COATABILITY AND BONDING CHARACTERISTICS OF ASPHALT BINDERS MODIFIED WITH ALKYLAMINES-BASED AND POLYALKYLENE GLYCOL-BASED BONDING PROMOTERS

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SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2021

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By

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This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)

(CIVIL ENGINEERING)

School of Civil Engineering
Universiti Sains Malaysia

August 2021

Appendix A8

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2020/2021

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title**: Coatability And Bonding Characteristics of Asphalt Binders Modified with Alkylamines-Based and Polyalkylene Glycol-Based Bonding Promoters**

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2/8/2021

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Date: 2/8/2021

ACKNOWLEDGEMENT

In the name of Allah, and honor to Prophet Muhammad S.A.W, thanks for blessing and giving me the strength to complete my final year project.

First and foremost, I would like to express my appreciation to my supervisor, Assoc. Prof. Ts. Dr. Mohd Rosli Mohd Hasan, whose expertise, understanding, generous guidance and support made it possible for me to work on a topic that was of great interest to me. The completion of this study could not have been done without his guidance. I am very grateful that he constantly monitored and checked my progress to ensure that I am on the right track.

I would like to give the appreciation to all staff including the Dean, Professor Ir. Dr. Taksiah A.Majid, lecturers, and technical staffs at the School of Civil Engineering, Universiti Sains Malaysia, especially Mr. Mohd Fouzi Ali. I will always be grateful to them for helping me during my research as well as for all the useful advice. I would also like to thank the postgraduate students in the lab, particularly Hanizah Binti Osman and Mohd Fahmi Haikal Bin Mohd Ghazali for their time and effort to assist me during the laboratory works.

Next, I want to express my gratitude to my parents and family, who have provided me with unwavering support and motivation throughout the project's completion. Without their advice and support, this project might not have been completed. My thanks also go to my lab mates, Tracy Wong Leh Xin and Mok Tai Han, for being with me to face the hardship of doing the final year project. Finally, special thanks to my friends Anis Nazihah, Muhamad Shazarul, Kamal Safwan, Khairul, Hashim and Cheng Yi for helping me mentally during my final year project.

ABSTRAK

Asfalt konvensional digunakan secara meluas dalam penghasilan campuran asfalt. Kelemahan sifat reologi asfalt konvensional telah menarik minat para penyelidik untuk mengubahsuai asfalt dengan menggunakan pelbagai jenis bahan tambah atau pengubahsuai. Mekanisma dan fungsi pengubahsuai adalah bergantung kepada komposisi dan jenis bahan yang digunakan. Penggunaan peningkat ikatan sebagai pengubahsuai mempunyai kesan yang ketara dalam meningkatkan sifat reologi asfalt. Selain itu, prestasi ikatan asfalt juga boleh ditingkatkan. Dari sudut ekonomi, kaedah ini dikenalpasti bersesuain untuk meningkatkan jangka hayat turapan. Tujuan kajian ini dijalankan adalah untuk menilai kebolehlekatan dan ciri-ciri ikatan asfalt yang diubahsuai menggunakan peningkat ikatan yang berasaskan Alkylamines dan Polyalkylene Glycol. Peratus yang berbeza digunakan untuk kedua-dua peningkat ikatan iaitu 0.5% dan 1.0%. Prestasi asfalt yang diubahsuai telah dibandingkan dengan asfalt konvensional. Kerja-kerja penyelidikan makmal telah dibahagikan kepada tiga tahap. Tahap yang pertama adalah untuk mengkaji sifat fizikal asfalt yang telah diubahsuai dengan menjalankan ujian titik lembut, ujian penusukan, ujian kemuluran dan ujian pemulihan anjal. Seterusnya, penilaian prestasi kebolehlekatan asfalt diuji menggunakan ujian rendaman air statik dan ujian rebusan air. Penggunaan natrium karbonat telah disertakan bagi meningkatkan keadaan kerosakan kelembapan. Akhirnya, ujian tarik keluar dan ujian pemamptan ricih telah dijalan untuk menentukan prestasi ikatan substrat-asfalt. Keputusan sifat fizikal menunjukkan penggabungan peningkat ikatan telah mengurangkan nilai tusukan yang menunjukkan kebolehupayaan untuk meningkatkan pengerasan asfalt. Namun, gred penusukan untuk kesemua asfalt yang telah diubahsuai adalah masih dalam gred 60/70. Dalam konteks titik lembut, ianya tidak menunjukkan keputusan yang ketara apabila dibandingkan dengan asfalt

konvensional. Selain daripada itu, indeks kemuluran dan peratus pemulihan anjal menunjukkan peningkatan apabila dicampurkan dengan peningkat ikatan. Dalam konteks kebolehlekatan, ujian rendaman air statik tidak menunjukkan keputusan yang ketara, namun, dalam rebusan sodium karbobat, indeks kebolehlekatan untuk kesemua asfalt menurun dan keadaan ini boleh dikatakan sebagai keadaan kerosakan kelembapan yang paling teruk. Namun begitu, indeks kebolehlekatan sampel yang mengandungi peningkat ikatan adalah lebih baik jika dibandingkan dengan sampel kawalan. Ini menunjukkan bahawa kewujudan peningkat ikatan meningkatkan indeks kebolehlekatan. Manakala, keputusan prestasi ikatan substrat-asfalt, kedua peningkat ikatan mampu meningkatkan kekuatan tegangan dan menentang tegangan ricih.

