EVALUATION OF CRUMB RUBBER AND LATEX MODIFIED ASPHALT BINDERS FOR PAVEMENT CRACK SEALANT PURPOSE

SHARVIN A/L M POOVANESHVARAN

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By

SHARVIN A/L M POOVANESHVARAN

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Name of Student: SHARVIN A/L M POOVANESHVARAN

I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

Signature: Approved by:

_____ _____

(Signature of Supervisor)

Date: Name of Supervisor: Dr. Mohd Rosli Mohd Hasan

Date:

Approved by:

_____

(Signature of Examiner)

Name of Examiner: Professor Dr. Meor Othman Hamzah

Date:

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In the name of God

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ABSTRAK

PENILAIAN PENGUBAHSUAIAN ASFALT MENGGUNAKAN SERBUK GETAH DAN SUSU GETAH UNTUK TUJUAN PENAMPALAN RETAKAN TURAPAN

Asfalt konvensional digunakan secara meluas sebagai bahan penampalan retakan turapan. Penampalan retakan turapan adalah salah satu kaedah penyelenggaraan turapan yang paling kerap dilakukan. Tahap prestasi atau tempoh hayat perkhidmatan turapan mempunyai hubungan rapat dengan sifat asfalt yang digunakan di dalam turapan atau sebagai bahan penampalan retakan turapan. Kelemahan sifat reologi asfalt konvensional mencetuskan minat penyelidik untuk menggunakan asfalt yang diubah suai menggunakan polimer. Tujuan kajian ini adalah untuk menghasilkan asfalt yang diubah suai menggunakan susu getah dan serbuk getah untuk tujuan penampalan retakan turapan. Peratusan yang berlainan digunakan untuk pengubahsuaian asfalt iaitu 5 %, 10 %, 15 % untuk serbuk getah manakala 5 % dan 10 % untuk susu getah. Ini adalah kaedah yang paling ekonomik yang boleh dilakukan untuk memanjangkan jangka hayat turapan dengan cara penampalan retakan turapan untuk mengelakkan penyusupan air ke dalam turapan. Zycotherm dengan kandungan 0.1 % daripada berat asfalt telah digunakan untuk memastikan ikatan kekuatan yang baik diantara agregat dan asfalt. Kajian ini terbahagi kepada dua fasa. Matlamat fasa pertama adalah untuk menguji dan membandingkan sifat reologi asfalt yang diubah suai dengan asfalt konvensional. Sifat reologi yang telah diuji adalah titik melembut, ujian penusukan, pemulihan anjal dan pemulihan kilasan. Sifat-sifat ini diuji kerana ujian ini mempengaruhi prestasi bahan penampalan retakan jalan. Pada fasa kedua, ujian kekuatan ikatan dan ujian daya ricih dijalankan. Ujian kekuatan ikatan telah dijalankan untuk menilai kekuatan tegangan bahan penampalan retakan

turapan. Ujian daya ricih telah dijalankan untuk mengukur rintangan pengikat kepada tekanan ricih.

Hasil keputusan sifat reologi menunjukkan bahawa dengan kenaikan kandungan serbuk getah dan susu getah dalam asfalt, titik melembut meningkat dengan sangat ketara. Nilai penusukan berkurangan dengan penambahan serbuk getah dan susu getah. Ini disebabkan getah mempunyai keupayaan untuk mengeraskan asfalt. Selain itu, pemulihan anjal dan pemulihan kilasan menunjukkan hasil yang positif dengan penambahan serbuk getah dan susu getah. Menurut keputusan ujian kekuatan ikatan, dengan menggunakan susu getah dan serbuk getah, ia dapat meningkatkan kekuatan tegangan pengikat. Kesan penuaan jangka panjang tidak diambil kira dalam penyelidikan ini. Ujian daya ricih membuktikan bahawa serbuk getah dan susu getah yang digunakan untuk mengubahsuai asfalt mempunyai rintangan yang sangat baik terhadap tekanan ricih.

Serbuk getah dan susu getah yang digunakan untuk pengubahsuaian asfalt akan dapat menghasilkan bahan penampalan retakan jalan yang mesra alam kerana ia menggunakan bahan kitar semula dan bahan berasaskan tumbuhan. Ia bukan sahaja mesra alam, tetapi prestasi bahan penampalan retak yang diubah suai jauh lebih baik daripada asfalt konvensional.

ABSTRACT

EVALUATION OF CRUMB RUBBER AND LATEX MODIFIED ASPHALT BINDERS FOR PAVEMENT CRACK SEALANT PURPOSE

Conventional asphalt binder is widely used as the crack sealing material. Crack sealing is one of the most frequent pavement maintenance method. The level of performance during service life has a close relationship with the properties of asphalt binder used in the pavement or as crack sealant material. The rheological weakness of the conventional asphalt binder had sparked the interest of researchers to use polymer modified binder. The aim of this study is to develop crumb rubber and latex modified asphalt binders for crack sealant purpose. Different percentage of crumb rubber and latex were used which are 5 %, 10 %, 15 % for crumb rubber while 5 % and 10 % for latex. This is the most economical method that can be done in order to prolong the life span of pavement. Sealing the crack can prevent infiltration of water. Zycotherm with the content of 0.1 % by weight of binder was used to ensure strong coating bonds between aggregate and asphalt binders. The study was divided into two phases. The goal of first phase is to test and compare the rheological properties of modified binders and unmodified binder. The rheological properties that had been tested are softening point, penetration value, elastic recovery and torsional recovery. These properties were all tested because it influences the performance of the sealant material. In the second phase, bond test and layer-parallel direct shear (LPDS) test were conducted. Bond test was carried out in order to evaluate the tensile strength of sealant material. LPDS was conducted to measure the asphalt binder resistance to shear stress.

The results of rheological properties showed that with the increment in crumb rubber and latex content in the asphalt binder, the softening point of the binder increased

significantly. This proved that modified binders are less temperature susceptible. While the penetration value decreases with the addition of crumb rubber and latex. This is due to crumb rubber and latex that has the ability to stiffen the binder. Other than that, elastic recovery and torsional recovery showed a positive result with the addition of modifier. The percentage of recovery for both elastic and torsional are relatively good with the presence of crumb rubber and latex. According to bond test results, by incorporating crumb rubber and latex, it is able to increase the tensile strength of the binder. Long term ageing effect were not considered in this study. While the results from LPDS showed that crumb rubber and latex modified binders have a very good resistance to shear stress.

