	55
57	**E11**	0.72	0.30	0.27	0.218	60
58	**E12**	0.64	0.26	0.25	0.208	61
59	**E13**	0.61	0.25	0.25	0.205	48

APPENDIX E: DATA USED FOR INITIAL ANALYSIS

Location No.	SMT *(mm)*	ART *(l/m²)*	ARG *(l/m²)*	RAR *(l/m²)*	RAR *(g/m²)*	AEC *(g/m²)*	AEC *(%)*	CAE*(%)*
1	0.53	0.29	0.37	0.198	217.3	16	7	65
2	0.70	0.16	0.21	0.153	167.9	6	4	54
3	0.45	0.54	0.68	0.325	357.1	40	11	79
4	0.69	0.11	0.15	0.069	75.5	3	4	48
5	0.48	0.26	0.33	0.219	241.2	6	3	70
6	0.79	0.18	0.24	0.158	173.5	7	4	49
7	0.80	0.37	0.46	0.233	256.3	59	23	54
8	1.03	0.29	0.37	0.208	228.5	30	13	41
9	0.95	0.45	0.56	0.219	240.7	167	69	46
10	0.56	0.23	0.29	0.158	173.9	44	25	61
11	0.56	0.28	0.36	0.142	155.8	71	46	60
12	1.14	0.17	0.22	0.102	112.0	14	13	28
13	0.86	0.28	0.36	0.163	178.8	122	68	46
14	0.71	0.32	0.41	0.181	199.1	73	37	55
16	0.91	0.25	0.32	0.153	167.9	101	60	43
17	0.90	0.22	0.28	0.154	169.1	89	53	44
19	0.67	0.14	0.19	0.078	85.9	56	65	50
20	0.41	0.12	0.14	0.055	60.5	5	8	62
21	0.70	0.28	0.36	0.212	233.7	63	27	58
23	0.42	0.50	0.63	0.241	265.4	204	77	74
24	0.47	0.70	0.87	0.337	370.9	176	47	79
26	1.07	0.43	0.54	0.286	314.7	176	56	44
27	0.93	0.23	0.36	0.148	162.3	128	79	42
28	0.71	0.25	0.34	0.154	169.8	40	24	53
29	0.66	0.25	0.34	0.121	133.6	24	18	54
30	0.60	0.21	0.31	0.152	166.9	88	53	59
31	0.79	0.23	0.36	0.171	188.0	120	64	50

32	0.82	0.26	0.40	0.158	174.1	24	14	48
33	0.71	0.22	0.35	0.166	182.4	8	4	54
34	0.83	0.19	0.30	0.149	163.4	8	5	47
36	0.81	0.42	0.71	0.336	369.8	232	63	61
37	0.79	0.46	0.77	0.310	341.2	120	35	60
38	0.83	0.39	0.38	0.161	177.2	72	41	48
39	0.81	0.45	0.46	0.189	207.4	136	66	51
40	0.80	0.56	0.87	0.338	372.4	136	37	62
41	0.73	0.59	0.53	0.208	228.9	120	52	56
42	0.73	0.30	0.53	0.199	219.4	80	36	55
43	0.99	0.33	0.50	0.201	221.3	96	43	42
44	0.89	0.24	0.47	0.190	209.5	72	34	47
45	0.80	0.32	0.38	0.168	184.5	96	52	50
46	0.77	0.25	0.41	0.209	229.8	8	3	54
47	0.58	0.17	0.17	0.132	145.2	16	11	58
48	0.55	0.15	0.18	0.150	164.6	24	15	61
49	0.48	0.17	0.30	0.246	271.1	48	18	71
50	0.49	0.18	0.19	0.176	193.6	48	25	66
51	0.54	0.21	0.21	0.194	213.0	56	26	65
52	0.67	0.23	0.25	0.220	242.0	32	13	60
53	0.68	0.35	0.42	0.282	309.8	32	10	64
54	0.74	0.43	0.33	0.238	261.4	32	12	58
55	0.79	0.29	0.26	0.194	213.0	48	23	52
56	0.66	0.29	0.26	0.215	236.6	55	23	60
57	0.72	0.30	0.27	0.218	239.4	60	25	58
58	0.64	0.26	0.25	0.208	228.4	61	27	61
59	0.61	0.25	0.25	0.205	226.0	48	21	62

APPENDIX F: DATA USED FOR DEVELOPMENT OF FINAL MODEL

Core Sample No.	SMT *(mm)*	ART *(l/m²)*	ARG *(l/m²)*	RAR *(l/m²)*	CAE *(%)*	ISS *(kPa)*
A3	0.45	0.54	0.68	0.325	79	620
A5	0.48	0.26	0.33	0.219	70	667
A6	0.79	0.18	0.24	0.158	49	473
A7	0.80	0.37	0.46	0.233	54	489
A8	1.03	0.29	0.37	0.208	41	412
B2	0.56	0.23	0.29	0.175	62	476
B5	0.86	0.28	0.36	0.163	46	263
B8	0.91	0.25	0.32	0.153	43	278
C7	0.47	0.70	0.87	0.337	79	318
C8	0.60	0.83	1.02	0.390	76	340
D1	0.93	0.23	0.36	0.148	42	410
D3	0.66	0.25	0.34	0.121	54	385
D4	0.60	0.21	0.31	0.152	59	437
D5	0.79	0.23	0.36	0.171	50	464
D6	0.82	0.26	0.40	0.158	48	329
D7	0.71	0.22	0.35	0.166	54	512
D11	0.79	0.46	0.77	0.310	60	299
D12	0.83	0.39	0.38	0.161	48	258
D15	0.73	0.59	0.53	0.208	56	432
D17	0.99	0.33	0.50	0.201	42	188
D19	0.80	0.32	0.38	0.168	50	283
D20	0.77	0.25	0.41	0.209	54	330
E1	0.58	0.17	0.17	0.132	58	603
E2	0.55	0.15	0.18	0.150	61	712
E4	0.49	0.18	0.19	0.176	66	777
E5	0.54	0.21	0.21	0.194	65	536

