ASSESSMENT ON THE PERFORMANCE OF ASPHALT MIXTURES PREPARED WITH ADHESION PROMOTERS

NGE JIA SHENG

SCHOOL OF CIVIL ENGINEERING
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By

NGE JIA SHENG

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Name of Student: Nge Jia Sheng

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

Signature:

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Date:

Approved by:

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(Signature of Supervisor)

Name of Supervisor: Dr. Mohd Rosli Mohd Hasan

Date:

Approved by:

____

(Signature of Examiner)

Name of Examiner: Dr. Izwan Johari

Date:

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ABSTRAK

Turapan asfalt kebiasaanya cenderung terhadap kerosakan disebabkan kelembapan dan memiliki ketahanan yang lebih rendah berbanding turapan konkrit. Walaubagaimanapun, kebolehupayaan turapan asfalt boleh ditingkatkan dengan penggunaan bahan tambah atau modifikasi melalui pengubahsuain asfalt. Objektif kajian ini ialah untuk mengkaji kesan pemangkin lekatan dinamakan PBL dan M5000 ke dalam campuran asfalt bersuhu tinggi (HMA). Kebolehupayaan campuran boleh ditafsirkan melalui ciri-ciri perkhidmatan dan ikatan, serta prestasi mekanikal. Ciri-ciri perkhidmatan boleh dinilai melalui indeks kebolehkerjaan (WI) dan indeks tenaga mampatan (CEI) yang menunjukkan sifat campuran asfalt ketika digaul dan dimampatkan mengikut kadar ketumpatan yang dikehendaki. Ciri-ciri ikatan campuran asfalt yang diubahsuai dikenalpasti menggunakan ujian air mendidih dan kaedah rendaman statik bagi menunjukkan tahap salutan setelah menjalani tempoh pengamatan dan suhu yang spesifik. Kebolehupayaan mekanikal bagi campuran asfalt yang telah diubahsuai dinilai melalui kestabilan Marshall, ujian daya ricih Leutner, lenturan separa bulat dan ujian Lottman terubahsuai. Semua sampel telah disediakan dengan gabungan pemangkin lekatan pada sukatan 0.5% dan 1.0% berbanding berat pengikat asfalt bagi kedua-dua bahan tambah tersebut. Daripada ujikaji ini, ciri-ciri ikatan telah meningkat dengan ketara untuk campuran asfalt yang telah diubahsuai berbanding campuran terkawal. Indeks kebolehkerjaaan bagi campuran asfalt yang telah diubahsuai meningkat dan indeks tenaga mampatan menurun berbanding campuran terkawal. Hal ini menunjukkan kebolehkerjaan asfalt yang telah diubahsuai lebih tinggi dan memerlukan kurang tenaga untuk dimampatkan. Campuran asfalt yang telah diubahsuai secara umumnya mempunyai kebolehupayaan yang lebih baik dalam kebanyakkan prestasi mekanikal kecuali keputusan ujian daya ricih Leutner. Campuran terkawal mencapai

daya ricih yang lebih tinggi berbanding PBL dalam kedua-dua sukatan. Manakala M5000 pada kadar 0.5% mempunyai daya ricih yang lebih tinggi berbanding M5000 dengan sukatan 1.0% dan campuran terkawal. Oleh itu, campuran asfalt yang telah diubahsuai mempunyai prestasi keseluruhan yang lebih baik berbanding campuran terkawal. Secara amnya, campuran asfalt yang telah diubahsuai mempunyai ketahanan yang lebih tinggi terhadap kelembapan, dan mempunyai daya tahan yang lebih baik terhadap beberapa kondisi cuaca dan beban lalu lintas.

ABSTRACT

Asphalt pavement is typically susceptible to moisture damage and is less durable compared to concrete pavement. However, the performance of the asphalt pavement could be improved with the incorporation of additives or modifiers thru binder modifications. The objective of the study is to assess the effect of adhesion promoters, namely PBL and M5000 onto the Hot Mix Asphalt (HMA). The performance has been assessed in terms of the service characteristics, the bonding properties and the mechanical performances. The service characteristics were assessed using Workability Index (WI) and Compaction Energy Index (CEI) to show the ease of asphalt mixture to be mixed and compacted to the desired density. The bonding properties of the modified asphalt mixtures were determined using the boiling water test and static test method to indicate the degree of coating after undergoing specific conditioning time and temperature. The mechanical performances of the modified asphalt mixture were evaluated by Marshall stability, Leutner shear, semi-circular bending and Modified Lottman tests. All specimens were prepared by incorporating adhesion promoters at the dosage rates of 0.5% and 1.0% by weight of asphalt binder for both additives. From the investigation, the bonding properties were significantly improved for the modified asphalt mixture compared to the control mixture. The WI of the modified asphalt mixture was increased and the CEI was decreased in comparison to the control specimen, which means the workability of the modified asphalt mixture is higher and requires less energy to be compacted. Modified asphalt mixture generally had better performance in most of the mechanical performances except the Leutner shear test result. The control specimen achieved a higher shear strength than the PBL at both dosages. While the M5000 at 0.5% had higher shear strength than the M5000 at 1.0% dosage and the control specimen. Therefore, the modified asphalt mixtures have better overall performance than the control mix. Overall, the modified asphalt mixture is more moisture resistant and durable against severe weather condition and traffic loadings.

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LIST OF ABBREVIATIONS

AASTHO	**A**merican **A**ssociation of **S**tate **H**ighway and **T**ransportation **O**fficials
AIMS	**A**ggregate **Im**aging **S**ystem
ASTM	**A**merican **S**ociety for **T**esting and **M**aterials
AV	**A**ir **V**oid
BSI	**B**ritish **S**tandards **I**nstitution
CEI	**C**ompaction **E**nergy **I**ndex
DSR	**D**ynamic **S**hear **R**heometer
GTM	**G**yratory **T**esting **M**achine
HMA	**H**ot **M**ix **A**sphalt
ITS	**I**ndirect **T**ensile **S**trength
ITSR	**I**ndirect **T**ensile **S**trength **R**atio
M5000	**M**orlife **5000**
OBC	**O**ptimum **B**inder **C**ontent
PBL	**P**ave **B**ond **L**ite
PWD	**P**ublic **W**orks **D**epartment
RAP	**R**eclaimed **A**sphalt **P**avement
RAS	**R**ecycled **A**sphalt **S**hingles
RPM	**R**evolutions **P**er **M**inute
RTFOT	**R**olling **T**hin **F**ilm **O**ven **T**est
SGC	**S**ervopac **G**yratory **C**ompactor
UTM	**U**niversal **T**esting **M**achine
WI	**W**orkability **I**ndex
WMA	**W**arm **M**ix **A**sphalt

NOMENCLATURES

G_{mm}	Theoretical Maximum Specific Gravity
G_{mb}	Bulk Specific Gravity
σ_{max}	Maximum Tensile Stress at Failure
J'	Volume of Absorbed Water
Va	Volume of Air Void
S'	Degree of Saturation

CHAPTER 1

INTRODUCTION

1.1 Background

Hot Mix Asphalt (HMA) is the most common type of asphalt pavement used in Malaysia. HMA is defined as a complex mixture composed of asphalt binder, aggregates and mineral filler. The bitumen, black or dark brown in colour, acts as an adhesive, gluing the aggregate into a dense mass and waterproofing the aggregate particles. The mineral aggregate, when bound together, acts as a stone framework to give strength and toughness to the composite system.