This crumb rubber and latex modified asphalt binders would lead to produce the most environmental friendly sealant material by using recyclable material and plant-based material. It is not only environmental friendly, but the performance of modified binder is far more better than conventional binder.

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LIST OF ABBREVIATIONS

ASTM	**A**merican **S**ociety for **T**esting and **M**aterials
CRM	**C**rumb **R**ubber **M**odifier
EVA	**E**thylene **V**inyl **A**cetate
HMA	**H**ot **M**ix **A**sphalt
LPDS	**L**ayer **P**arallel **D**irect **S**hear
PI	**P**enetration **I**ndex
PMBs	**P**olymer **M**odified **B**inders
PVC	**P**olyvinyl **C**hloride
PWD	**P**ublic **W**orks **D**epartment
RPM	**R**evolution **P**er **M**inute
RTFOT	**R**olling **T**hin **F**ilm **O**ven **T**est
SBR	**S**tyrene **B**utadiene **R**ubber
SBS	**S**tyrene **B**utadiene **S**tyrene
UTM	**U**niversal **T**esting **M**achine

CHAPTER ONE

INTRODUCTION

1.0 Background

Crack treatment including crack sealing, crack filling and crack repair is one of the most typical maintenance method done on the road surface. Crack sealing is one of the most frequent pavement preservation and maintenance method rather than repaving the entire section of the pavement. Pavement cracking phenomena often occurs due to hot mix asphalt (HMA) shrinkage and daily temperature variation or cycles. It is typically caused by an inability of binder to expand and contract with temperature variation. Crack sealing has to be done towards the pavement to prevent infiltration of water in the pavement that can cause further deterioration. This is the most economical maintenance method that can be done in order to extend the pavement life by preventing or substantially reducing the infiltration of water into the pavement structure. Various research had been carried out on the crack sealing performance, however limited literatures and result are available for the crack sealing performance in regard to the overall performance of the asphalt pavement.

In order to ensure that the pavement life could be extended by the method of crack sealing, the binder plays a very important role as sealant. Only a proper binder with good rheological properties could extend the life of the pavement. However different highway agencies use different sealant materials. The effectiveness of the crack treatment often gambles on the situation or condition where the binder was used. The common sealing material that is used widely is hot poured bituminous based sealant which consist of virgin binder modified by polymer or natural rubber. Addition of polymer or natural rubber significantly affects the rheological properties of the modified binder. It can be

said that most of the highway agencies uses crumb rubber modified binder as crack sealant material and it is considered to be efficient crack sealant material due to its ductile properties. Habitually, the crumb rubber crack sealant material provides an elastic sealing that will adhere to the pavement and contract or expand very well with movement of the pavement. Amount of sealant should be applied in an adequate manner so that it will perform as intended. Inadequate or excessive amount of sealant would cause other pavement problem as well.

In this study, manufactured rubber and natural rubber are used as the binder modifier. Both of this modifier is categorised as rubber modifier and not polymer modifier. The production of crumb rubber modified binder and latex modified binder will be tested on its rheological behaviour and properties as well. The crack sealant test will be done as well to evaluate whether the binder is performing well as intended or not. If the crack sealant material performs well, then it would be a cost-effective maintenance treatment that can extend pavement service life substantially.

The establishment of this research is mainly to evaluate the crumb rubber and latex modified binder for the crack sealant purpose. These two types of modified binder will be compared with the unmodified binder in order to conclude which binder has the ability to perform as the best crack sealant material. Zycotherm was incorporated into the binder by terminal addition where it is added during the production of unmodified binder, crumb rubber modified binder and latex modified binder. Zycotherm with 0.1 % by mass of binder was used in the production of binder to enhance the moisture resistance of pavements by serving as an anti-stripping agent. Usage of Zycotherm is universally compatible with all type of modified binder as well as unmodified binders, it does not affect binder grading or change any other binder properties.

1.1 Problem Statement

Commonly in Malaysia, virgin asphalt binder is use as crack sealant material. The binder grade that will be used in this study is binder penetration grade of 60/70 as this is the most common binder grade currently used. However, in this study, crumb rubber and latex were suggested to be used to modify the virgin binder for the purpose of crack sealant material. Therefore, it is crucial to evaluate the binder performance that are incorporated with crumb rubber and latex. Laboratory work was carried out in order to evaluate the rheological properties of crumb rubber and latex modified binders. By obtaining the rheological properties of the modified binder, we will be able to conclude whether crumb rubber modified binder and latex modified binder are essential to be used as the crack sealant material.

The most common problem that usually arise when it comes to crack sealant material are the cohesive and the adhesive failure of binder towards the asphalt pavement. Cohesive failure is the failure that occurs inside the sealant itself. While adhesive failure is the failure that occurs due to debonding of sealant material from the asphalt pavement. Therefore, it is necessary to study the bonding between crumb rubber and latex modified binder for the purpose of crack sealant material in terms of strength of bond and the resistance of bond to shear stress.

Occurrence of crack in pavement generally causes water or other any debris to enter into the pavement and causing further damages. However, crack sealant substantially reduces the infiltration of water and other any debris inside the crack area. A study will be conducted in order to ensure that the crack sealant can perform well under the occurrence of moisture.

1.2 Objective

The main purpose of this study is to evaluate the crumb rubber and latex modified binder for the crack sealant application. The specific objectives of this study are:

1. To evaluate the rubberised modified binder in term of basic rheological properties and performance.
2. To assess the bonding and resistance to shear of modified sealant material and compare it with the unmodified binder at different conditions.
3. To recommend the optimum crumb rubber and latex content for the modified crack sealant material.