ABSTRACT

Conventional asphalt binder is widely used in the production of asphaltic concrete mixture. The rheological weakness of conventional asphalt binder had developed the interest among researchers to modify conventional asphalt binder by using various kinds of additives. The function and mechanisms involved are relying on the type and composition of additives used. Bonding promoters is an additive in asphalt binder that has shown a significant effect in enhancing the rheological properties of asphalt binder. The bonding performance of the asphalt binder is well improved. Economically, this is the best modification to be done to increase the lifespan of the pavement. The aim of this study is to enhance the coatability and bonding characteristics of modified asphalt binders by using bonding promoters, namely Polyalkylene Glycol-based (PLG) and Alkylamines-based (ALM). Different percentages were used, which are 0.5% and 1.0% for both bonding promoters. The evaluation of modified asphalt binder performance was compared with the conventional asphalt binder. The laboratory study was divided into three phases. The first phase is to determine the physical properties of modified asphalt binder by conducting softening point test, penetration test, ductility test, and elastic recovery test. Then, followed by evaluation of coatability performance of modified asphalt binder using static water immersion test and boiling water test. The utilization of sodium carbonate solution was included to enhance the moisture damage condition. Lastly, the pull-out test and shear compression test were conducted to determine the asphalt-substrate bonding performance under severe moisture damage conditions. The results of physical properties showed that incorporation of bonding promoter reduces the penetration values which indicates the increment of the ability to stiffen the binder. However, the penetration grade of all modified binders is still within 60/70 range. In terms of softening point, the results show

no significant effect when compared to conventional asphalt binder. Apart from that, the ductility index and elastic recovery values show increment with bonding promoter. In terms of coatability performance, the static water immersion test shows no significant result. Still, under the action of boiling sodium carbonate, the coatability index of all modified asphalt binder reduces as the condition are considered as the most moisture damage condition. However, the coatability index is slightly higher than the control sample, indicating that bonding promoters are still enhancing the coatability performance. Based on the asphalt-substrate bonding performance, both bonding promoters can increase tensile strength and resist shear stress.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ALM	Alkylamines-based (Bonding Promoter)
ASTM	American Society for Testing and Materials
BBS	Bitumen Bond Strength
HMA	Hot Mix Asphalt
NIST	National Institute for Standardization and Testing
OD	Oven Dry
PATTI	Pneumatic Adhesion Tensile Testing Instrument
PG	Performance Grade
PI	Penetration Index
PLG	Polyalkylene Glycol-based (Bonding Promoter)
SFE	Surface Free Energy
SSD	Saturated Surface Dry
UTM	Universal Testing Machine

CHAPTER 1

INTRODUCTION

1.1 Background

Hot Mix Asphalt (HMA) technology is widely used in Malaysia. The asphalt mixture consists of aggregate, asphalt binder, and mineral filler. The strength of the pavement is determined by the layered portion of the pavement and the mixture's bonding strength and efficiency. The presence of asphalt binders in the mixture is crucial as it promotes bonding between materials. The bonding properties of asphalt binders and aggregate improve the mixture's strength. Thus, a strong bond between the aggregate and bitumen and the cohesion bond of the bitumen in the HMA are critical components of the asphalt mixture's strength. Additionally, it is well proven that an asphalt binder's adhesion and cohesion bond are strong indicators of an asphalt mixture's efficiency (Kanitpong and Bahia, 2005).

The interaction between particles at the interface of two substances is referred as the adhesion (Cihlářová et al., 2018). A bonding promoter can help with the adhesive bond between the aggregate and the asphalt binder and the cohesive bond of the asphalt binder itself. Bonding promoters are present in solid and liquid states where the characteristics of these states differ. Adhesion promoters are substances, primarily fatty acids or polyamides, that can improve the adhesion of the asphalt binder to the aggregates, extending the asphalt mixture's lifespan (Cihlářová et al., 2018).

This study was conducted to determine the coatability and bonding characteristics of the modified asphalt binders in the presence of a bonding promoter. An experimental study was carried out to quantify both bonding characteristics under several different moisture conditions.

1.2 Problem Statement

The cohesion bond within the asphalt binder and the adhesion between the binder-aggregates can be severely affected by the moisture. On the other hand, the aging of the pavement structure and material may also reduce bonding strength. Significantly, the most prevalent forms of distress in HMA are associated with the presence of moisture, and this has become a topic of debate among researchers. This is because water is the major cause of adhesion and cohesion failure, resulting in a stripping and raveling phenomenon between the binder and the aggregate. Moisture damage is also attributed to the lack of bonding between the asphalt and aggregate interfaces, as well as a decrease in the bonding within the asphalt binder itself. On the other hand, damage attributed to aging conditions can also cause pavement problems. This is because the bonding characteristics of the mixture may be reduced over time.

Theoretically, the presence of a bonding promoter in an asphalt mixture may enhance the binder and aggregate bonding properties. By its mechanism, the reduction of bonding strength due to the presence of moisture may be eliminated by enhancing the cohesion and adhesion bond. Other mechanisms that are possibly attributed to this bonding improvement include a reduction in asphalt binder viscosity, which results in a change in surface tension. Additionally, the cohesion and adhesion bond between the aggregate and asphalt binder is likely related to aggregate-binder bonding performance.

Problems that may arise due to moisture are keen to be examined and resolved to reduce the possibility of pavement distresses. The utilization of this additive has become a widespread asphalt binder modification technique. As a result, the study was conducted to prove that bonding promoters may reduce pavement distresses by enhancing aggregate-binder bonding properties.