However, typical asphalt pavement roads are less durable and highly susceptible to bad weathers particularly rainy weather if compared to the cement concrete roads. Moisture damage is a prevalent failure of bonding in asphalt pavement that remains a topic of debate among researchers for years (Kakar *et al*., 2015). Moisture damage is defined as the loss of strength, bonding and stability caused by the presence of moisture in asphalt pavement according to Al-Qadi *et al*. (2014). Behiry (2013) stated moisture damage usually causes the loss of bonding between aggregate particles and asphalt binder and also the reduction of bonding within the asphalt binder itself. Sebaaly *et al.* (2015) mentioned this problem could cause pavement distresses such as ravelling, stripping, cracking, rutting and potholes.

The propagation of moisture damage generally occurs through two mechanisms: the loss of adhesion and cohesion (Bhasin *et al.*, 2006). Adhesion is the bonding mechanism between the aggregate particles and asphalt binder. Cohesion is the bonding mechanism present in the molecules within the asphalt binder film. The adhesion and cohesion between the asphalt binders and aggregates are the forces holding the asphalt mixtures together. According to Lytton *et al.* (2005), these are the factors affecting the resistance of moisture damage, such as asphalt film thickness, aggregate shape characteristics and surface energy. Abuawad *et al.* (2015) specified the most common technique to mitigate moisture damage is using additives or modifiers with the asphalt binder or the aggregate. Various additives and modifiers worldwide are used to enhance the performance of asphalt mixtures.

1.2 Problem Statement

In asphalt mixtures, the binder serves to hold the aggregates firmly and act as a sealant against moisture ingress. The HMA is sensitive to the presence of water in the pavement. Water can penetrate thru cracks on the surface of the pavement, thru the interconnectivity of the air voids system or cracks. Besides, during the mixing process, the insufficiently dried aggregates may cause to the presence of trapped moisture in the coated aggregates. Moisture damage is a major cause of premature failure in asphalt pavement as it accelerates some typical pavement distresses such as bleeding, rutting, cracking, ravelling and potholes. Additionally, the weakening or detachment of the asphalt film adhering to the surface of the aggregate as known as stripping is another major trigger for the deterioration of road pavement due to moisture damage.

In addition, the large increase in the number of vehicles and the volume of heavy traffic on the roads have consequently increased the tire pressure and axle loads imposed on the pavement structure, generating enormous burden on the asphalt pavement structure.

However, it is possible to ensure better bonding between aggregates and asphalt binder by using adhesion promoters. Hence, it is necessary to carry out the study on the characteristics of the modified asphalt binder and the performance of asphalt mixture prepared with adhesion promoters in terms of the workability, compactability, tensile property, shear strength, fracture resistance, bonding between the aggregate and binder itself. It is essential to ensure the modified asphalt mixture is able to withstand the increase in loading, mitigate the adverse effects of moisture damage on pavement performance and reduce the occurrence of premature distresses.

1.3 Objectives

The objectives of the study are:

1. To assess the effect of adhesion promoters on the workability and compactability of the asphalt mixtures.
2. To determine the adhesion and cohesion bonding properties of the asphalt mixtures incorporating adhesion promoters.
3. To evaluate the mechanical performance of the asphalt mixtures prepared with adhesion promoters.

1.4 Significance of Study

Moisture damage has always been a serious bond failure issue leading to asphalt pavement distresses. A scientific study that could possibly lead to the enhancement of durability of the asphalt pavement shall be carried out by looking into the bonding mechanism that exists between the aggregate and the binder. Also, understand the working mechanism of adhesion promoters with the asphalt binder in order to enhance the resistance of asphalt mixture towards moisture susceptibility. The performance of the asphalt mixture prepared with adhesion promoters has been evaluated and compared with the performance of asphalt mixture prepared with conventional bitumen. This data is crucial to demonstrate to the local authority and relevant stakeholders on how adhesion promoters could improve the durability and longer the service life of asphalt pavements. Having said that extended service life of asphalt mixture, the cost of maintenance could be greatly reduced in the long run and the use of natural resources such as aggregate and bitumen are decreased to ensure the continuity supply of the non-renewable resources in the future. Not only that, by incorporating adhesion promoters in asphalt mixture, it is believed that it can provide a more conducive paving environment to the workers due to its low odour and high workability.

1.5 Scope of Work

Crushed granite aggregate and asphalt binder of penetration grade 60/70 were used in the study. Asphalt binders were modified by incorporating adhesion promoters: Pave Bond Lite (PBL) and Morlife 5000 (M5000). The dosage rates were 0.5% and 1.0% for both types of adhesion promoters. The aggregate gradation of the asphalt mixture was based on the Malaysian Public Works Department (PWD) AC14 wearing course with the optimum binder content (OBC) 5.0%. The mixing and compaction temperatures were set at 160°C and 150°C, respectively. Servopac Gyratory Compactor (SGC) was used to compact the cylindrical specimen at 4.0 ± 1% or 7.0 ± 1% air void depending on the designated test requirements. All specimens were subjected to the short-term aging prior to the compaction process. The specimens were tested for its serviceability, bonding and coatability, as well as the mechanical performance tests.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Asphalt pavement is a multi-layered composite road pavement system that has been widely constructed worldwide. Its notable purpose is to transfer and distribute the traffic loading exerted effectually from the wearing course to the subgrade. Good bonding characteristics between asphalt pavement layers can provide the structural integrity by ensuring the high-quality pavement performance (Chun *et al.*, 2015).

In general, conventional asphalt binder is used in Malaysia and most of the pavements able to perform satisfactorily. However, bad weather could still be a threat to the conventional asphalt pavement. This is because during extreme hot weather, the high temperature will soften the asphalt binder causing permanent deformation when a heavy load is applied onto it. While during rainy days, rainwater will seep down into the structure of asphalt pavement layers causing wear away at the bond between the aggregates and the asphalt binder and maximising the potential of moisture damage. Bad weather spurs the action of pavement distresses such as ravelling, stripping, cracking and potholes, shortening the service life of asphalt pavement. Thus, adhesion promoters are introduced into the conventional asphalt binder to enhance the bonding and the strength of the asphalt pavements. Besides, incorporating adhesion promoters could effectively enhance moisture resistance and stripping resistance of the asphalt pavement.

