EFFECTS OF AGING CONDITION, PRECONDITIONED TEMPERATURE AND ANTI-STRIPPING AGENT ON THE ADHESIVE AND COHESIVE BEHAVIOUR OF ASPHALT BINDER AND MASTICS

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UNIVERSITI SAINS MALAYSIA
2017

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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

June 2017

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2014/2015

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: EFFECTS OF AGING CONDITION, PRECONDITIONED TEMPERATURE AND ANTI-STRIPPING AGENT ON THE ADHESIVE AND COHESIVE BEHAVIOUR OF ASPHALT BINDER AND MASTICS

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ACKNOWLEDGEMENT

An ocean of thanks to my supervisor, Professor Dr. Meor Othman bin Hamzah for his continuous guidance, support and supervision. Thank you for always keeping track on my thesis writing and sponsoring me financially since the very first day of my laboratory work. It is very comforting to know that I am in such good hands.

I would like to thank post-graduate students, Dr. Bashir M. Bashir Aburawi and Mr. Teh Sek Yee, for their willingness to impart their knowledge and assist me whenever I faced problems in my laboratory work. I am also indebted to the kind and supportive technicians of Highway Engineering Laboratory, Universiti Sains Malaysia, Mr. Mohd Fouzi bin Ali and Mr. Zulhairi bin Ariffin. My appreciation goes to the very cooperative technician of Polymer Research Laboratory, School of Materials and Mineral Resources Engineering, Mr. Muhammad Sofi bin Jamil for lending me equipment to complete my laboratory work. My thanks also go to Universiti Sains Malaysia for providing me with the laboratory facilities and financial support.

ABSTRAK

Campuran asfalt suam (WMA) telah diterima secara meluas oleh industri asfalt terutamanya di Amerika Syarikat kerana kemampuannya yang membolehkan penghasilan campuran asfalt suam dan pemadatan pada suhu 20°C hingga 55°C, lebih rendah berbanding campuran asphalt panas (HMA). Oleh itu, WMA telah dilabelkan sebagai teknologi mesra alam kerana ia mengurangkan pelepasan bahan toksik ke udara. Namun demikian, penurunan suhu penghasilan WMA menimbulkan kecenderungannya terhadap masalah kelembapan, kelekatan dan kekuatan. Untuk mengatasi masalah berikut, penambahan agen anti-pelucutan telah diperkenalkan. Antara agen anti-pelucutan yang digunakan dalam kajian ini adalah ZycoTherm dan Tough Fix. Thesis ini bertujuan untuk mengkaji kesan penambahan agen anti-pelucutan, penuaan dan suhu pernyediaan terhadap ciri dan perekatan bitumen PG 64. Ujian hentaman telah dijalankan atas asfalt dengan mengunakan acuan yang baru direka. Keputusan analysis menunjukkan bahawa rekatan adalah paling kuat pada suhu 35°C dalam keadaan penuaan jangka panjang. Selain itu, keputusan keseluruhan menunjukkan bahawa penambahan ZycoTherm dan Tough Fix memberi kesan dalam meningkatkan prestasi asfalt dari segi kukuatan perekatan dan keliatan. Teknik analisis imej juga digunakan untuk mengukur kegagalan perekatan yang dialami oleh asfalt selepas menjalani ujian hentaman. Melalui teknik ini, peratusan kegagalan perekatan didapati meningkat apabila mengalami penuaan jangka panjang dan disediakan pada suhu yang rendah.

ABSTRACT

Warm Mix Asphalt (WMA) has gain wide acceptance by asphalt industry especially in the United States due to its ability to lower asphalt mixing and compaction temperatures by 20°C to 55°C compared to the conventional Hot Mix Asphalt (HMA). This characteristic makes WMA a greener technology as less emission will be released into the air. However, the lowered temperature gives rise to greater moisture susceptibility, which related to coating and bonding problems. Addition of anti-stripping agents is a feasible solution to the current predicament. The two anti-stripping agents used were ZycoTherm and Tough Fix. The impact test was conducted, using a newly fabricated mould, and the effects of aging conditions and preconditioning temperatures of bitumen incorporating either ZycoTherm or Tough Fix, were investigated. The analysis results showed that bond strength of binder and mastics was at their strongest at intermediate temperature (35°C) and it improved directly proportional to the aging condition. The overall test results indicated that both ZycoTherm and Tough Fix had significant effects on improving the performance of bitumen in terms of bond strength and fracture toughness. Image analysis technique was used to classify the adhesive and cohesive failures of bitumen after undergoing impact test. It was found that percentage adhesive failure of bitumen increases at aged condition and low temperature.