1.3 Scope of Work

The study characterized on how unmodified binder, crumb rubber modified binder and latex modified binder influences the basic rheological properties of binder that significantly could affect the performance of modified binder for the purpose of crack sealant material. Penetration grade of 60/70 asphalt binder was utilized for this study. Crumb rubber modifier and latex modifier was incorporated into the production of binder at the rate of 5 %, 10 %, 15 % and 5 %, 10 % respectively by weight of binder using wet process method. Zycotherm as additive was used in this study. Zycotherm of 0.1 % by weight of the asphalt binder was added during the blending of crumb rubber and latex with asphalt binder. The mixing temperature used in this study was 160˚C for the duration of 30 minutes by using high shear mixer with the operational speed of 1000 revolution per minute (rpm). The unmodified binder and modified binder with different percentage of crumb rubber and latex were tested for the basic rheological properties such as penetration test and softening point test. Other than that, elastic recovery test and torsional recovery test were also done. This test was done to determine the percent recovery. The percent recovery was intended to provide a means to determine the

presence of elastic response and stress dependence of crumb rubber and latex modified binder and unmodified binder. Since unmodified binder and modified binder will be use as a crack sealant material, the most important lab testing which is bond test and layer-parallel direct shear test (LPDS) was carried out in order to evaluate the performance of unmodified binder and modified binder. Bond test was carried out under three different condition which were unconditioned, immersion in distilled water and immersion in sodium carbonate. The layer-parallel direct shear (LPDS) test was done under two different condition which were unconditioned and immersion in sodium carbonate.

1.4 Significance of Study

In recent years, researchers had been putting their efforts to recycle waste materials and reuse them for the purpose of sustainability, such as reclaimed asphalt pavement for reuse and recycled wood chip and saw dust to make binder materials. Due to high cost in addressing waste tire, much attention had been given in recycling waste tire. Break down of waste tire into crumb rubber and incorporating it into binder can bring benefits such as improved binder performance and the recycling of waste tires as well. There are few environmental benefits that can be obtained by reusing the waste tire such as reduce waste tire disposal in landfill and less atmospheric pollution from burning. From the perspective of pavement industry, by reusing waste tire, it is able to reduce the production cost as well.

Other than using waste tire in pavement industry, the other option will be using latex which could be easily obtain from rubber tree. Other than processing the latex into different end product, it can also be used in pavement industry as material to improve the properties of binder. Latex can be used as modifiers as well since it can act as elastomers. This would also be a great benefit to pavement industry as incorporating latex could reduce the production cost and there will be no needs to produce synthetic rubber which

could be costly since we do have waste tire and latex which can improve the properties and performance of binder. Reuse of waste tire and usage of latex leads to economic.

Addition of Zycotherm in the production of binder which will act as a substance to increase the viscosity of binder. Zycotherm has a good resistance to moisture damage which could protect the pavement from getting attack by water easily. 0.1 % of Zycotherm by weight of binder is sufficient to be used in binder production. Other than that, Zycotherm could also act as an anti-stripping agent. Strong coating bonds between aggregate-asphalt binders promise the strength of pavement and reduce the chances of aggregates stripped off from the pavement. This would be very useful as we are going to evaluate the performance of modified binder for crack sealant purpose where we need a strong bonding between aggregate and asphalt binder so that it could prolong the life cycle of the pavement.

1.5 Organization of Dissertation

This dissertation presents the introduction of study, literature review, materials, and methodology. Results, discussion, conclusions and recommendation based on the extensive laboratory experimental work and findings obtained throughout this study were also presented in this dissertation. The dissertation is divided into five chapters. An overview of the execution of the tasks is illustrated in the flowchart in Figure 1.1 and a brief description of the contents of each chapter is presented in Figure 1.2.