1.3 Objectives

The main objective of this study is to identify the coatability and bonding characteristics of asphalt binder modified with bonding promoter. This study is carried out to accomplish the objectives as listed below:

1. To determine the physical properties of asphalt binder modified with bonding promoters.
2. To evaluate the effect of moisture conditioning on aggregate coatability.
3. To assess the effect of bonding promoters on the asphalt-substrates bonding performance based on the compression-shear and pull-out tests.

1.4 Scope of work

The experimental work of this research is limited to the usage of binder, aggregate, and bonding promoter, namely Polyalkylene Glycol-based (PLG) and Alkylamines-based (ALM). First, the properties of the asphalt binder modified with those bonding promoters were determined by using physical tests. On the other hand, modified asphalt binders are compared to conventional asphalt binders in terms of their properties. Besides, the effect of moisture on the aggregate coatability is also being identified by subjecting the sample to moisture conditioning to mimic the actual condition. The pull-out test and shear compression test were conducted in three different conditions which were dry, immersed in distilled water, and sodium carbonate.

1.5 Significant study

Nowadays, superior pavement and highway structures are highly desired to provide good serviceability to road users.

The high quality of the pavement is usually lead by a better interlocking bonding within the pavement materials. A good adhesion and cohesion bond within the asphalt mixture contributes to the quality of the road surfacing. Pavements are typically designed to support higher vehicle loading that requires greater structural integrity.

The application of bonding promoters in asphalt binder improves adhesion and cohesion bonding, leading to greater pavement durability. This sort of situation may allow a higher load demand on the pavement structure. This type of modification would therefore improve the mixture's ability to withstand moisture. Moisture resistance may aid in reducing the occurrence of unfavourable pavement conditions. Other than that, reduction of bonding is typically related to aging conditioning, where this kind of damage commonly occurs in Malaysia due to its tropical conditions.

In this study, coatability and bonding characteristics of the asphalt binder incorporating bonding promoters were evaluated. Although this type of modification technique is not widely used in Malaysia, it is required to gain a better understanding of this bonding enhancement technique. This research will cultivate new knowledge for the construction of high-load demand pavement within tropical climate countries, as well as reduce the likelihood of unfavourable premature pavement damage.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Typically, pavement technology in Malaysia uses the conventional binders for pavement construction purposes. Theoretically, it provides satisfactory performance in most constructed pavements. However, due to moisture and aging conditions, some undesired pavement distresses could happen. The aforementioned issues are significantly related to weather conditions that are continuous heat and heavy rain. Other than that, higher traffic volume and overloading could also lead to deterioration of pavements. Depletion of cohesion and adhesion bonding between binder-binder and binder-aggregate are part of the causes. Therefore, to overcome this phenomenon, the usage of the modified binder as additives is necessary to increase the bonding performance. Additives present in many forms and sources where it provides different usage and function. Lately, the use of additives has gained acceptance by researchers, and many approaches are adopted to assess the efficiency of this material. In this study, polymer-based bonding promoters are proposed to enhance the cohesion and adhesion bonding performance of asphalt binders, thus improving the strength and durability of pavement.

This chapter presents a comprehensive review of the asphalt binder, using an additive to improve bonding in asphalt mixtures. It also included a review on the bonding type and failure characteristics, bonding failure mechanisms, and evaluation methods for evaluating bonding performance.

2.2 Asphalt Binders

Asphalt binder is known as a viscoelastic material that acts as a binding agent in asphalt pavements. Generally, most asphalt binders used in commercial paving applications are produced from the distillation of crude oil. Additionally, various types of refining techniques are available to suit the source of crude oil. Asphalt typically consists of oxygen, nitrogen, sulfur, and other heteroatoms where this kind of composition varies with their source of crude oil. In terms of its composition of elemental, a common binder comprises 90-98% by weight of hydrocarbons. The hydrocarbons represent in the form of saturated branched or unbranched alkanes and cyclic alkene as well as unsaturated aromatics (Little et al., 2018). Similar to what being stated by Abdullah et al. (2016), this kind of material is related to a colloidal system where this system is made up of asphaltenes micelles covered with stabilizing phase of polar resins. However, although the chemical composition of bitumen is very complex due to the different structures of the individual molecules that create a bitumen, it is nearly possible to separate the bitumen into several compositions, which are aromatic, saturate, resin and asphaltenes. Aromatic and saturate have soft components, while resins and asphaltenes have hard components. The hard components of resin and asphaltenes are also found to contribute to the stiffness of the asphalt binder.

2.2.1 Modified Binders

A modified binder is the combination of a mixture produced from an unmodified base binder with a certain type of additives or modifiers. The main purpose of modification of binder is to enhance the rheological and mechanical properties of modified asphalt binders itself. Thus, the use of additives was expected to lead to a better binder in terms of its ability to withstand damage. Eventually, this is depends on the types and portions of the usage of additives (Abdullah et al., 2016). In other words, different types of additives or modifiers will eventually produce different functions of modified binders. Production of modified binders is vary based on the different type of additives used. Generally, the modification technique of the modified binder is by directly added the additive into the mixture. Somehow, other modification techniques can be used by adding the additive directly to the base binder (Aksoy et al., 2005).