This chapter provides wide ranges of literature from numerous researchers on the similar topic of study area pertaining to adhesion promoters, bonding characteristics, moisture susceptibility, stripping resistance and mechanical performance of asphalt mixture incorporating adhesion promoters.

2.2 Hot Mix Asphalt (HMA)

Hot mix asphalt (HMA) is made up of coarse and fine aggregates bound together into a solid mass by asphalt binder. The aggregates amount to 93% to 97% by weight of the total asphalt mixture and are blended with 3% to 7% asphalt binder depending on the design mix (The Maryland Asphalt Association Inc., 2008). Aggregates and asphalt binder are combined in a mixing facility in which all the component materials are heated, proportioned and mixed to produce the desired paving mixture. Upon completion of plant mixing, the hot mixture is transported to the site and compacted by heavy motor-driven rollers to produce a smooth, well-consolidated pavement layer (McAsphalt Industries Limited, 2019).

The HMA is a commonly used conventional mixture in Malaysia. HMA production needs a high temperature between 160°C and 190°C that produces high emissions of carbon dioxide and adversely affects the environment. While cool weather is one of the factors affecting the temperature of the HMA mixture during construction as it will lower the asphalt mixture temperature. From the study, although HMA mixture is manufactured at high temperature, the cooling rate is also high compared to Warm Mix Asphalt (WMA) (Kamarudin *et al.*, 2018).

In early 80s, Kennedy *et al.* (1984) carried out a study to examine the effect on the engineering properties of HMA with lower compaction temperature. The study was triggered by an investigation into premature rutting of a recycled asphalt pavement overlay that had met in-place density specifications although unusually low compaction temperature had been used. Field records indicated that the average delivery temperature to the roadway was 93°C. Laboratory experiments involved compacting samples over the range of temperatures during construction and determining the sample tensile strengths. The study deduced that low compaction temperature negatively affected on the properties of the HMA and hence led to the early pavement failure.

2.3 Asphalt Binder

Asphalt binder is a viscoelastic material. The word ‘viscoelastic’ refers to asphalt binder showing both viscous and elastic behaviour depending on factors like temperature and loading time. For instance, the same load introduced for a different duration will result in different properties being displayed by an asphalt binder. As with temperature, a load rate must be specified for asphalt binder tests.

Asphalt binder acts like a viscous liquid and flows at high temperatures, while it acts like an elastic solid at low temperatures as shown in Figure 2.1. In another words, it behaves as a lubricant when asphalt binder is heated, allowing the binder to be mixed with aggregate and mineral filler. The asphalt can behave as a glue after cooling to hold the aggregates together. At intermediate temperature, asphalt binder exhibits viscous and elastic characteristics which happen to be those in which pavements are expected to function (Yildirim *et al.*, 2000).

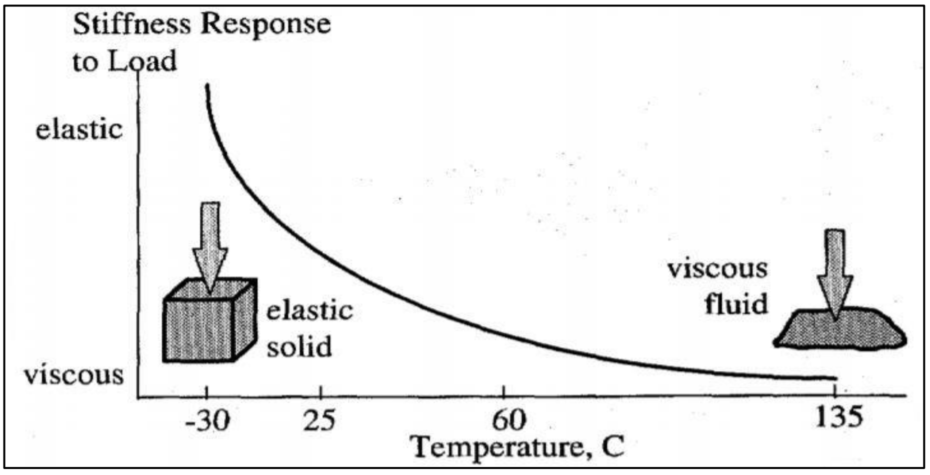

Figure 2.1: Visco-Elastic Behaviour of Asphalt Binder

(Source: McGennis *et al.*, 1995)

Asphalt binder is composed of organic molecules. It can react with oxygen from the atmosphere, this reaction is referred to as oxidation. Oxidation modifies the structure and composition of the asphalt molecules in such way that when an asphalt binder reacts with oxygen, it becomes harder and more fragile. At high temperatures, oxidation occurs even more quickly. It seems that a considerable amount of hardening takes place during HMA production, when the asphalt binder is merely heated to make mixing and compaction better.

Asphalt binders can be modified by adding polymers, chemical modifiers, extenders, oxidants and antioxidants, hydrocarbons or anti-stripping additives in order to alter and strengthen the asphalt properties for long-term pavement reliability. The modifiers may try to minimise temperature dependency and oxidative hardening of asphalt binder and the moisture susceptibility of the asphalt mixture by altering the properties of the asphalt binder (McGennis *et al*., 1995).

2.4 Adhesion Promoter

Adhesion promoter is a surface active material that concentrates at the interface between the aggregate surface and the bitumen.

Bitumen is a low-polarity oily material with low chemical affinity for aggregates, while the aggregates have high water affinity. This implies that bitumen can be easily displaced by water. Adhesion promoter works in a way that they displace most of the weakly adsorbed components of the bitumen to form strong chemical bonds to the aggregate surface as in Figure 2.2.

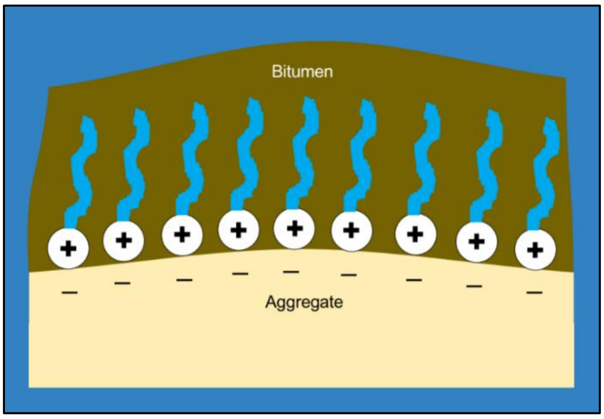

Figure 2.2: Adhesion Promoter Molecules Act as Bridge between Aggregate and Bitumen

(Source: Akzo Nobel N.V., 2019)

Aggregates are categorised as "acidic" type whose surfaces tend to be charged negatively, or "basic" with surfaces that tend to be charged positively. Acidic aggregates are high in silica, whereas basic aggregates contain carbonates. Bitumen particularly those of high acid value, tend to be negatively charged and adhesion problems occur with acidic aggregates in particular, but not solely.