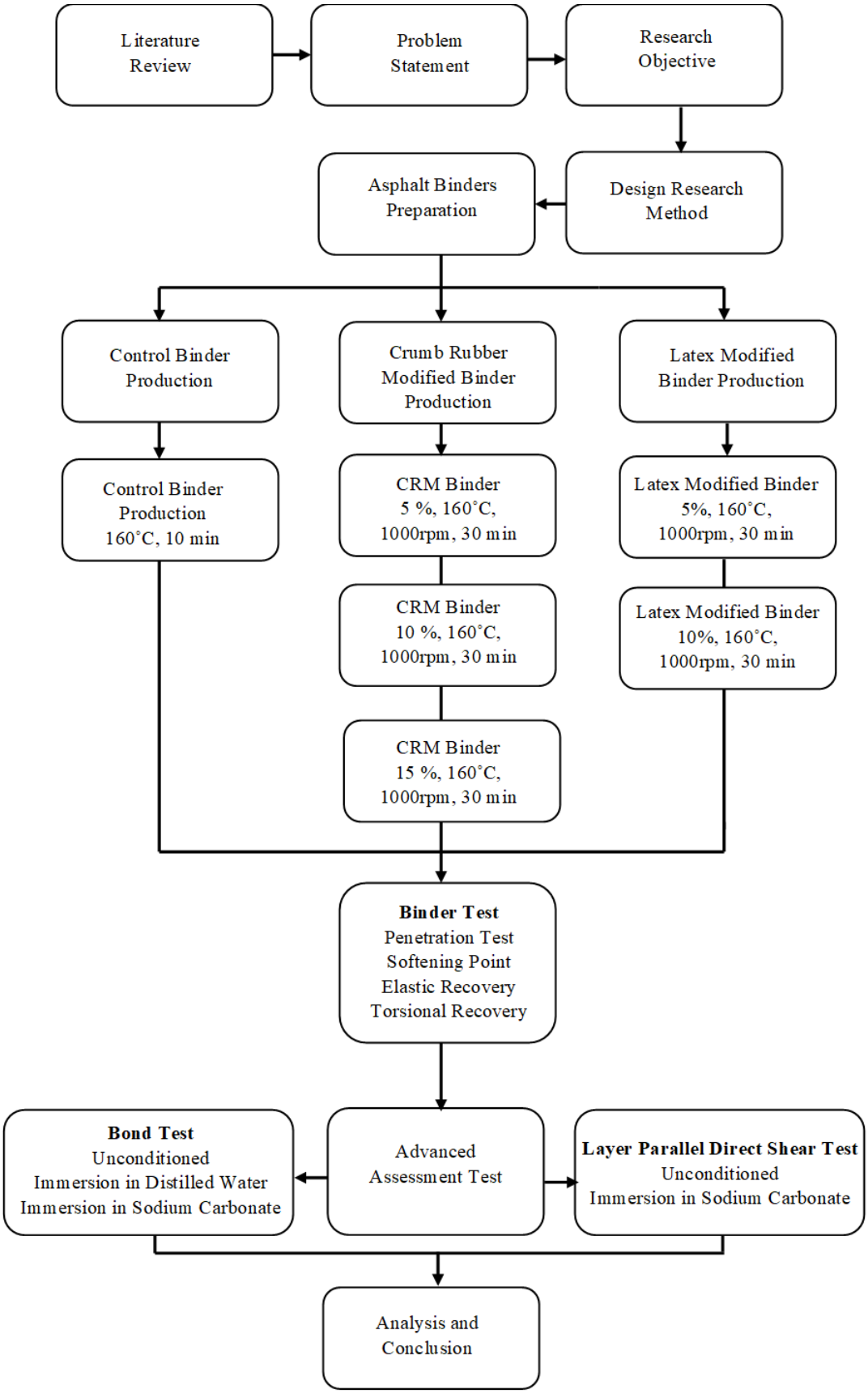

Figure 1.1: Execution of Tasks

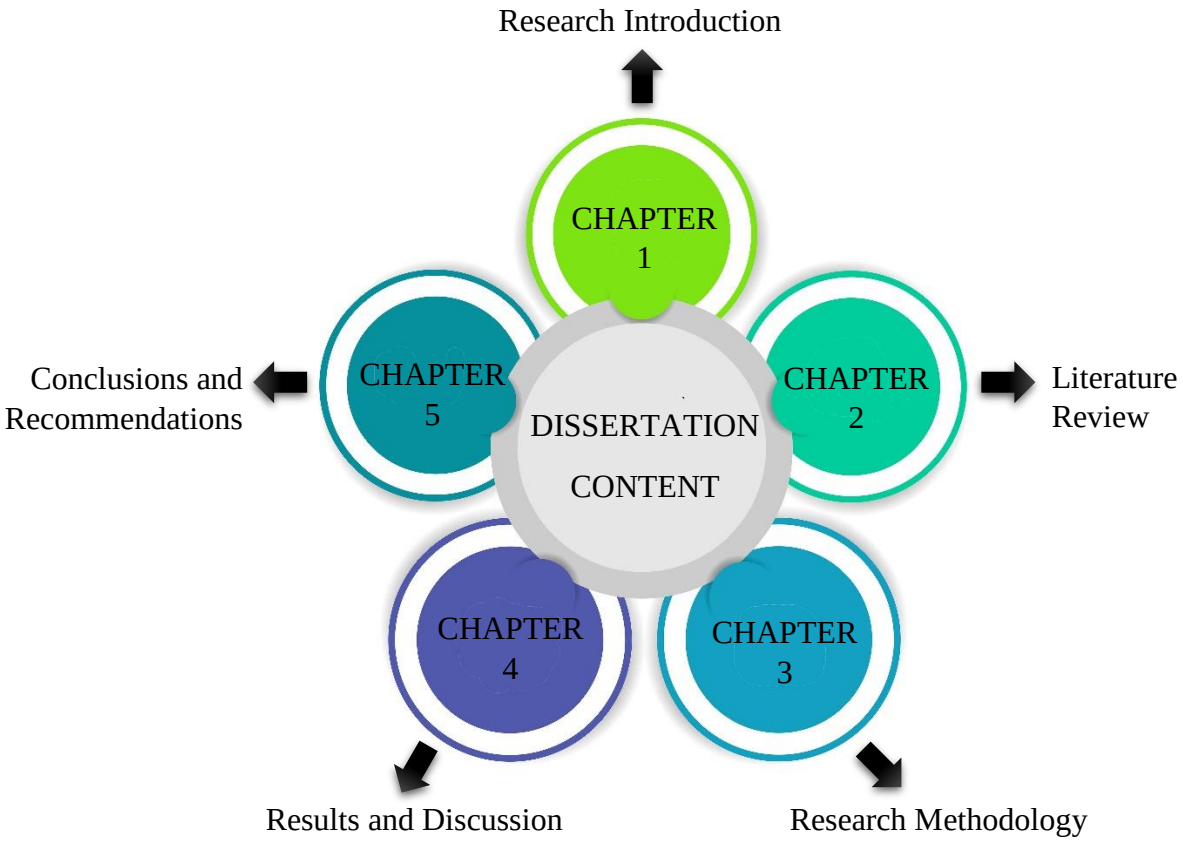

Figure 1.2: Contents of Dissertation

In Chapter one, the background of the research study, problem statement involved in this research study, objectives to be achieved from this study, scope of work involved in this research study and significant of the study were briefly discussed.

In Chapter two, a brief literature review of previous research findings pertaining to crack sealant material, use of crumb rubber and latex as elastomer to modify binder, issues related to crack sealant material, interaction of modifier and binder, mechanism of cohesion and adhesion and other relating study regarding crack sealant were discussed.

In Chapter three, the material properties of binder, crumb rubber and latex are described. This chapter also explains the binder rheological properties test that will be conducted, crack sealant performance test and the experimental approach designed for this research study.

In Chapter four, the results of rheological properties test conducted on the unmodified binder and modified binder using crumb rubber and latex were presented. A detailed discussion regarding the results obtained through the various test and analysis done were also discussed in this chapter.