E7	0.68	0.35	0.42	0.282	64	698
E8	0.74	0.43	0.33	0.238	58	629
E9	0.79	0.29	0.26	0.194	52	680
E10	0.66	0.29	0.26	0.215	60	795
E11	0.72	0.30	0.27	0.218	58	687
E12	0.64	0.26	0.25	0.208	61	743
Summary						
Min.	*0.45*	*0.15*	*0.17*	*0.12*	*41*	*188*
Max.	*1.03*	*0.83*	*1.02*	*0.39*	*79*	*795*
Avg.	*0.71*	*0.32*	*0.39*	*0.20*	*57*	*485*

APPENDIX G: DATA USED FOR VALIDATION OF FINAL MODEL

Core Sample No.	**ARG** *(l/m^2)*	**CAE** *(%)*	**ISS** *(kPa)*	**ISS - Predicted** *(kPa)*
A1	0.37	68	655	698
A2	0.21	54	505	610
B6	0.41	58	489	549
C4	0.36	58	572	583
D8	0.30	47	330	497
D10	0.71	61	668	522
D14	0.87	62	291	438
D16	0.53	55	495	529
E3	0.30	71	670	830
E6	0.25	60	623	638
E13	0.25	62	588	654
Summary				
Min.	*0.21*	*47*	*291*	*438*
Max.	*0.87*	*71*	*670*	*830*
Avg.	*0.41*	*59*	*535*	*595*

APPENDIX H: RESULTS FROM MINITAB SOFTWARE

Result sheets of final model developments by Minitab software presents here.

Regression Analysis: ISS (kPa) versus ARG (l/m2), CAE (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	633294	316647	29.53	0.000
ARG (l/m2)	1	466122	466122	43.47	0.000
CAE (%)	1	429499	429499	40.05	0.000
Error	29	310995	10724		
Total	31	944289			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
103.557	67.07%	64.79%	60.56%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	24	107	0.22	0.827	
ARG (l/m2)	-689	105	-6.59	0.000	1.21
CAE (%)	12.88	2.04	6.33	0.000	1.21

Regression Equation

ISS (kPa) = 24 - 689 ARG (l/m2) + 12.88 CAE (%)

Fits and Diagnostics for Unusual Observations

Obs	ISS (kPa)	Fit	Resid	Std Resid	
10	340.0	299.0	41.0	0.50	X

X Unusual X

Final Model:

Regression Analysis: ISS (kPa) versus ARG (l/m2), CAE (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	8162883	4081441	393.06	0.000
ARG (l/m2)	1	470126	470126	45.27	0.000
CAE (%)	1	3028859	3028859	291.69	0.000
Error	30	311516	10384		
Total	32	8474399			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
101.901	96.32%	96.08%	95.87%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
ARG (l/m2)	-691	103	-6.73	0.000	6.22
CAE (%)	13.298	0.779	17.08	0.000	6.22

Regression Equation

ISS (kPa) = -691 ARG (l/m2) + 13.298 CAE (%)

Fits and Diagnostics for Unusual Observations

Obs	ISS (kPa)	Fit	Resid	Std Resid	
10	340.0	305.2	34.8	0.41	X

X Unusual X

APPENDIX I: DATA OF SAMPLES NOT FAILED PROPERLY

Field tests results of samples which separated during coring.

Core No. (new)	SMT (mm)	ART (l/m2)	ARG (l/m2)	RAR (l/m2)	AEC (g/m2)	CAE (%)
A4	0.69	0.11	0.15	0.069	3	48
B4	1.14	0.17	0.22	0.102	14.4	28
C2	0.67	0.14	0.19	0.078	56	50
C3	0.41	0.12	0.14	0.055	5	62

All test results of samples which were not failed at bond:

Core No. (new)	SMT (mm)	ART (l/m2)	ARG (l/m2)	RAR (l/m2)	AEC (g/m2)	CAE (%)	ISS (kPa)
B1	0.95	0.45	0.56	0.219	167	46	207
B3	0.56	0.28	0.36	0.142	71	60	152
B9	0.90	0.22	0.28	0.154	89	44	374
C1	2.24	0.28	0.35	0.146	104	-25	187
C5	2.37	0.85	1.04	0.429	240	-11	526
C6	0.42	0.50	0.63	0.241	204	74	217
C9	1.07	0.43	0.54	0.286	176	44	654
D2	0.71	0.25	0.34	0.154	40	53	165
D13	0.81	0.45	0.46	0.189	136	51	195
D18	0.89	0.24	0.47	0.190	72	47	63