2.3 Application of Additives to Improve Bonding in Asphalt Mixtures

Over the years, various additives being manufactured and accepted by most road authorities as it can help to improve the bonding properties in asphalt mixtures. Besides, various portions of additives being used where this percentage values by weight of asphalt binder are usually recommended by the manufacturer (Zhu et al., 2018). However, several assessment approaches are keen to be conducted in a way to evaluate the optimum dosage of additives needed to improve bonding in asphalt mixture. Other than that, the dosage also depends on the aggregate and bitumen used (Aksoy et al., 2005). Additive to asphalt mixture has been categorized in many ways, such as its type and purposes. Several types of additives and their examples are summarized in Table 2.1.

Table 2.1: Type and examples of Additives

Type of Additives	Example	References
Anti-stripping agent	Wetfic I Lilamin VP 75P Iterlene in/400 Amines Limes EVOTHERM M1 (M1) Adhere LOF-65-00 (LOF-6500)	(Aksoy et al., 2005) (Nazirizad et al., 2015) (Little et al., 2018) (Zhu et al., 2018)
Surfactant	Rediset® Cecabase®	(Pereira et al., 2018) (Kakar et al., 2015)
Bonding Promoter	Paved Bond Lite (PBL) Morlife 5000 Amine-based Promoters	(Sheng et al., 2019) (Cihlářová et al., 2018)

2.3.1 Anti-Stripping

Stripping is one of the premature failure modes that lead to other pavement distresses. Stripping occurs due to the presence of moisture due to incomplete drying or any other sources of moisture after construction (Aksoy et al., 2005). It is also evident that moisture is one of the primary contributors to stripping. Nazirizad et al. (2015) also stated that water penetration through pavement surfaces causes bonding failure between bitumen and aggregate particles. This phenomenon may further result in the stripping and raveling of the pavements. Many types of anti-stripping agents are used to prevent the depletion of bonding between those particles, and their efficacy has been demonstrated by numerous researchers (Behiry, 2013). It is also stated that anti-stripping agents could increase the asphalt pavement's resistance to stripping.

The main purpose of the anti-stripping agent is to minimize the stripping of asphalt bitumen from aggregates (Little et al., 2018). Besides, the presence of anti-stripping agents may increase the bond between aggregates and bitumen. Additionally, it will also increase bitumen wetting resistance and reduce bitumen surface tension (Nazirizad et al., 2015). Thus, asphalt-aggregate with better bonding and appropriate bitumen coating resistance is required in pavement technology, as this type of modification would produce a good asphalt pavement. Wetfic I, Lilamin VP 75P (Aksoy et al., 2005), Iterlene In/400 (Nazirizad et al., 2015), Amines, Limes (Little et al., 2018), and Adhere LOF-65-00 (LOF-6500) (Zhu et al., 2018) are some of the anti-stripping agents being used widely, with some assessment approaches being conducted. Although there are several anti-stripping agents in the industry, their feasibility and performance must always be assessed. This is also intended to be done in such a way that the best dosage is used.

2.3.2 Surfactant

The utilization of surfactants has been one of the common modification techniques in asphalt pavement technology and is widely accepted by most researchers and engineers. This is because Kakar et al. (2015) stated that usage of these additives can improve the coating of aggregate particles, compaction, and workability during the mixing and laying process. In terms of its mechanism, surfactants will typically reduce asphalt surface energy and improve their wettability over the surface of aggregate particles (Kakar et al., 2015). Theoretically, as the surface tension or surface free energy (SFE) of the adhesion decreases, so does aggregate wettability. In another perspective, aggregate wettability can also be associated with the contact angle of the asphalt binder. This is because a higher contact angle of the asphalt binder will reduce wettability, as shown in Figure 2.1. In other words, a small contact angle between binder and aggregate will significantly increase the wettability surface. It is important to keep the asphalt's ability to wet the aggregate because this can result in a good bond between the asphalt and the aggregate.

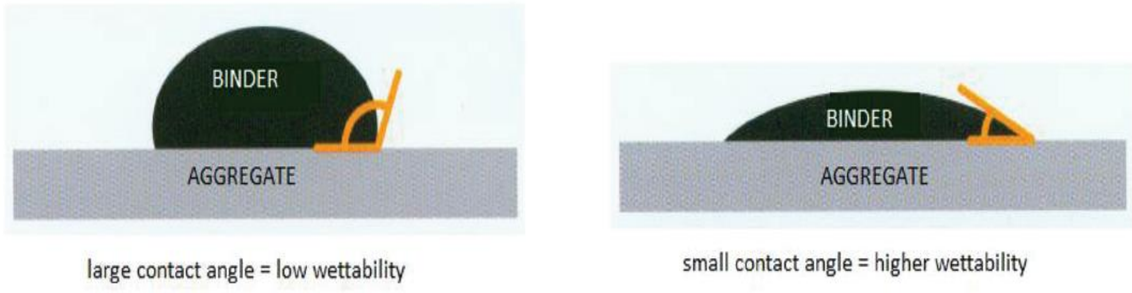

Figure 2.1: Asphalt binder contact angle (Source: Cihlářová et al., 2018)

On the other hand, it is also known that bitumen's mechanical and rheological properties are unaffected by the addition of a chemical surfactant. Besides, according to Pereira et al. (2018), the application of surfactant chemical additives was found to be the most economical and simple to be applied. Surfactants such as Rediset® (Pereira et al., 2018), Cecabase® (Kakar et al., 2015) are widely used and assessed by many researchers. Based on their study, it is also stated that those additives are efficient and suggested to be used in asphalt pavement technology.