In Chapter five, the conclusion that had been obtained through this research study were briefly listed and discussed. Besides that, recommendations are also given regarding the research work for further research.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

Generally, the pavement industry in Malaysia uses unmodified binder for road construction purpose or maintenance purpose. Conventional binder exhibits a satisfactorily performance in most pavements. However, due to the rapid increase in traffic volume, increase in number of high axle load vehicle in road and different weather condition, damages often occur to the pavement surface. Airey (2004) stated that increase traffic levels and new axles' designs with heavier loads and different configurations as well as harsh climates conditions spur the deterioration of the pavements. Therefore, using modifier will be the most suitable option to overcome this situation as we know that modified binder could enhance the performance of pavement since it exhibits improved binder properties. Modifier that had been widely used by most researchers according to Gogoi et al., (2016) and Diab and You (2017) are polymers and crumb rubber by many highway agencies to surpass the characteristics of the unmodified or conventional binder. In this study, pavement crack and crack sealant material will be mainly studied. The modifier that will be used throughout this study are manufactured rubber which is crumb rubber and latex. It will be mainly investigated as the suitability of these modified binder as crack sealant materials. Zycotherm was also utilized in this study, which is a silane-based technology and seems to be more efficient unlike common chemical additives that are based in amines, because it creates a molecular level hydrophobic zone which is water repellent and could also act as anti-stripping agent.

This chapter presents a brief review of literature on topics related to crumb rubber, latex, type of cracks, type of sealants material, the mechanism of sealant material, criteria

of crack sealing, issues related with sealant materials, and interaction of modifier with conventional binder.

2.1 Types of Sealant Material

Currently in highway industry, there are many different types of sealant materials. Each of the sealant material has its own characteristics and properties. Type of sealant usage varies according to the country and highway industry. Different type of sealant usage is due to the weather condition that differs across the world and magnitude of load applied on the pavement section. Even though there are different types of sealant materials, but all of these sealant materials are basically established to adhere to the wall of the cracks, have the ability to stretch over the movement of the crack at different conditions, able to resist abrasion and the load acting on the crack location. The most favourable sealant material for crack sealing is sealant material which has elastomeric characteristics. Such sealant has the ability to elongate without fracture and has the ability to return to its original dimension or shape. As reported by California Department of Transportation (2003), in California most of the hot pour materials for crack sealant were rubber modified asphalt binder. These materials have excellent abrasion resistance and are useful for high traffic loading surfaces. Cold pour materials for crack sealing in California are usually silicone based and often used prior to paving. It is said that these materials have poor abrasion resistance and it should not be used in high traffic loading areas.

The United States Federal Highway Administration (1999) and Malaysian Public Works Department (2008) stated that sealant material essentially comprises of three material families and are often grouped by material type, composition and manufacturing process. The principal material families and types are as follows:

i. Cold-applied thermoplastic bituminous materials

- Bitumen emulsion
- Polymer modified bitumen emulsion

ii. Hot-applied thermoplastic bituminous material

- Penetration grade bitumen
- Asphalt cement
- Fiberized asphalt
- Asphalt rubber
- Rubberized asphalt
- Low-modulus rubberized asphalt

iii. Chemically cured thermosetting materials

- Self-levelling silicone

Cutback bitumen, mineral-filled (granite dust, limestone dust etc) bitumen and sand-bitumen mixes are excluded from the list above as crack sealant material because cutback bitumen is rarely used because of environmental hazards. Whereas mineral-filled bitumen is not cost effective while sand-bitumen mixes are considered to be crack repair (partial-depth patching, spot patching etc.) materials.

Table 2.1 shows the general information about each sealant material type, including applicable specification and recommended application established by United States Federal Highway Administration and California Department of Transportation. The material type recommended for crack sealing purpose was almost similar to the material type stated in Malaysian Public Works Department which are polymer modified emulsion, polymer modified bitumen and self-levelling silicone. The first step in selecting a material is to identify the key properties that a material must possess to be

efficiently placed and to perform successfully under the conditions provided for the time desired.

Table 2.1: Summary of Crack Treatment Material
(Source: United States Federal Highway Administration, 1999)

Material Type	**Applicable Specifications**	**Recommended Application**
Asphalt Emulsion	ASTM D 977, AASHTO M 140, ASTM D 2397, AASHTO M 208	Filling
Asphalt Cement	ASTM D 3381, AASHTO M 20, AASHTO M 226	Filling
Fiberized Asphalt	Manufacturer's recommended specification	Filling
Polymer Modified Emulsion	ASTM D 977, AASHTO M 140, ASTM D 2397, AASHTO M 208	Filling (possibly sealing)
Asphalt Rubber	State specification, ASTM D 5078	Sealing (possibly filling)
Rubberized Asphalt	ASTM D 1190, AASHTO M 173, Fed SS-S-164	Sealing
	ASTM D 3405, AASHTO M 301, Fed SS-S-1401	Sealing
Low-modulus Rubberized Asphalt	State-modified ASTM D 3405 Specification	Sealing
Self-Levelling Silicone	ASTM D 5893	Sealing

2.2 Criteria for Crack Sealing

The crack sealing material shall be able to fill and/or seal the cracks to prevent water and incompressible materials entering the pavement at the surface. It is stated in Malaysian Public Works Department (2008) that the material shall be selected based on

the key properties that it has in order to be efficiently placed and perform satisfactorily. The desirable properties are short preparation time, quick and easy to place (good workability), short curing time, adhesiveness, cohesiveness, resistance to softening and flow, flexibility, elasticity, resistance to ageing and weathering and resistance to abrasion by traffic. The United States Federal Highway Administration (1999) stated that the first most frequent crack to appear in a pavement are transverse crack. However, several different types of cracks may appear at one time. In this case, one treatment, using a material appropriate for the most demanding crack type, is desirable. In order to determine whether to seal or fill a crack, it must be established whether the crack is working or non-working and whether the crack undergoes horizontal or vertical movement. Crack sealing is suitable for working crack, while crack filling is suitable for non-working crack or known as low movement crack. Crack sealing requires comprehensive preparation and often requires the use of specialized high-quality materials placed either into or above working cracks to prevent the intrusion of water and incompressible materials. According to the United States Federal Highway Administration (1999), working crack are usually transverse in orientation. However, some longitudinal and diagonal cracks may be classified as working cracks if they meet the movement criteria while non-working crack include diagonal cracks, most longitudinal cracks, and some block cracks. Little movement occurs due to the relatively close spacing or free edges between non-working cracks. Working cracks are also expressed as having 3 mm or more in vertical or horizontal movement as shown in Figure 2.1. Vermont Agency of Transportation (2014) mentioned that horizontal movement was caused by shrinkage and expansion of pavement due to the thermal changes in pavement material while vertical movement was caused by moisture related changes within the substrate and typically applies to concrete pavement. Table 2.2 shows the criteria for

crack sealing and filling by United States Federal Highway Administration. As a result of moving nature of working cracks, California Department of Transportation (2003) stated that a relevant crack sealant must be proficient of:

- Remain adhered to the walls of the crack,
- Elongate to the maximum opening of the crack and recover to the original dimensions without rupture,
- Expand and contract over a range of service temperatures without rupture or delamination from the crack walls, and
- Resist abrasion and damage caused by traffic.