Introducing adhesion promoter into the asphalt mixture can improve the chemical affinity between the bitumen and the aggregate. The adhesion promoter molecules rapidly find their way to the interface where they bind to the aggregate surface so strongly that the binder film can push away any water present. The head groups of the surface active agents are attached firmly to the aggregate surface. The hydrocarbon tails of the surface active agent molecules are compatible with the bitumen. Consequently, the adhesion promoter functions as a bridge between the bitumen and the surface which resists water action. Figure 2.3 shows the typical adhesion promoter molecule (Akzo Nobel N.V., 2019).

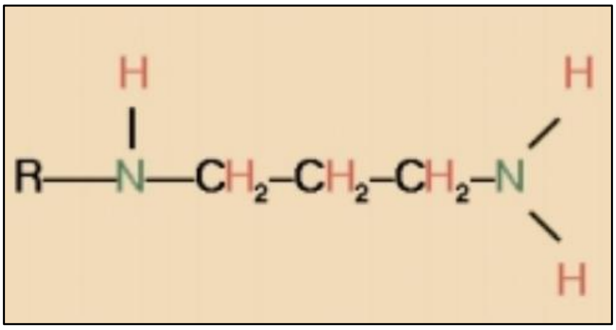

Figure 2.3: Typical Adhesion Promoter Molecule - Diamine Type

(Source: Akzo Nobel N.V., 2019)

2.5 Effects of Adhesion Promoter on Asphalt Mixture

2.5.1 Reduction in Age Hardening Rate

Bitumen undergoes oxidation process rapidly during the mixing process, during the storage of the mix and more slowly during the lifetime of the roadway. The effect of the oxidation causes bitumen to harden and loss in flexibility of the asphalt pavement that can result in cracking. However, due to the chemical nature of the adhesion promoter, it slows down the age-hardening of the asphalt binder.

From the study by Akzo Nobel N.V. (2019), the Rolling Thin Film Oven Test (RTFOT) simulated the hardening during mixing in the laboratory where the hot asphalt binder was subjected to an air stream. The viscosity of the asphalt binder was then compared to an untreated control. The slower age-hardening during road service life could be simulated through the Pressure Ageing Vessel (PAV) test. In this test, the bitumen was exposed to air in an autoclave and then compared its rheology with an untreated control.

From Figure 2.4, it showed the increase in stiffness of binders before and after RTFOT and PAV tests, as measured by the Dynamic Shear Rheometer (DSR), indicated the tendency to age during mixing and service. However, the study showed reduced age-hardening with treated binder with adhesion promoter, that resulted in less tendency to crack fatigue during the service life of the asphalt pavement.

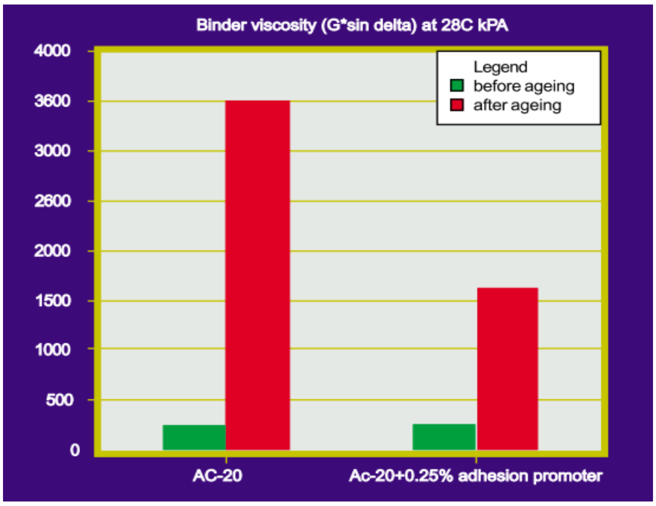

Figure 2.4: Binder Viscosity of Bitumen Before Ageing and After Ageing

(Source: Akzo Nobel N.V., 2019)

2.5.2 Mixing and Compaction

Adhesion promoters ease binder spread across the aggregate surface and facilitate to disperse mineral fillers in asphalt mixture. The result is less uncoated particles and a more consistent mixture which compacts easier. This contrasts with the addition of lime and cement fillers, which are sometimes used to improve the water resistance of asphalt mixtures, which tend to stiffen the asphalt binder and thus deter wetting and spreading during mixing. Then, a higher mix temperature or longer mix time may be required. (Akzo Nobel N.V., 2019).

Zhu *et al.* (2018) also studied on the effect of different types of adhesion promoters, namely M5000, Evotherm M1 (M1) and AD-here LOF-65-00 (LOF-6500) at different dosage rates on the rotational viscosity at 60°C of asphalt binder before and after RTFOT as shown in Figure 2.5. Before aging, three types of adhesion promoters showed an increased viscosity effect on the asphalt binder when the dosage was less than a certain dosage, but a decreasing viscosity effect occurred once the dosage exceeded a certain dosage. This was because with the presence of adhesion promoters, a chemical reaction between nitrogen groups of amine-based adhesion promoter and polar groups of asphalt binder could occur, forming compounds without anti-stripping property, leading to the increased viscosity. However, after RTFOT, three types of adhesion promoters clearly decreased the viscosity of asphalt binder compared with the control sample. This meant that the workability of the asphalt mixture with adhesion promoters was improved and so the compactability, thus resulted in a more thorough mixing and easy compaction.

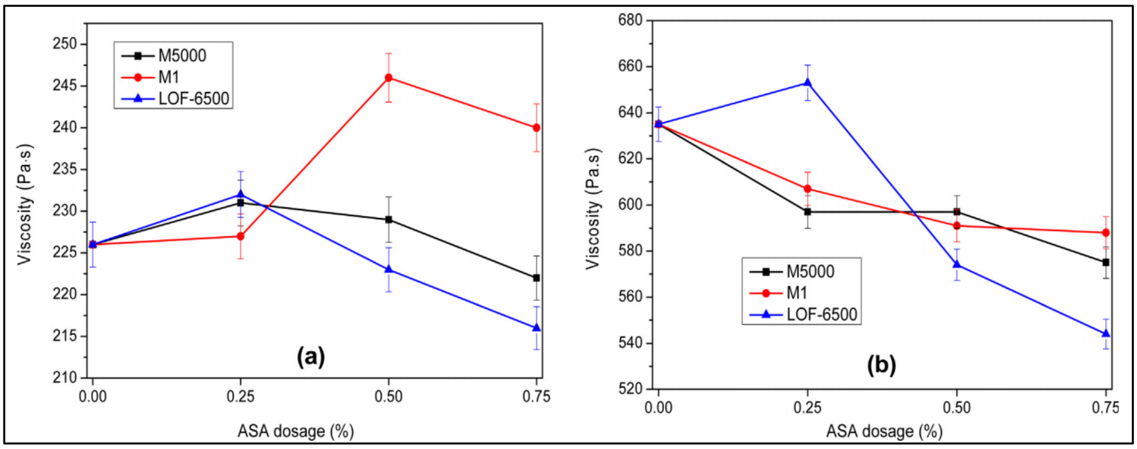

Figure 2.5: Rotational Viscosity of Various Binder at 60°C
(a) Before Aging (b) After RTFOT