2.3.3 Bonding Promoter

Good adhesion and cohesion bonding in asphalt mixtures is a desired way to provide asphalt pavement with better strength and durability. The enhancement of the cohesion and adhesion bond between the asphalt binder and the aggregate is closely linked to the utilization of bonding promoters. On the other hand, moisture damage, as a common bonding problem on asphalt pavement, remains a point of discussion among experts. The feasibility of using a bonding promoter as an additive in an asphalt mixture has been evaluated and assessed by many researchers. This modification technique could resist damage due to moisture. According to Cihlářová et al. (2018), adhesion bonding promoters are chemicals that influence the interface between an organic polymer and an inorganic substance, resulting in a stronger adhesion bond between the two materials.

In terms of its mechanism, asphalt binder improves aggregate surface area by lowering viscosity and changing surface tension, resulting in a strong bond between the asphalt binder and aggregates. On the other hand, an efficient bonding promoter is related to a reduction in contact energy between the mineral aggregate and asphalt binder. As demonstrated by Rossi et al. (2017), an effective adhesion promoter would reduce the contact energy between the bituminous polar liquid phase and the solid mineral phase through intermolecular interactions between residual water and the polar aggregate surface.

It has also become challenging to prove this additive's efficiency because some of the assessment approaches are conducted in a quantified way. Paved Bond Lite, Morlife 5000 (Sheng et al., 2019), Amine-based adhesion promoters (Cihlářová et al., 2018) were some of the bonding promoters used and assessed. They have also performed many tests to determine the best dosage of bonding promoter. The optimal dosage of the bonding promoter must be determined to obtain an effective bonding characteristic.

2.4 Bonding Types and Failure Characteristics

2.4.1 Cohesion and Its Failure Characteristics

A cohesion bond is characterized as a bonding mechanism that is presented within the molecules of the asphalt binder. Based on Chaturabong and Bahia (2018), an intermolecular force that holds molecules in a solid or liquid together is defined as cohesion. On the other hand, Tan and Guo (2013) stated that the cohesive bond of asphalt is defined by the capability of the asphalt molecular structure to resist deformation. Over the years, many assessments have been conducted by many researchers to quantify this bonding characteristic. The evaluation methods regarding asphalt cohesion are commonly related to its rheological indicators and mechanical indexes. Based on Tan and Guo (2013), viscosity can be categorized as rheological indicators, while tensile strength includes mechanical indexes.

Unfortunately, failure of cohesion bond commonly occurs in the asphalt mastic. The cohesion failure characteristics are typically due to moisture. To be precise, cohesion failure happens due to the deterioration of the bond between molecules in the asphalt film due to the presence of moisture (Moraes et al., 2011). The weakening of the mastic due to diffusion of water into the asphalt as well as the migration of water through the asphalt may be the factors of the cohesion failure (Chaturabong and Bahia, 2018). Additionally, the emulsification process can also be included as one of the cohesion failure mechanisms. If the emulsification effects reach the aggregate surface, a cohesive failure mechanism can lead to an adhesive failure (Canestrari et al., 2010).

2.4.2 Adhesion and Its Failure Characteristics

Adhesion is classified as the interface bonding between asphalt and aggregate particles. According to Cihlářová et al. (2018), the attractive interaction between the particles at the interface is induced by the contact of a solid substance with another solid, liquid, or gas substance, where this attractive power is called adhesion. Mechanical theory, chemical theory, weak boundary theory, and thermodynamics theory are also theories that fundamentally explain the adhesive bond between the asphalt binder and the aggregate (Moraes et al., 2011). To be precise, Cihlářová et al. (2018) classified every interaction that exists significantly on every proposed theory, as shown in Table 2.2.

Table 2.2: Adhesion models between asphalt aggregate and binders (Source: Cihlářová et al., 2018)

Theory	**Interaction**
Weak Boundary Layer theory	Layering
Mechanical theory	Interlock
Chemical theory	Covelent and ionic bonds
Thermodynamic theory	Surface energy

Theoretically, there are two types of adhesion of asphalt mixture, namely passive and active. When an asphalt binder and an aggregate have active adhesion, the binder may displace water from the aggregate's wet surface. In contrast, passive adhesion is caused by some external force mechanism and is defined as resistance to water penetrating a system (Cihlářová et al., 2018). Adhesion bond between asphalt binder and aggregate may also be described by its bonding strength. Additionally, the adhesive strength is influenced by the relative capacity of functional groups to adsorb at the aggregate surface and the relative desorption by water (Rossi et al., 2017).

Despite its bonding mechanism, the asphalt-aggregate adhesion bond can also exhibit its failure characteristics. Adhesion failures include pore pressure, displacement, infiltration, and boundary layer damage models (Cihlářová et al., 2018). Although there are many failure characteristics of adhesion bonds, the only thing that all these mechanisms have in common is that they are all affected by water. Based on Rossi et al. (2017), since water is a bipolar liquid, water molecules are drawn to the hydrophilic surface of the aggregate, resulting in the gradual displacement of non-polar asphalt binder from the aggregate's surface. In other words, adhesion failure is described as the separation of the asphalt coating from the aggregate when the action of water takes place at the asphalt-aggregate interface. This will consequently reduce adhesive strength between asphalt and aggregate surface (Canestrari et al., 2010).