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LIST OF ABBREVIATIONS

B	Pure Binder
BZ	Binder Incorporating ZycoTherm
M	Mastics
Z	ZycoTherm
MZ	Mastics Incorporating ZycoTherm
T	Tough Fix
MT	Mastics Incorporating Tough Fix
PAV	Pressure Aging Vessel (Long Term Aging Method)
RTFOT	Roll Thin Film Oven Test
WMA	Warm Mix Asphalt
HMA	Hot Mix Asphalt
OPC	Ordinary Portland Cement

CHAPTER 1

INTRODUCTION

1.1 Background

Warm Mix Asphalt (WMA) was introduced in Europe in 1997 and in the USA in 2002. Then, it rapidly gains acceptance especially over conventionally used Hot Mix Asphalt (HMA). WMA is an energy-saving technology as it lowers asphalt mixing and compaction temperatures by 20°C to 55°C compared to HMA (D'Angelo et al., 2008). This helps to reduce the emission of volatile organic compounds at asphalt plants. In addition, it ensures safety of workers at job site as they are subjected to less fume exposure and burn hazards.

However, the use of these mixes has its drawbacks, such as greater moisture susceptibility due to lower production temperatures, and coating and bonding problems (Rubio et al., 2012). Although lower production and paving temperatures scale down the mixes cost, it creates problems like incomplete drying of the aggregates and poor bitumen coating. These issues subsequently lead to potential moisture damage, as shown in the studies carried out by (Hurley and Prowell, 2006) that will eventually result in poor performance. For instances, premature rutting of the pavement surface due to the insufficiently aged binder under lower compaction temperature (Rubio et al., 2012; Zaumanis, 2010; Corrigan, 2009).

1.2 Problem Statement

Stripping is a major source of pavement distress and takes place in the presence of moisture. This results in an unforeseen increase in maintenance budgets (Hicks et al., 1991). Over the years, many laboratory tests have been proposed to evaluate moisture sensitivity of asphalt mixtures. Stripping of asphalt binder from aggregate surfaces due to moisture action is the main reason for poor durability of asphalt pavement especially in the tropical monsoon climate countries like Malaysia.

According to Dawson et al. (2009), stripping was generally attributed to water infiltration into the asphaltic mixture, causing weakening of the mortar, and aggregate-mortar bond. Zhang et al. (2016) mentioned that deterioration can be in the form of cohesive failure of the bitumen and/or bitumen-filler mastics or by adhesive failure between bitumen and aggregate. It has been demonstrated that the service performance and durability of an asphalt mixture depend on the strength of the bituminous film and the properties and strength of the bitumen-aggregate bond interface (Mo, 2010). Therefore, this study was conducted to study the roles of aging, temperature and incorporation of anti-stripping agents in bitumen adhesive and cohesive behaviours.

1.3 Objectives

The specific objectives are outlined as follows:

1. To investigate the combined effects of preconditioned temperature, aging condition and anti-stripping agents on adhesive and cohesive properties of asphalt binder and mastics.
2. To quantify the percentage of failure attributed to adhesive and cohesive properties under various conditioning methods.
3. To evaluate and compare the performance of binder and mastics with and without incorporating ZycoTherm and Tough Fix additives.

1.4 Scope of Work

This study was designed to ascertain the effectiveness of these two anti-stripping agents on bond strength of bitumen. The scope of work was limited to evaluate the effects of aging, production temperature on the performance of binder and mastics incorporating Tough Fix and ZycoTherm additives. Bitumen of penetration grade PG64 was selected for the preparation of all impact test samples. Meanwhile, Ordinary Portland Cement (OPC) was selected to act as filler to produce mastics specimen samples. Customized metal fixtures were employed to act as the aggregate surface adhered by bitumen. An impact test setup was used to examine the binder-aggregate bond strength. Fractured surfaces of binder and mastics samples were accessed using imaging analysis software Earth Resource Data Analysis System (ERDAS) to quantify the percentage of failure attributed to adhesion and cohesion. The effectiveness of the anti-stripping agents added to asphalt binder or mastics was explained using graphical and statistical analysis.