(Source: Zhu *et al*., 2018)

2.6 Bonding Mechanism

2.6.1 Adhesion

Adhesion is defined as the intimate interfacial contact which holds two different bodies together so that mechanical force or work can be transferred across the interface. The interfacial force that hold both phases together can arise from the forces of van der Waals, chemical bonding or electrostatic attraction. Hefer and Little (2005) mentioned the fact that good bitumen-aggregate adhesion is a key matter for good performance is as old as the first bitumen bound macadam pavements built in the late 1800s. The main concern that would lead to large-scale research on the adhesion of bitumen to aggregate over the coming decades is adhesive failure caused by the water entering the asphalt mixture, known as moisture damage or stripping. Adhesive failure can be regarded as the displacement of bitumen from the surface of aggregates which may indicate a low adhesive bond strength (Jakarni, 2012). Theories for adhesive bonding mechanism are discussed in the following sub-sections (Ebnesajjad, 2009).

2.6.1.1 Mechanical Interlocking

Mechanical interlocking involves the mechanical gripping of the adhesive into the cavities, pores and asperities of the substrate surface on a microscopic scale. The 'lock and key' effect when the adhesive phase penetrates a pore in the solid substrate with physical anchoring (Figure 2.6). The trapped air at the interface is displaced by the adhesive. It is concluded that an adhesive penetrating into the surface roughness of two adherends can bond the two contributing to the good adhesive bond strength due to the mechanical interlocking between adhesive and the adherends. Adhesives often form stronger bonds to abraded porous surfaces than smooth surfaces (Clearfield, 1991).

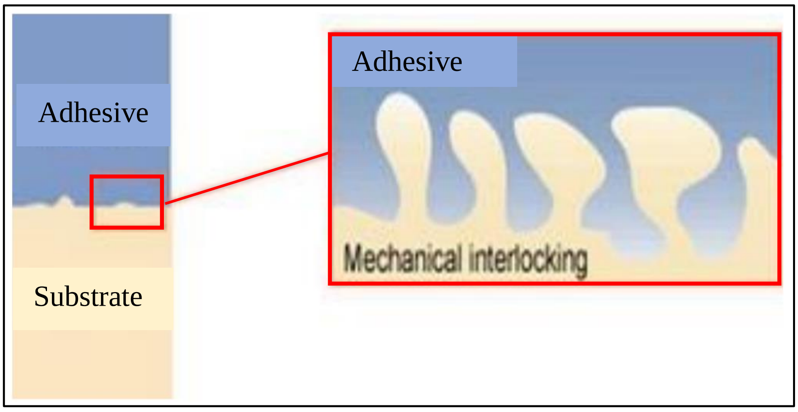

Figure 2.6: Mechanical Interlocking between Adhesive and Substrate

(Source: Clearfield, 1991)

2.6.1.2 Wetting

Wetting is the process of forming continuous contact between the adhesive and the substrate. Adhesion from wetting is resulted from molecular contact of two materials and the surface forces developing between them. The adhesive should have a lower surface tension for it to wet a solid surface than the critical surface tension of the solid. The complete and incomplete wetting of the spreading of the adhesive over the surface is illustrated in Figure 2.7. Good wetting is deemed when the adhesive flows into the valleys and crevices on the surface of the substrate. Poor wetting develops when the adhesive bridges over the valley and reduces the actual contact area of the adhesive and the adherend, leading to a lower overall joint strength. Incomplete wetting causes interfacial defects, thus adhesive bond strength is lowered (Ebnesajjad, 2009).

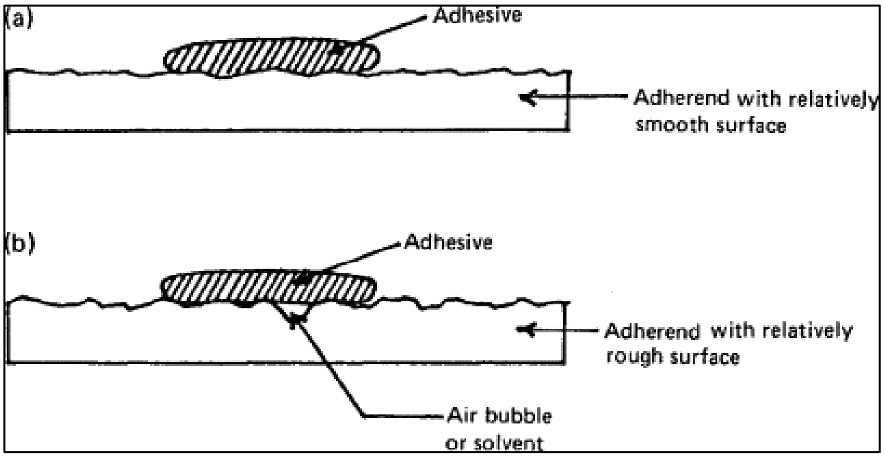

Figure 2.7:(a) Good and (b) Poor Wetting by An Adhesive Spreading Across A Surface (Source: Ebnesajjad, 2009)

2.6.1.3 Chemical Bonding

The bonding mechanism attributes the formation of an adhesion bond to surface chemical forces. There are generally four types of interactions during chemical bonding: covalent bonds, hydrogen bonds, Lifshitz–van der Waals forces, and acid–base interactions summarised in Table 2.1. Hydrogen, covalent, and ionic bonds between the adhesive and the adherends are stronger than the attractive forces of dispersion (Ebnesajjad, 2009).

Table 2.1: Energies of Lifshitz–van der Waals Interactions and Chemical Bonds (Source: Ebnesajjad, 2009)

Type	Example	E (kJ/ mol)
Covalent	C–C	350
Ion–Ion	$Na^+ \ldots Cl^-$	450
Ion–dipole	$Na^+ \ldots CF_3H$	33
Dipole–dipole	$CF_3H \ldots CF_3H$	2
London dispersion	$CF_4 \ldots CF_4$	2
Hydrogen bonding	$H_2O \ldots H_2O$	24

2.6.2 Cohesion

Cohesion, in general, is defined as an intermolecular force holding molecules together in a solid or liquid. Cohesive forces are the integrity of the material when subjected load or stress at the macro level of a compacted asphalt mixture. At the micro level, taking into account the asphalt film surrounding the aggregate, cohesion can be defined as a load deformation occurring at a distance from the aggregate surface and beyond the influence of mechanical interlocking and molecular orientation (Terrel and AI-Swailmi, 1994). One mechanism affecting moisture damage in HMA is the cohesive failure of the asphalt mastic bond. Cohesive failure happens because of the separation of molecules within the asphalt film. Cohesion loss typically occurs in asphalt mastic due to moisture. This failure can be due to two factors: weakening of mastic due to water diffusion into the bitumen and water migration via the mastic to the mastic aggregate interface (Cheng *et al.*, 2002).