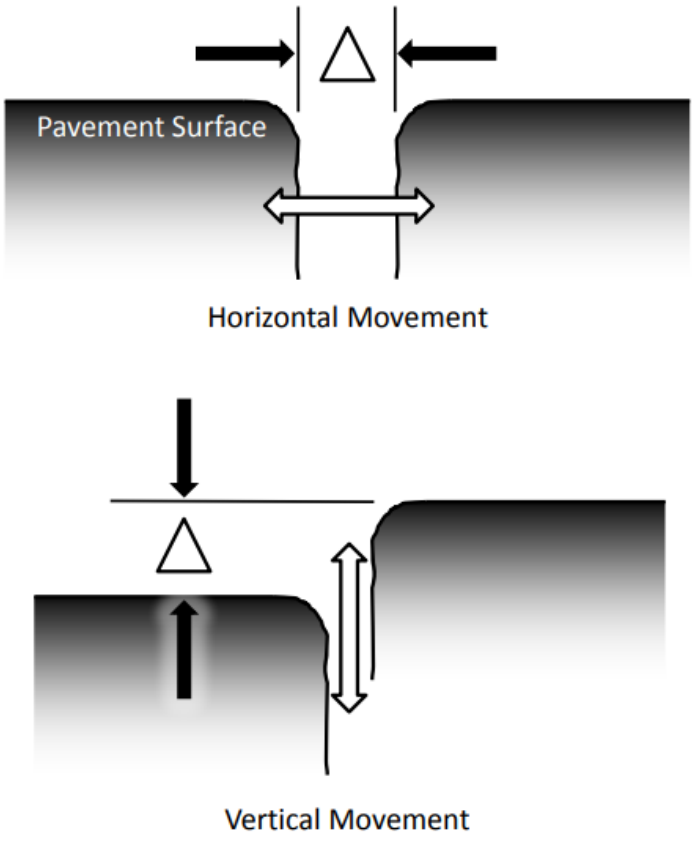

Figure 2.1: Δ is 3 mm or greater for working cracks
(Source: Vermont Agency of Transportation, 2014)

Table 2.2: Criteria for Crack Sealing or Filling
(Source: United States Federal Highway Administration, 1999)

Crack Characteristics	**Crack Treatment Activity**	
	Crack Sealing	**Crack Filling**
Width, mm	5 to 19	5 to 25
Edge Deterioration	Minimal to None (≤ 25 percent of crack length)	Moderate to None (≤ 50 percent of crack length)
Annual Horizontal Movement, mm	≥ 3	< 3
Type of Cracks	• Transverse Thermal Cracks • Transverse Reflective Cracks • Longitudinal Reflective Cracks • Longitudinal Cold-Joint Cracks	• Longitudinal Reflective Cracks • Longitudinal Cold-Joint Cracks • Longitudinal Edge Cracks • Distantly Spaced Block Cracks

While conforming to Malaysian Public Works Department (2008), it is stated that the most appropriate pavement for crack sealing were relatively new pavements where cracks begins to form, with crack width greater than 3 mm but less than 20 mm. The crack width stated in Malaysian Public Works Department (PWD) guide for crack sealing was almost similar to the value stated by Federal Highway Administration. Anyhow the crack width value for crack filling was not stated by Malaysian Public Work Department.

2.3 Issues with Sealant Material

Despite the usage of sealant to seal the pavement crack is very high, but there are still some issues that occurs with the usage of sealant. Research conducted by Chong and Phang (1988) and Masson et al., (1999) said that the crack sealing approach was still expanding, however even with available technology, sealants often exhibits premature

failure. When there is failure, the specific reason behind the sealant failure couldn't be identified while successful sealant installation cannot be repeated consistently despite evidence for extended service life of crack sealant. Masson and Lacasse (2000) said that crack sealant that were modified with polymers or crumb rubber has potential to fail either adhesively or cohesively. This had become an issue in the application of sealant for pavement's crack. However, over the years, researcher had obtained a good understanding on the properties and performance of crack sealant and had been able to improve their physical properties as well. Evers (1983) and Masson et al., (1999) mentioned that good understandings on the crack sealant properties had lead the manufacturers to produce crack sealant with good cohesion ability and thus this helps in the reduction of cohesive failure. Even though the cohesion properties of crack sealant are easily understandable by the researcher, but the adhesion mechanism of the crack sealant are not well understood. Thus, a sealant with good adhesion properties has been deceptive.

Fini (2008) stated that the most important condition to be considered in the crack sealant performance was the sealant adhesion, which is the most important aspect in the field performance. According to the research done previously, adhesive failure was categorised as the most common sealant failure issue. Although after the adhesive failure, the detached sealant may remain in the crack, but that detached sealant does not any longer preserve the integrity of the pavement. Adhesion is known to be as the bonding of one material to another, namely an adhesive to a substrate. In this context, adhesion means the ability of sealant to hold against the separation of pavement crack for a period of time. Wu (1982) also studied the phenomenon of adhesion from both physical and chemical point of view on how to develop a sealant that has a better adhesive bond. In order to bring this issue to an end, Fini (2008) developed a laboratory testing approach

to evaluate the adhesion of crack sealant. It is stated in that research that it is very necessary to have a standard test method which can evaluate the adhesion bond characteristic based on sealant rheology, because bituminous material used as sealant material faces difference in temperature and traffic loading conditions throughout their service life. The test developed were able to study more details regarding the adhesion mechanism of crack sealant which had been a very common failure in crack sealant.