2.5 Mechanism of Bonding Failure

2.5.1 Moisture Damage

Moisture damage is considered one of the most common causes of severe pavement deterioration in HMA. The presence of moisture minimizes the service life of the asphalt mixture and results in many pavement distresses such as alligator cracking, raveling, and potholes (Kakar et al., 2015). Moisture damage can be defined as the loss of strength or stiffness in asphalt mixtures due to the presence of moisture (Moraes et al., 2011). Theoretically, moisture damage is strongly linked to the cohesion bond, which involves the internal cohesion of the asphalt matrix. In contrast, the adhesion bond is related to the interaction strength between aggregate and bitumen (Aguiar-Moya et al., 2015). Additionally, moisture damage significantly affects internal structure bonding and consequently results in pavement degradation (Park et al., 2020).

According to Kakar et al. (2015), the mechanism of moisture damage can be classified into two major steps. The first one is moisture transport, where moisture in either liquid and vapor infiltrates into the asphalt mixtures as well as asphalt binder and further reaches the asphalt binder-aggregate interface. Secondly, changes in the internal structure of the material will result in depletion of load-carrying capacity. However, moisture damage is commonly not limited to one mechanism but exhibits in a combination of many mechanisms (Park et al., 2017). Detachment, spontaneous emulsification, displacement, pore pressure-induced damage, hydraulic scour, and environmental effect are among the mechanisms involved.

2.5.2 Aging and Oxidation

The aging condition may lead to a reduction of bonding properties, thus reducing the pavement strength. The aging process in asphalt pavement occurs in two stages which are short-term and long-term aging. According to Xu and Wang (2017), the short-term aging process initiate by the time asphalt is subjected to heat and air during the production and paving process. On the other hand, long-term aging occurs over the service life of road pavement. With the advancement in the design life, aged roads deteriorate and result in a reduction of their performance characteristic (Kumbargeri and Biligiri, 2016). This is because long-term aging caused asphalt binders to stiffen and embrittle, which leads to a high potential of cracking (Park et al., 2020). Additionally, negative consequences associated with the aging process can be predicted through the bonding characterization material, which is the asphalt binder and aggregate (Aguiar-Moya et al., 2015).

In terms of chemicals, oxidation of asphalt binder is also highly related to the aging process. Exposure of asphalt binder in pavement mixture towards oxygen may result in oxidation of its chemical composition (Qu et al., 2018). The reaction process between oxygen and reactive components of asphalt leads to changes in its physical and mechanical properties. To be more precise, the oxidation process of asphalt binder is attributed primarily to the introduction of polar. Then, chemical functions on asphalt molecules that contain oxygen increase molecular interactions, and some aromatization of asphalt molecules may arise due to this process (Petersen, 2009). The changes in chemical composition would eventually improve asphalt hardening. Although asphalt hardening could benefit pavement durability, aging could be harmful to pavement distresses that lead to premature pavement failure.

2.6 Assessment Approaches to Evaluate Bonding Performance

2.6.1 Pneumatic Adhesion Tensile Testing Instrument (PATTI)

The National Institute for Standardization and Testing (NIST) was the first to develop PATTI. The main objective of this test is to induce tensile force to test the coating-substrate system's pull-off strength (Canestrari et al., 2010). A part of the asphalt binder is placed on a metal pull-stub and pressed onto a prepared aggregate surface immediately in the PATTI procedure. Pulling force exerted by using the pneumatic system is produced by reaction plates screwed to the pull-stub. The pulling force is further increased until the failure occurs when the cohesive strength of asphalt is reached. The recorded failure force will then be converted into pull-off tensile strength (kPa). However, modified PATTI was implemented by improving the pull-stub with a 0.2 mm thick perimetrical edge. Modified PATTI has also been shown to be a reliable and practical approach for examining the bonding properties of asphalt aggregate bonding (Canestrari et al., 2010). A precise and convenient method is important to determine cohesion and adhesion bonding properties to obtain better laboratory results.

2.6.2 Luetner Shear test

The Luetner Shear test was invented in Germany by R. Luetner in 1979. The purpose of this test equipment is to assess the bonding between pavement layers. Luetner Shear tester is carried out on cores with a diameter of 150 mm either taken from a pavement or produced in the laboratory. The test's theory is to apply a constant rate of shear displacement across the interface while monitoring the shear force that results. Based on Sudarsanan et al. (2018), no usual force was applied to the interface on the interface. After many assessment approaches, the Luetner test's theory and use as a bond evaluation test can be claimed as the most relevant method.

2.6.3 Bitumen Bond Strength Test

Bitumen Bond Strength Test (BBS) is an assessment approach to evaluate the asphalt-aggregate bond strength. BBS is a modified version of the original PATTI and performed in accordance with AASHTO TP-91. A portable pneumatic adhesion tester, pressure hose, piston, reaction plate, and a metal pull-out stub make up the system device of BBS (Aguiar-Moya et al., 2015). During the test, the metal stub exerts a pulling force on the specimen. When the applied stress surpasses the binder's cohesive strength or the bond strength of the binder-aggregate contact, failure occurs. The BBS test is also said to effectively measure the effects of moisture conditioning time and modification on the bond strength of asphalt-aggregate systems (Moraes et al., 2011).