1.5 Significance of Research

Utilization of WMA technology comes with benefits and drawbacks. Incorporation of Tough Fix and ZycoTherm is potential to be the key solution to minimize the deficiency. Based on previous findings, binder and mastics incorporating anti-stripping additives exhibits higher workability and coat ability. These characteristics may improve adhesive strength of bitumen which improve anti-stripping properties and hence reduce moisture damage on the pavement, thus giving rise to pavement with extended life cycle. Previous study also suggested that asphalt mixtures incorporating one of the additives used, Tough Fix may improve the resistance against pavement distress (Hamzah and Mohd Hasan, 2016).

Apart from that, this project supplements the normally measured mechanical properties with fundamental properties that affect physical adhesion between the bitumen and aggregate and internal mastics cohesion and the tendency to lose these bonds in the presence of water. This is important as according to Masad et al. (2006) and Hefer et al.

(2005), a comprehensive characterisation of moisture damage should include measurements of fracture, healing, and viscoelastic properties.

1.6 Dissertation Outline

This dissertation is divided into five chapters. Chapter 1 presents an overview of WMA benefits, shortcomings and solutions. The chapter briefly explains the research background, problem statement, objectives, scope of work and justification of the study.

The literature review of related studies is summarized in Chapter 2. The literature review includes results from earlier laboratory studies conducted on the warm asphalt binders and mixtures and the limitation and deficiencies in them. Chapter 2 also brief through the explanation of several terminology by previous researcher.

Chapter 3 describes the methodology to achieve the objectives. In this chapter, the materials used, the research approach and the test methods are mentioned. Image analysis and statistical analysis used have also been discussed.

Chapter 4 gives a detailed discussion and analysis of the data obtained to highlight the influence of aging condition, temperature and incorporation of anti-stripping additives on bitumen properties. Statistical, tabulated and graphical data obtained is shown in this chapter to aid understanding.

Finally, the conclusions and recommendations for future studies are deliberated in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Degradation of asphalt pavements is an inevitable phenomenon due to the combined effects of high repeated traffic loading and harsh environmental conditions. Sources of degradation include load-induced fatigue cracking, temperature-induced thermal cracking and permanent deformation. Two influencing factors that affect the structural integrity of an asphalt mixture and essentially control its performance are the adhesive bond between the bitumen and aggregates and the cohesive strength of the bitumen (Poulikakos et al., 2013). This chapter surveys scholarly articles, books and other sources such as dissertations, conference proceedings which are relevant to this area to provide detailed description, summary, and appraisal of each work to assist understanding of the subject matter.

2.2 Warm Mix Asphalt Technology

WMA is mix that are manufactured and spread at lower temperatures compare to HMA. This temperature reduction of 20-40^{0}C has led to the following temperature based classification of asphalt mixes (Vaitkus et al., 2009) as shown in Table 2.1.

Table 2.1: Temperature Based Classification of Asphalt Mixes

Asphalt Mix Types	Production and Compaction Temperatures (^{0}C)
Hot Mix Asphalt	150-190
Warm Mix Asphalt	100-140
Half-Warm Mix Asphalt	60-100
Cold Mix Asphalt	0-40

Due to the lower production and compaction temperatures and reduced carbon emission, WMA has been widely used as an environmentally friendly technology. It is learnt that the benefits of WMA technologies include reduced fuel usage and emissions in support of sustainable development, improved field compaction, which can facilitate longer haul distances and cool weather pavement, and better working conditions (D'Angelo et al., 2008).

WMA technologies can be divided into three types: are foaming processes, usage of organic additives or chemical additives. Foaming process entails the addition of small amounts of water, either injected into the hot binder or directly into the mixing chamber. Then, water added will be evaporated by the heat, forming entrapped vapor. This alleviate the situation by temporarily expand the volume of the binder and reduces mix viscosity, enhancing the coating ability and workability of the mix for a limited time (Capitão et al., 2012).