Chaturabong and Bahia (2018) mentioned cohesion of mastics is a control factor in understanding moisture damage. Adhesive failures for well-coated and well-produced mixtures could only be secondary. Presuming that mastic cohesion is the main factor, more attention should be paid to the composition of mastic, including fillers and polymers. Mastic composition and water sensitivity controls are therefore required to ensure an acceptable level of pavement moisture resistance.

2.7 Bonding Failure to Asphalt Pavement

2.7.1 Moisture Damage

Tarefder and Zaman (2010) discovered that asphalt pavements are susceptible to moisture damage, it is one of the most common pavement distresses caused by moisture interaction with bonds in asphalt system. Kakar *et al.* (2015) wrote that the bond between asphalt aggregate constituents fails within the presence of water interacting at the interface, leading to the stripping of binder from the aggregate surface and cohesive failure among the asphalt binder. The adhesion and cohesion between the asphalt binders and aggregates are the forces holding the asphalt mixtures together. Moisture damage results in pavement failures such as alligator cracks, ravelling, potholing and rutting.

Arambula *et al.* (2007) mentioned the moistures can infiltrate into an asphalt pavement by permeation of rainwater, rising of groundwater table and absorption and adsorption of water vapour. According to Lytton *et al.* (2005), these are the factors affecting the resistance of moisture damage, such as asphalt film thickness, aggregate shape characteristics and surface energy, are discussed in the following sub-sections.

2.7.1.1 Asphalt Film Thickness

Moisture damage in asphalt mixtures occurs within the mastic (pure asphalt binder and the aggregate particles finer than 75 μm) or at the aggregate-mastic interface, the former is cohesive failure and the latter is adhesive failure. It is dependent on the thickness of the mastic around the aggregates and the nature of the mastic whether cohesive or adhesive failure would occur. A study on the relationship between asphalt binder film thickness and failure type has shown that for thinner asphalt binder film, the cohesive tensile strength is higher than the adhesive tensile strength whereas for thicker asphalt binder film the cohesive tensile is lower than the adhesive tensile strength (Figure 2.8). As the asphalt binder film thickness differs in every single asphalt mix, both adhesive and cohesive failure could happen with one of the failures being more significant (Lytton, 2004).

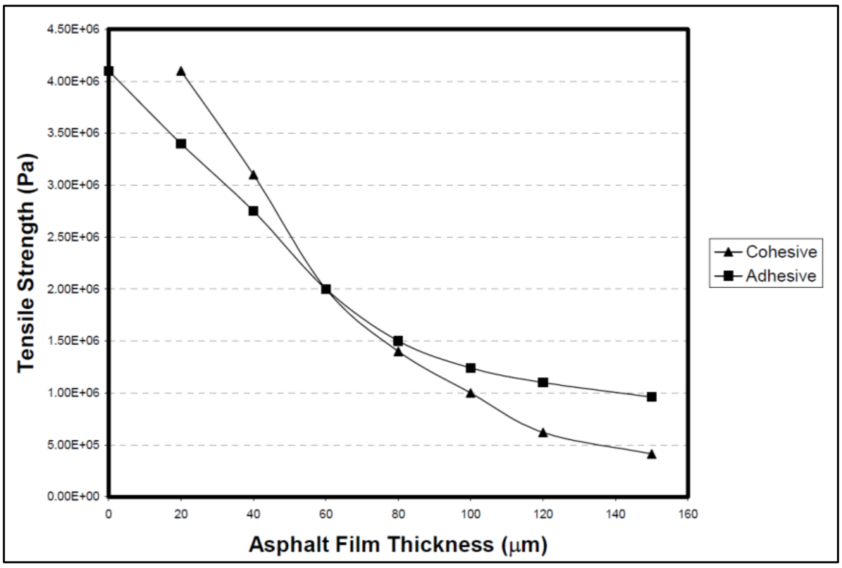

Figure 2.8: Tensile Strength versus Asphalt Film Thickness

(Source: Lytton, 2004)

2.7.1.2 Aggregate Shape Characteristics

Aggregate shape characteristics affect mechanical adhesion between the aggregates and asphalt binder. Masad *et al.* (2004) studied the aggregate particle geometry in terms of the shape properties namely form, angularity and surface texture using Aggregate Imaging System (AIMS) as shown in Figure 2.9. Cubical shape aggregate, increased aggregate texture and angularity consequently increase total surface area enhances mix resistance to deformation and the relative sliding between aggregates through the asphalt binder film, leading to increased total bond energy in the asphalt mix. Despite that aggregate angularity may increase the probability of puncturing the asphalt film causing intrusion of water to the asphalt- aggregate surface resulting in moisture damage.

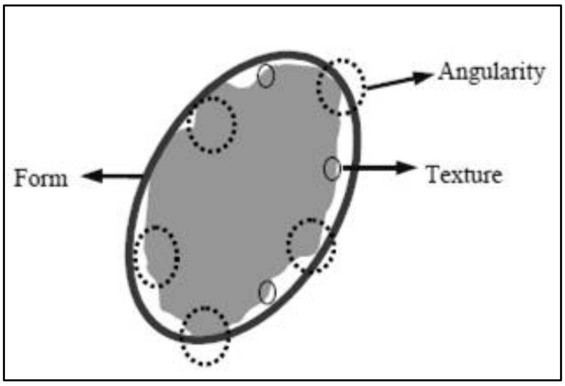

Figure 2.9: Components of An Aggregate Shape: Form, Angularity, and Texture (Source: Masad *et al.*, 2004)

2.7.1.3 Surface Energy

Surface energy is known as the amount of external work done on a material to create a new unit surface area in a vacuum. Materials like asphalts and polymers have low-energy surfaces; in other words, the solid's total surface energy is less than the liquid's total surface energy. When a liquid enters into contact with a low-energy surface for example, when an asphalt slide is immersed in a liquid probe, it forms a finite angle of contact measured at the boundary of the liquid meniscus and the solid. While the surface energy of water is much greater than the surface energy of the most common types of asphalt binders, therefore the water present at the interface of the asphalt binder and the aggregate tends to replace the asphalt binder, resulting in pavement distress related to bond failure called stripping (Bhasin *et al.*, 2006).