2.6.4 Static Water Immersion Test

The objective of the water immersion test is to determine the percentage of asphalt binder that remained coated after being immersed in water. This kind of assessment being conducted according to BS EN 12697-07 (BS EN, 2007). Water immersion tests are closely related to the assessment of aggregate coatability. Coatability of asphalt mixtures is defined as the degree of coating of the aggregates by the asphalt binder. Yin et al. (2014) stated that well-coated aggregates are likely to have a stronger bond between the particles and the binder. According to Sheng et al. (2019), partial removal of the coated film due to water infiltration between the thin asphalt binder film signifies the adhesion strength between aggregates and the asphalt binder is weak. It is also stated that the degree of coating for each mineral aggregate is assessed by a visual method.

2.6.5 Boiling Water Test

The boiling water test is used to assess the loss of adhesion in loose asphalt mixtures caused by the action of boiling water. This test is carried out according to ASTM D3625 (ASTM, 2013). Practically, a loose mix is desired to conduct this test. Due to the utilization of loose asphalt mix, the requirements for this test are simpler and less expensive to run. However, defining the passing or failing criterion of this test is quite difficult. This is because the observation of this test is conducted by a visual method. Thus, to overcome this issue, computer tools imaging is used to assess the results obtained efficiently. Amelian et al. (2014) used digital image analysis to transform the subjective rating into a more objective evaluation.

2.7 Summary

The literature review shows that the mechanism of aggregate and asphalt binder failure is mostly related to moisture, especially when considering pavement in the tropics. It can also be summarized that many additives are being used widely as every type of additive possesses a different function and characteristic. The adhesion and cohesion bonding characteristics are also widely being assessed by many researchers. In this chapter, suitable assessment approaches were also discussed and studied related to the bonding of asphalt and aggregate. A detailed laboratory experiment should be done specifically on the utilization of bonding promoters to better understand the bonding characteristics in terms of adhesion and cohesion bonds.

CHAPTER 3

METHODOLOGY

3.1 Overview

An experimental approach was used in this study. Modified asphalt binder with PLG and ALM was prepared to evaluate their properties. On the other hand, the preparation of a loose asphalt mixture using conventional and modified asphalt binders also took place. The control sample used is a typical asphalt binder with a 60/70 penetration grade. The comparison between the control sample, asphalt binder modified with PLG, and ALM was notable for this research. The first part of this testing was to determine the binder properties of the control (60/70), asphalt binder modified with 0.5% and 1.0% of PLG and ALM. Properties such as ductility, softening point, and penetration grade were conducted. The second part of this testing was to determine the coatability index of the prepared loose asphalt mixture. Water immersion and boiling water tests were also performed. The compression-shear and pull-out tests were also used to evaluate the asphalt-substrate bonding performance under different moisture conditions.

Figure 3.1 represents an overview of the research methodology of this study. The experimental laboratory begins with the preparation of loose asphalt mixture and modified asphalt binder samples by using aggregate, asphalt binder and certain amounts of bonding promoter. In terms of the coatability test, a loose asphalt mix is required. On the other hand, modified asphalt binder samples are required to conduct both binder properties and asphalt-substrate performance tests.