On the other hand, organic additives aid by adding waxes to the mix. A decrease in viscosity takes place when wax melted as the mix is heated (Zaumanis, 2010). Then, these additives are solidify into uniformly distributed discrete particles when the mix has cooled down, increasing the stiffness of the binder like a fiber-reinforced materials (Rubio et al., 2012). Sasobit, Asphaltan-B are two of the most commonly used organic additives (Xu et al., 2017).

Chemical additives conclude emulsification agents, surfactants, polymers (polymer-modified binder), and additives to improve coating, workability, and compaction, as well as anti-stripping properties. Additives are commonly mixed with bitumen prior to mixing. Examples of popular chemical additives are Rediset and Cecabase that not only improve the adhesion between aggregate and binder, they also contribute to the aggregate coating. Some chemical additives like Evotherm ET can even reduce temperature ranges from 15-30^{0}C to 50-75^{0}C (Von Devivere, 2011).

2.3 Moisture Damage Mechanism

Moisture damage is an extremely complicated mode of asphalt mixture distress that leads to the loss of stiffness and structural strength of the bound pavement layers. These eventually give rise to failure of the road structure. The damage is caused by loss of adhesion between aggregate and bitumen, and loss of cohesion strength in the bitumen due to the presence of moisture in the asphalt mixture (Airey et al., 2007).

According to Kringos and Scarpas (2005), moisture damage in asphaltic mixes, which usually open-graded asphalt, that occurs on a relatively short timescale is identified as advective transport phenomenon. Water flow through an asphaltic mix causes desorption of the outer layers of the mastics films which are in direct contact with the water flow. Once the outer layer of a mastics film is completely "washed away" or stripped by advective transport, the next layer of mastics, now exposed to the water flow field, will be damaged.

Although moisture damage occurs in both HMA and WMA, the problem is proved more dominant in WMA according to Kanitpong (2012). It is stated that the reduction in the mixing temperature could adversely affect the moisture sensitivity of asphalt mixtures due to the entrapment of moisture in the aggregate particles or the inferior coating (Kanitpong, 2012).

There are three main physicomechanical processes found in the literature about porous asphalt: moisture diffusion, asphalt binder erosion due to fast water flows and cyclic pore pressure development from entrapped water in air voids (Hicks et al., 1991). Moisture diffusion is defined as a long-term moisture damage process, where penetration of moisture is controlled by the air void content, distribution and interconnectivity of pores within asphaltic components (Varveri et al., 2016). Meanwhile, pumping action is a short-term moisture damage mechanism. Dynamic water flow phenomena are developed in asphalt pavements in shorter times and can act accumulatively, and accelerate the long-term process. In addition, dynamic traffic loads can cause high water pressure fields within the pores that are filled with water. These high pore pressures can lead to cracking of the binder film thus facilitating the ingression of moisture to the asphalt binder-aggregate interface (Varveri et al., 2015).

2.4 Stripping

Stripping or removal of bitumen from an aggregate because water penetrates into the interface which then caused many pavements to fail. Moisture vapour seeps between the asphalt-aggregate surface and replaces the asphalt coating. This leads to the breakdown of the adhesive bond between the aggregate and the asphalt binder and eventually causes functional weakening of pavements leading to costly repairs (Bagampadde et al., 2004).

Stripping happened progressively over time, weakening the entire structure through its progression. Common symptoms of asphalt stripping are ravelling and potholes. To prevent stripping, proper mix design is thus essential. Of the many ways to prevent stripping in a pavement, the use of anti-stripping agents (ASA) is the most common method. One of the most frequently used ASA is hydrated lime (Rubio et al., 2012)

2.5 Anti-Stripping Agents

Moisture damage is a source of pavement distress that leads to the adhesion loss between bitumen and aggregate, especially in WMA mixtures. Therefore, a lot of anti-stripping agents are developed as a solution to this problem. Anti-stripping agents aimed to improve the adhesion between bitumen and aggregate and subsequently prevent stripping of asphalt pavement from moisture damage. This is achieved by altering the surface characteristics of aggregate by converting it from water-loving to bitumen-loving (Xu et al., 2017). Then, the bitumen becomes more compatible with the aggregates than water and possesses better coating capability on the aggregates. Example of anti-stripping agent is hydrated lime which has been used a lot during the last several decades. Due to the weak resistance of WMA mixtures to moisture damage, it is important to add anti-stripping agent into WMA mixtures.