2.7.2 Stripping

Stripping is defined as the breaking of the adhesive bond between the aggregate surface and the asphalt binder in an asphalt mixture. Before complete disintegration, stripping can exhibit itself in several forms. Excessive deformation can occur because of a loss of shear strength; it can appear as cracking, rutting, corrugation or shoving. If stripping becomes excessive, loss of strength and excessive deformation can lead to the complete disintegration of the asphalt pavement such as potholes (Taylor and Khosla, 1983). Mechanisms such as detachment, displacement and pore pressure that cause stripping to happen are explained in the next sub-sections.

2.7.2.1 Detachment

Detachment is the separation of asphalt from aggregate surfaces with an intact asphalt coating intact (Majidzadeh and Brovold, 1968). The detachment is usually interpreted by the thermodynamic replacement of the asphalt by a thin film of water.

2.7.2.2 Displacement

Stripping by displacement results from water penetration through a break in the asphalt film to the aggregate surface. This break can initially be caused by incomplete coating of the aggregate or film rupture. Stripping by displacement occurs at the three phase interface between water, asphalt binder and aggregate (Majidzadeh and Brovold, 1968). This asphalt - water interface is retracted over the aggregate surface. It is believed that displacement is a function of viscosity, meaning that high viscosity binders have a higher resistance to displacement.

2.7.2.3 Pore Pressure

Porous pressure was suggested as a stripping mechanism in high-void mixtures where water can circulate freely via interconnected voids. Water can be trapped in impermeable voids that previously allowed water circulation when the mix is densified due to traffic loading. Further traffic loading may lead to high excess pore pressure in the trapped water causing the asphalt film to be stripped from the aggregate.

2.8 Serviceability Characteristics of Asphalt Mixture

2.8.1 Compaction Energy Index (CEI)

Compaction Energy Index (CEI) is defined as the area under the densification curve from the eighth gyration to 92% of maximum specific gravity denoted by G_{mm} as illustrated in Figure 2.10. Theoretically, CEI represents the work to compact the mixture by the roller to the permitted density during construction. The number of eight gyrations is selected as to simulate the effort applied by a typical paver during laying down the mixture process. The 92 % of G_{mm} is the density at construction completion and the pavement is open to traffic. Lower CEI value is preferred but CEI of too low value indicates that the mixture is tender should be avoided (Bahia and Faheem, 2004).

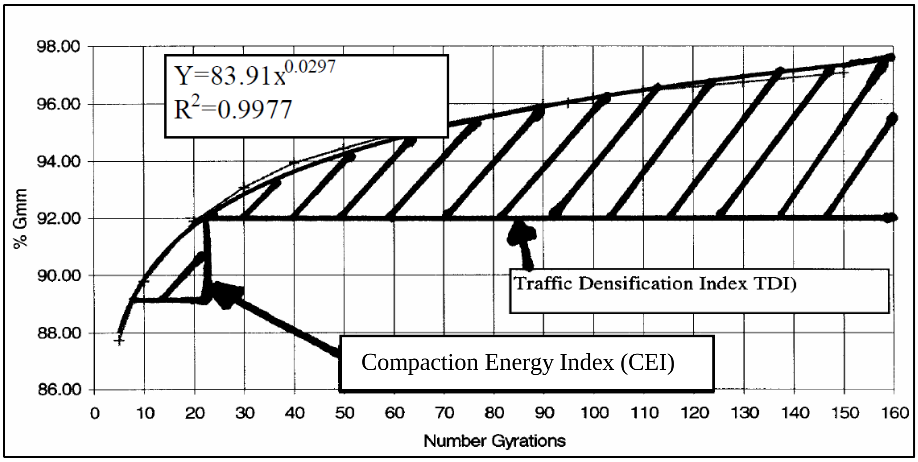

Figure 2.10: Illustration of CEI

(Source: Bahia and Faheem, 2004)

According to Goh and You (2012), the study assessed the CEI for porous asphalt mixture using warm mix asphalt (WMA) technology with and without reclaimed asphalt pavement (RAP). In both porous asphalt mixtures with and without RAP, the CEI was observed to be lower when WMA additive was added as shown in Figure 2.11. This showed that during construction, the energy used by WMA was lower, which was preferred over HMA. Porous asphalt mixtures with RAP also had a higher CEI as the stiffness of the asphalt mixture containing RAP was typically higher due to stiffer asphalt binder.

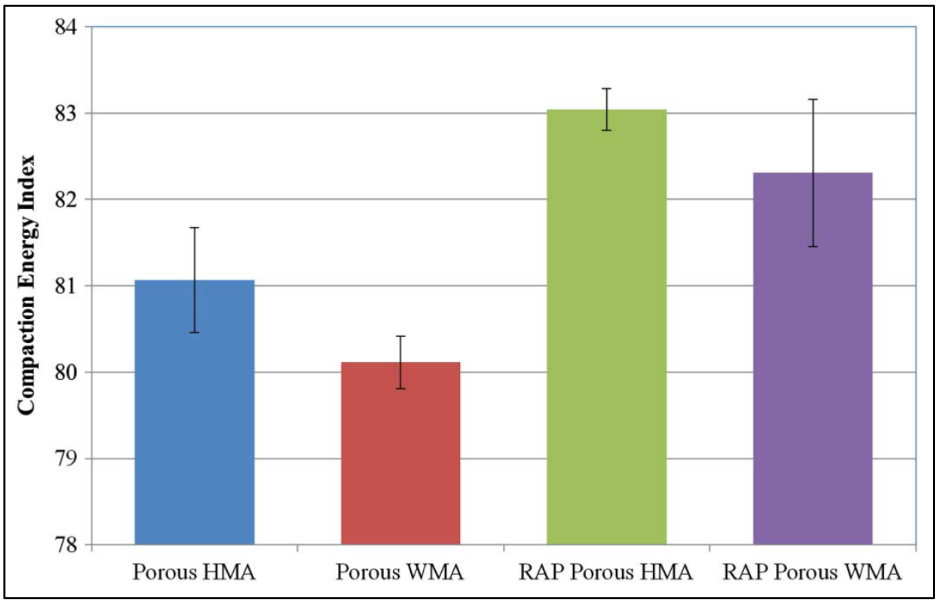

Figure 2.11: Compaction Energy for Porous Asphalt With and Without RAP
(Source: Goh and You, 2008)

2.8.2 Workability Index (WI)

Kamaruddin *et al.* (2010) stated that the workability of asphalt mixtures relies on factors such as binder content and its viscosity, aggregate types and the mixing and compaction temperature. Workability is defined as a property that enables the production, handling and compaction of a mixture with minimum energy use. As claimed by Cabrera (1991), the study quantified the workability of asphalt mixtures using Gyratory Testing

Machine (GTM). Firstly, the height reduction of the specimen was recorded at five revolutions interval during compaction. The heights recorded at five revolution intervals were used to determine the volume of the specimen. He also measured the specimen weight and together with data obtained, used for calculation of the porosity of the asphalt specimen at different levels of gyratory compaction. A graph relating the porosity at i number of revolutions (P_i) to log of the number of revolutions (log i) was drawn as Figure 2.12. The experimental points should approximate a linear relationship in the form as Equation (2.1).

$$P_i = A - b(\log i) \tag{2.1}$$

Where A and b are constants of the regression line.