Guo et al., (2017) also studied the cohesion and adhesion of hot-poured crack sealants. The cohesion and adhesion were evaluated in terms of influenced of temperature on crack sealants and effect of moisture on low temperature performance of crack sealant. According to the study done, the cohesion force of crack sealant increased significantly while the adhesion force changes little with the decreased of temperature. When the temperature is higher, the adhesion force was said to be greater than cohesion force and the cohesion failure will happen more easily. As a summary of the study, the adhesion failure will happen easily when the temperature is lower than critical value. Critical value is the temperature at which the cohesion force is equal to the adhesion force. For the effect of moisture on low temperature, the sample that was soaked in 25˚C water showed slight improvement on the low temperature tension performance of crack sealant. While soaking in 60˚C will decrease the failure energy of low temperature tension and damage the durability of crack sealant.

2.4 Cohesion and Adhesion Mechanism of Sealant-Asphalt Concrete Interface

Bituminous sealants are used to seal the crack in the asphalt concrete pavement. The crack sealing method play a crucial role in order to ensure that the sealant does not face any failure. According to Chong and Phang (1988) and Masson et al., (1999), they mentioned that crack sealing technique was still developing, however despite recent advances, sealant material often shows premature failure. As we know, the most common

failure of sealant material is either cohesively or adhesively. Cohesive failure is characterised as the failure of the sealant in the bulk or usually termed as failure within the asphalt binder itself, but the sealant material is still adhered to the crack wall. From the point of view of Masson et al., (1999), cohesive failure is an uncommon condition in cold weather location. While the adhesive failure is failure that occur where sealant material detaches from the asphalt concrete interface. Adhesive failure is the most common failure that occur compare to cohesive failure. However, over the years, researcher had obtained a good understanding on the properties and performance of crack sealant and had been able to improve their physical properties as well. Evers (1983) and Masson et al., (1999) mentioned that good understandings on the crack sealant properties had lead the manufacturers to produce crack sealant with good cohesion ability and thus this helps in the reduction of cohesive failure. Even though cohesive failure had been well studied among researchers, but the nature of adhesion between bituminous sealants and asphalt concrete is still not well understood. The lack of knowledge on this has become a barrier for highway industry to design the strongest sealant-asphalt concrete interface.

For maximum effectiveness, a sealant must remain firmly attach to asphalt concrete at all times. As such, the performance of the sealant-asphalt concrete joint is governed by the strength of the interface, the adequacy of the sealant and the integrity of the asphalt concrete pavement. Masson and Lacasse (1999) stated that the sealant material sustains its integrity during cold weather when the cohesive strength of the interface, that is adhesion force is equal to or greater than the tensile force due to thermal contraction of asphalt pavement as shown in Figure 2.2(a). Tons (1962) mentioned that the tensile stress at the interface was governed by the temperature, the geometry of the sealant and its viscoelastic properties. Masson and Lacasse (1999) had explained clearly regarding the

sealant-asphalt concrete interface model of the system resulting from crack sealing in bituminous pavements. Sealant failure was said to be adhesive if tensile stress is greater in cold weather than in warm weather and that when it exceeds the cohesive strength of the interface as shown in Figure 2.2(b). The failure can be fast if the tensile force at the interface are higher. The failures are in the sealant or asphalt concrete if strength of the interface that is adhesion, exceeds that of the sealant or that of the asphalt concrete as shown in Figure 2.2(c) and Figure 2.2(d) respectively.

Masson and Lacasse (1999), Fowkes (1987) and Good (1992) mentioned that there were several mechanisms that had been used by various researcher to explain the adhesion mechanism between materials. The adhesion theory that had been used to explain the mechanism are adsorption theory, mechanical interlock theory, diffusion theory, chemical bonding theory, electrostatic theory, acid-base theory, weak boundary layer theory. It was established that only two out of seven theories can explain the adhesion mechanism of bituminous sealant to asphalt concrete which are adsorption and mechanical interlock. In this regard, intrinsic sealant properties such as viscosity and composition are particularly important. Aside of this, it is to be said that not only binder properties play an important role in failure of sealant that is related to adhesion mechanism. Presents of dust, void and microcrack in the sealant-asphalt concrete interface can also be closely related to sealant failure that affect the adhesion mechanism.

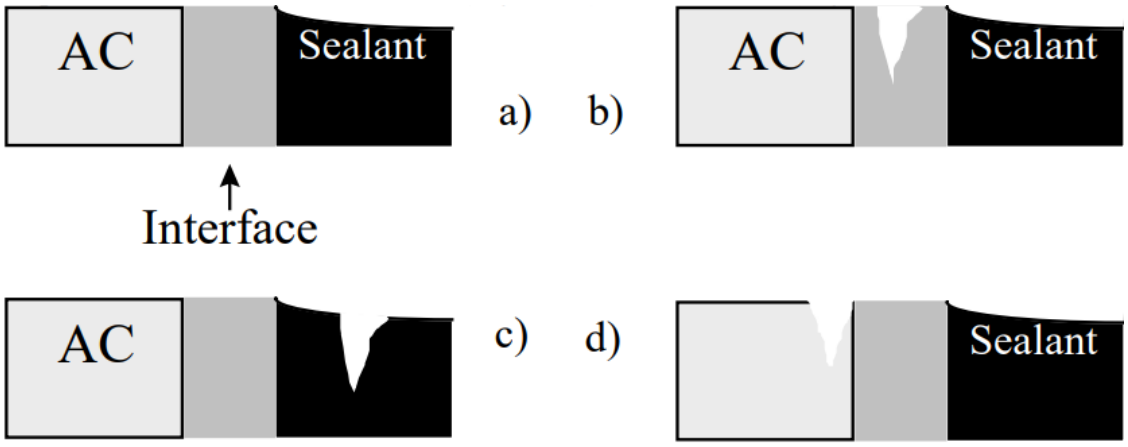

Figure 2.2: Three-phase sealant-interface-AC model of the system resulting from crack sealing in bituminous pavements. The model shows an intact seal (a), adhesive failure (b), and cohesive failures in the sealant (c) and asphalt concrete (d).
(Source: Masson and Lacasse, 1999)

2.4.1 Adsorption Theory

Adsorption theory is basically about the adhesion and adsorption phenomena of liquids onto solids. This theory explains the adhesion phenomena based on wetting, spreading and contact angle of liquid drop of adhesive onto the substrate. The liquid drop of adhesive meant in this context is bituminous sealant. In adsorption theory, wetting, spreading and contact angle are related to one another. Contact angle plays a very important role in ensuring good wetting and spreading occur on the substrate.