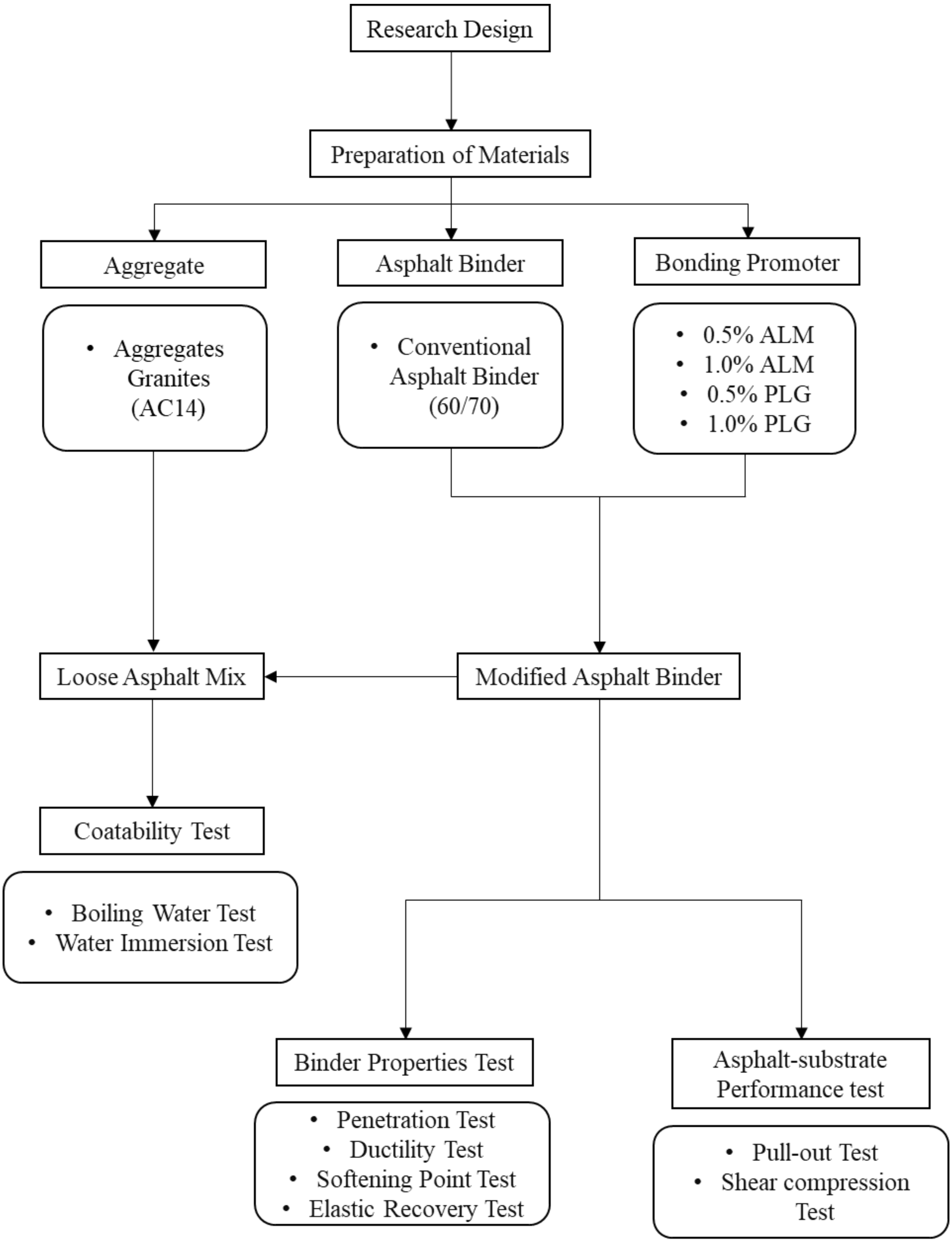

Figure 3.1: Flow chart of Research Methodology

3.2 Preparation of Materials

3.2.1 Asphalt Binder

Asphalt binders can be classified based on their penetration grade and its behavior. Over past decades, different binder with different penetration grade and performance characteristics are often used in pavement construction (Aliha & Shaker, 2020). Several standard grades of asphalt binder are available. Typically, binders with penetration grade 60/70 are classified as a conventional binder. On the other hand, conventional asphalt binders can be described based on other properties such as ductility, softening point, and specific gravity. These kinds of properties were also standardized through each specific laboratory test. Significantly for this study, a conventional asphalt binder with 60/70 penetration grade is used. Other than that, the asphalt binders used were obtained from Kamunting Premix Plant Sdn Bhd.

Additionally, this type of binder is also used as a control sample. The physical properties of the asphalt binder used in this study are summarized in Table 3.1 shown below. Theoretically, at room temperature, bitumen is a semi-solid material that must be heated before it can be used for the mixing and testing process.

Table 3.1: The Physical Properties of the Conventional Asphalt Binder

Test	Standard	Standard Requirement	Result
Penetration	ASTM D5	60-70	66
Softening Point	ASTM D36	42-52	46
Penetration Index (PI)	-	-2 to 2	-1.745
Ductility	ASTM D113	>100	>100
Elastic Recovery Test	ASTM 6084	>10%	10
Performance Grade (PG)	ASTM D6373	-	64

3.2.2 Aggregate

The physical properties of the granite aggregates used are summarized in Table 3.2. The granite aggregates were taken from stockpiles and washed. Before preparing a loose asphalt mixture, 10 mm granite aggregates were sieved through a 9.5 mm sieve and retained at a 6.3 mm sieve. The aggregates were heated for 24 hours before the mixing process. Prior to coatability test, the aggregates coated with binders were heated for 2 hours before the test to make sure the binders fully coat the aggregates.

Table 3.2: Granite Aggregate Properties

Properties	**Results**	**Test Methods**
Aggregate Crushing Value (%)	23.26	BSI 812-110
Flakiness Index (%)	22.81	BS 812-105
Elongation Index (%)	31.19	ASTM 4791-10
Loss Angeles Abrasion Value (%)	23.07	AASHTO T96
Coarse Aggregate Specific Gravity		
Oven Dried (OD)	2.593	AASHTO T85
Saturated Surface Dry (SSD)	2.61	
Apparent	2.637	
Water Absorption (%)	0.635	
Fine Aggregate Specific Gravity		
Oven Dried (OD)	2.533	AASHTO T 84
Saturated Surface Dry (SSD)	2.579	
Apparent	2.655	
Water Absorption (%)	1.825	

3.2.3 Preparation of Modified Asphalt Binder

The utilization of bonding promoters in asphalt pavement has been recently developed and adopted for road construction on certain countries. The presence of a bonding promoter as an additive in an asphalt mixture could improve the bonding characteristics. On the other hand, this modification could minimize the amount of damage caused by moisture and aging. Improvement of cohesion and adhesion bonding characteristics between asphalt and aggregate are highly related to this bonding promoter. Therefore, this study focused on the utilization of bonding promoter by mean of aggregate-binder bonding characteristics subjected to moisture damage.

Two liquids bonding promoters, namely Polyalkylene Glycol-based (PLG) and Alkylamines-based (ALM) as shown in Plate 3.1 and Plate 3.2, respectively, were used in this study. Both bonding promoters were manufactured by a company named Ingevity located in South Carolina, United States. The basic properties of the bonding promoters are shown in Table 3.3. Additionally, two percentages of these bonding promoters were used, which are 0.5% and 1.0% by weight of asphalt binder. The dosages were selected based on the recommendation by the manufacturer, which is between 0.25% and 1%. Practically, the asphalt binder was pre-heated at 160°C for 2 hours. Then, the required amount of bonding promoter was poured into the pre-heated asphalt binder and blended using a high shear mixer. To ensure the homogeneity of the asphalt binder, the blending process was carried out for 30 minutes at a speed of 1000 rpm.