Several studies have been conducted to investigate the effect of anti-stripping agents on the moisture susceptibility of WMA mixtures. It is found that the addition of anti-stripping agents can enhance the properties of asphalt binder by decreasing the acid-to-base ratio of asphalt binder so that asphalt binder can adhere to the aggregates easily (Xu et al. 2017). The findings by Khodaii et al. (2012) proved that hydrated lime can reduces the moisture susceptibility of mixtures. All these results are evidences to prove the effectiveness of anti-stripping agents in improving the moisture damage resistance of asphalt mixtures.

According to research results, hydrated lime with smaller size usually has rougher surface. And it was observed that hydrated lime with smaller size improves the moisture resistance of the mixture more significantly (Cheng et al. 2011) (Diab et al., 2013).

2.6 Image Analysis

In order to understand the fracture behaviour of complex cement-based composites, researchers have been drawn to a wide array of testing, imaging and modeling techniques (Mindess, 1986). Digital imaging techniques for asphalt mixture are effective tools for evaluating the internal structure. These techniques have been advanced throughout the years by a number of researchers (Coenen et al., 2012). In the past, obtaining images was treated as a two-step process in which a camera was used to obtain a photograph of a specimen and then digitised with a flatbed scanner (Yue et al., 1995). Guided by the concept that physical performance of asphalt concrete is significantly influenced by the aggregate structure of the mix, image analysis technique is believed to be a plausible method to study bitumen. (Olard and Perraton, 2010).

2.7 Limitation and Deficiency of Existing Testing Methods

2.7.1 Pneumatic Adhesion Tensile Testing Instrument

Pneumatic Adhesion Tensile Testing Instrument (PATTI) was used to evaluate the fracture strength of bitumen-aggregate sample geometry either in terms of the cohesive bond strength of the bitumen or the adhesive bond strength of the bitumen aggregate interface. The PATTI measures the maximum tensile pressure necessary to separate the binder from the aggregate substrate. The thickness of the binder must be controlled precisely and identically in all cases (Kim et al., 2012). According to Moraes et al. (2011), aggregate plates were first prepared by wet cutting stone. The slices were then polished to make sure the surface was flat. Then, the polished slices were cleaned and dried for at least 24 h. After that, the aggregate and pull-stub were placed in an oven and heated to 70^0C for one hour. The bitumen must be heated as well to allow it to be fluidic enough to coat the aggregate plate. Then, the liquid bitumen was poured onto a prepared aggregate plate and was pressed immediately by a metal pull-stub to establish a good bitumen-aggregate bond (so that bitumen thickness became 0.8mm). Finally, the excess bitumen was wiped off. During the test, air pressure generated is transmitted to the piston which is placed over the pull stub and screwed onto the reaction plate. The air pressure induces an airtight seal formed between the piston gasket and the aggregate surface. A constant rate of pulling pressure is applied to the sample. Tensile pressure versus testing time is recorded. The maximum tensile pressure to separate the bitumen from substrate is captured by the software. This pressure is converted to its pull-off tensile strength later on using Equation (2.2).

$$\text{POTS} = \frac{\left(\text{BP} \times \text{A}_\text{g}\right)\text{-C}}{\text{A}_\text{ps}} \tag{2.2}$$

Where POTS refers to pull-off strength (kPa); BP refers to the air pressure (kPa), A_g refers to contact area of gasket with relation plate (mm²), C refers to piston constant and A_{ps} refers to area of pull-stub (mm²).

This was thought to be an accurate method to not only determine the mechanical tensile strength of bitumen or bitumen-aggregate interface, but also identify the type of failure, either adhesive or cohesive, through the digital camera connected with the PATTI equipment (Kim et al., 2012). The pull-off test can also identify the type of failure, either adhesive or cohesive. According to a study by Kanitpong and Bahia (2005), when more than 50% of the aggregate is exposed from the debonding process between aggregate plate and binder film, the failure can be categorized as adhesive failure; otherwise, it is considered cohesive failure. From Kim et al. (2012) test results, it is clear that unconditioned samples typically presented cohesive failure in most cases, while adhesive