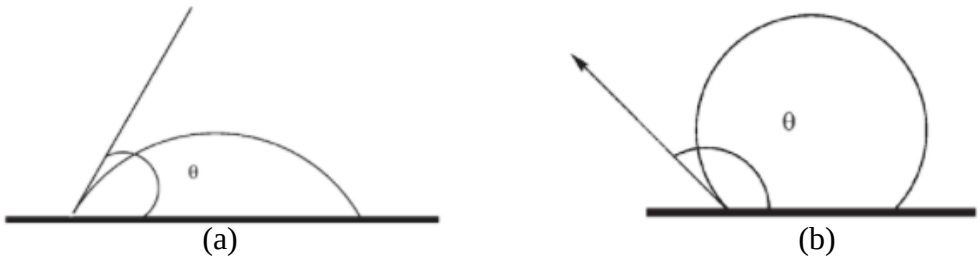

Figure 2.3: (a) Contact angle less than 90˚ and (b) Contact angle greater than 90˚
(Source: Brewis and Mathieson, 2001)

Contact angle has a significant effect towards the wetting of a solid surface by sealant material. When hot bituminous sealant material was placed onto the substrate, it will either remain stationary (contact angle more than 90˚) or it will spread out (contact angle less than 90˚) as shown in Figure 2.3. If the sealant material spreads on the substrate, then the substrate surface will be wetted sufficiently and the adhesion mechanism and performance between the sealant material and substrate is better. According to Brewis and Mathieson (2001), strong attraction force between solid and liquid were formed when the contact angle is zero. While when the force of attraction between solid and liquid is poor, then the contact angle is possibly greater than 90˚. The sealant and asphalt concrete composition govern the attraction force between the solid surface and liquid as well.

2.4.2 Mechanical Interlocking Theory

Mechanical adhesion occurs when the materials can mechanically interlock in some specific way. This can occur if a continuous sealant material fills the voids or pores of the crack wall. Therefore, adhesion relies on the mechanical interlocking between the substrate and adhesive, as shown in Figure 2.4, implying that rough surfaces provide higher adhesion compared to a smooth surface.

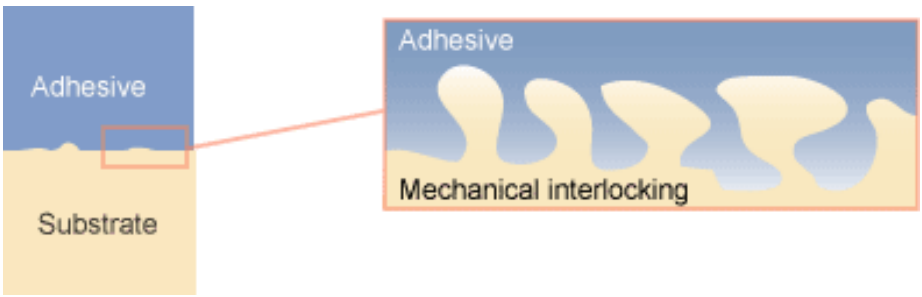

Figure 2.4: Mechanical theory of adhesion
(Source: Mattson, 2014)

Based on the study that had been conducted by Masson and Lacasse (1999), it was concluded that the formation of an interface that acts as a composite material with properties intermediate to those of each material surfaces was resulted due to the interlocking that combines the cohesive strength of both individual solids. Besides that, viscosity has a significant effect towards the interlocking theory. Sealant with low viscosities was said to have better interlocking properties since it can move deeper into the asphalt concrete and fill those void that presents. Anyhow even though it can create a better interlocking mechanism, but the low viscosity was closely related to the inadequacy of elastomer that presents in the binder. This may reduce the resistance of sealant to flow at high temperature and to elongate at low temperature. As a summary, a viscosity limit should be established so that the sealant could penetrate deeper into asphalt concrete and create a better interlocking mechanism between sealant and asphalt concrete.

2.5 Types of Crack in Asphalt Pavement

Crack in pavements occurs when a stress is built up in a surface layer that exceeds the tensile or shear strength of the pavement causing a fissure or crack to open. Crack sealing is one of the method that is commonly used to repair these cracks rather than reconstructing the entire section of that road. The success of crack sealing operations depends on the cause of the crack and its activity. These two criteria play an important role in determining the success of crack sealing repair method. Cracking may be associated with various distress mechanisms. There are several types of crack that presents in the flexible asphalt pavement which are fatigue cracks, longitudinal cracks, transverse cracks, block cracks, reflective cracks, edge cracks and slippage cracks.

2.5.1 Fatigue Cracks

Fatigue cracks are the result of repetitive traffic loads or high deflections often due to wet bases or sub grades. This type of cracking can also lead to potholes and pavement disintegration. As the number and magnitude of loads becomes too great, longitudinal cracks begin to form in the wheel paths. When cracking is characterized by interconnected cracks, the cracking pattern resembles that of an alligator's skin. Therefore, it is also referred to as alligator cracking as shown in Figure 2.5(a). (California Department of Transportation, 2003)

2.5.2 Longitudinal Cracks

This crack run longitudinally along the pavement, as shown in Figure 2.5(b). This type of crack occurs due to poorly constructed paving joint, shrinkage of surface layer due to temperature cycling or hardening of the asphalt. They occur frequently at joints between adjacent travel lanes or between a travel lane and the shoulder. (California Department of Transportation, 2003)

2.5.3 Block Cracks

Block crack is pattern of cracks that divides the pavement into approximately regular blocks as shown in Figure 2.5(c). Block cracks present by virtue of age hardening of the asphalt coupled with shrinkage during cold weather. (California Department of Transportation, 2003)

2.5.4 Reflective Cracks

Reflection crack were caused by cracks, or other discontinuities, in an underlying pavement surface that propagate up through an overlay due to movement at the crack. Development is especially like when the pavement below is a portland cement concrete