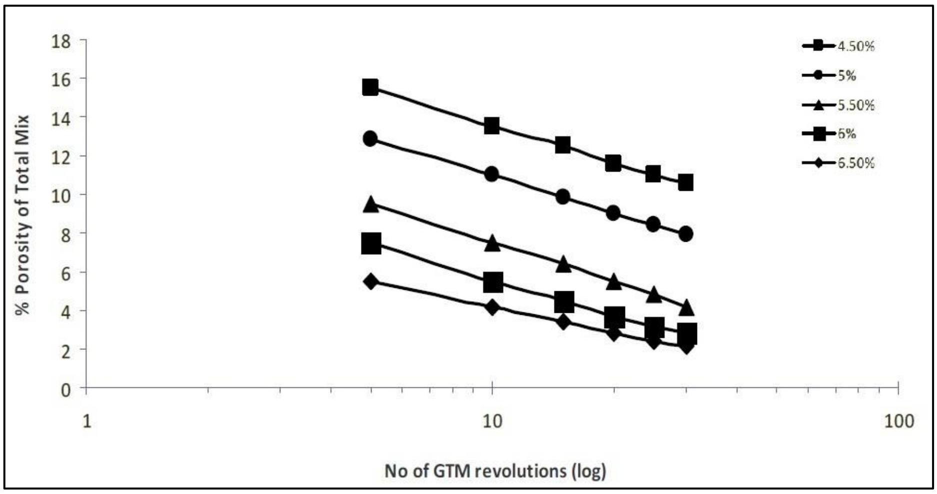

Figure 2.12: Porosity versus Number of GTM Revolutions for AC Mixtures
(Source: Kamaruddin *et al.*, 2010)

2.9 Static Test Method

Static test method is used for the purpose of assessment of affinity between aggregate and asphalt binder and its influence on the moisture susceptibility. However, there were several issues raised by the previous researcher Hugener *et al.* (2012), the study showed that the static test method was unsuccessful for the polymer modified binders and the hard bitumen 10/20, because complete coating was not possible and in some cases the coated particles did stick together and formed lumps. This was because in the BS EN 12697-11B, the mixing temperature of the asphalt binder and aggregates was 130°C and constant for all binders irrespective of the binder viscosity (BSI, 2012). This temperature was too low for hard binders and higher polymer modified binders.

In addition, the study mentioned that a water conditioning temperature of 19°C which was in accordance to BS EN 12697-11B did not cause any bitumen debonding from the aggregate for the bitumen sample studied. Wistuba *et al.* (2012) also stated that the standard test conditions were regarded as inappropriate and suggested to increase thermal stress to get a better differentiation of the asphalt binder coating on the aggregate. As the coating degree reduces with increasing conditioning temperature, the distinction between the studied binders would increase. It is vital for the comparison of the effects between different types of adhesion promoters on the bonding characteristics in asphalt mixture. Therefore, in this study, the conditioning temperature at 40°C is adopted instead of 19°C for 48 hours immersion in water.

2.10 Leutner Shear Test

Asphalt pavement is usually made of several layers of composition. Due to compaction difficulty offered by thicker lifts, asphalt pavements cannot be built in a single lift if the pavement thickness is greater than 2.5 - 3 inches. Asphalt pavements are therefore built instead in layers, making it unavoidable to have interfaces between layers. The life of an asphalt pavement, being a layered structure, relies not only on the strength and stiffness of its individual layers, but also on the bond between them (Mohammad *et* *al.*, 2010). Over the years, various test methods for assessing the degree of adhesion between two asphalt layers were presented.

Leutner shear test is used to assess bonding between pavement layers (Sangiorgi *et al.*, 2003). The Leutner test was invented in Germany in the late 1970s as a method of undertaking a direct shear test on the bond between two asphalt layers. The test specimen was performed on 150 mm diameter cores taken either from a pavement or made in the laboratory. Test specimens must be comprised of at least two layers and conditioned at 20°C for 12 hours. The test principle was to apply a constant shear displacement rate throughout the investigated interface and monitor the resultant shear force. A shear displacement rate of 50 mm/min was used so that Marshall loading devices can be used. A normal load was not applied to the specimen and a corresponding increase of the two variables was shown in the general trend of the curve shear stress-displacement (D’Andrea and Tozzo, 2012). This Leutner test arrangement as Figure 2.13 was simple but it suffered from non-uniform interface shear stresses (Collop *et al.*, 2009).

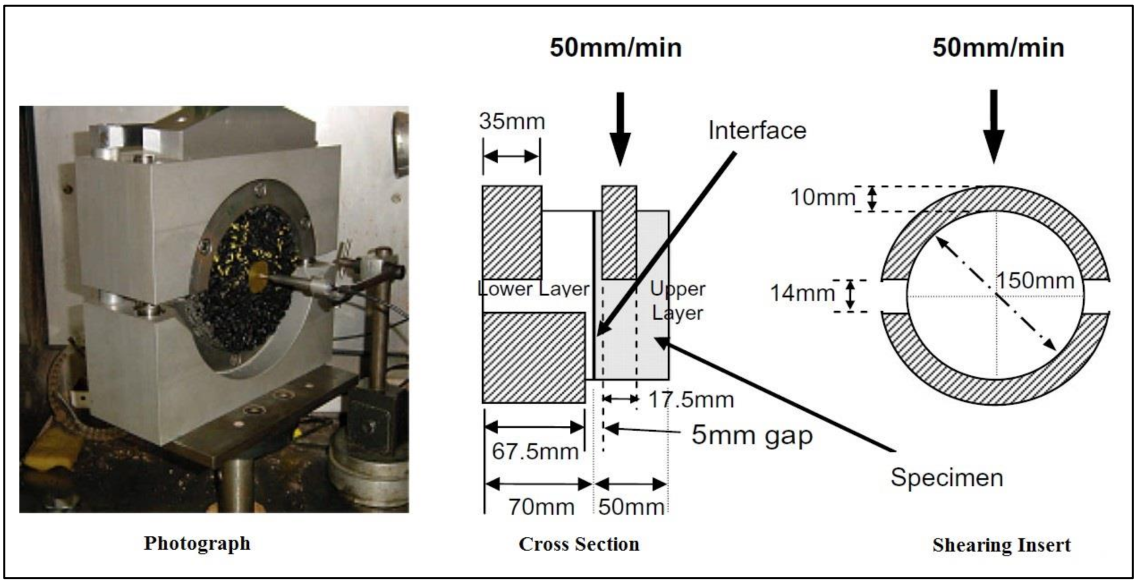

Figure 2.13: Photograph and Schematic Diagram of Leutner Load Frame

(Source: Collop *et al.*, 2009)