EVALUATION OF THE COMBINED EFFECTS OF LONG TERM AGING AND MOISTURE DAMAGE ON ASPHALT MIXTURE INCORPORATING CUBICAL AGGREGATES AND ZYCOTHERM

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By

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

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ABSTRAK

Asfalt campuran suam (WMA) merupakan satu teknologi lestari yang dibangunkan untuk mengurangkan suhu pencampuran dan pemadatan, tetapi boleh dihasilkan dengan menggunakan loji asphalt dan mesin penurap lazim. Dari segi aspek alam sekitar dan kelestarian, WMA dapat mengurangkan pelepasan gas rumah hijau secara berkesan. Oleh sebab suhu penghasilan yang lebih rendah, WMA lebih mudah terdedah kepada kerosakan lembapan kerana pengeringan agregat yang tidak lengkap menyebabkan lembapan terperangkap. Lebihan lembapan ke dalam turapan asfalt akan merosotkan kualiti turapan dan membawa kesan buruk ke atas bahan turapan asfalt. Bahan pemadatan suam dari India dinamakan Zycotherm ditambah dalam penghasilan WMA dan keberkesanannya sebagai ejen anti-pelucutan telah diselidiki. Untuk mensimulasikan keadaan sebenar di tapak, campuran asfalt telah didedahkan kepada penuaan jangka panjang dan kerosakan kelembapan secara serentak. Prestasi WMA dan asfalt campuran panas (HMA) dinilai dari segi kepadatan, kebolehkerjaan, kekuatan tegangan dan ricih. WMA didapati lebih mudah dipadatkan dan diterapkan berbanding dengan HMA. WMA juga dibuktikan mempunyai rintangan kelembapan yang lebih baik selepas didedahkan kepada pelaziman kelembapan. Penggunaan agregat berkubik dalam campuran asfalt menunjukkan prestasi yang lebih baik dari segi tegangan dan ricih. Pembentukan agregat patah berpunca daripada bentuk agregat dan bukannya orientasi agregat. Hal ini disebabkan kebanyakan agregat yang patah adalah agregat biasa yang memanjang dan bersepih. Agregat jenis ini mudah pecah di sepanjang satah lemah. Analisis terhadap penggredan agregat selepas pemadatan dan ujian prestasi membuktikan agregat berkubik terdegradasi kurang daripada agregat biasa.

ABSTRACT

Warm mix asphalt (WMA) is a sustainable technology developed to lower the mixing and compaction temperatures but can be prepared using conventional asphalt plant and paving machineries. In terms of environmental and sustainability aspects, WMA can effectively reduce greenhouse gas emissions. Due to its lower production temperature, WMA is more prone to moisture damage due to incomplete drying of aggregate thus results in trapped moisture. Excessive intrusion of moisture into the asphalt pavement would deteriorate the pavement quality and have adverse impact on asphalt pavement. A warm compaction additive from India named Zycotherm was added to produce WMA and its effectiveness as an anti-stripping agent was investigated. To simulate the actual condition on site, the asphalt mixtures were subjected to simultaneously long term aging and moisture damage. The performance of WMA and HMA were evaluated in terms of compactability, workability, tensile and shear strengths. From the investigation, WMA can be more easily compacted and more workable compared to HMA. WMA exhibited better moisture resistance after subjected to moisture conditioning. The utilization of cubical aggregates in asphalt mixture showed better performance in terms of tensile and shear stresses. From image analysis, WMA incorporating cubical aggregates demonstrated lower percentage adhesive failure which proved the effectiveness of Zycotherm. The formation of fractured aggregates was primarily due to the aggregate shape instead of aggregate orientation. This is because most of the broken aggregates were elongated or flaky normal aggregates that breaks easily along their weak plane when subjected to applied loads. Analysis on the aggregate gradation after compaction and performance tests proved that cubical aggregates degraded less than normal aggregates.

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LIST OF ABBREVIATIONS

HMA	**H**ot **M**ix **A**sphalt
WMA	**W**arm **M**ix **A**sphalt
SCB	**S**emi **C**ircular **B**ending
F-T	**F**reeze-**T**haw
LTA	**L**ong **T**erm **A**ging
CDD	**C**umulative **D**egree **D**ays
JKR	**J**abatan **K**erja **R**aya
CEI	**C**ompaction **E**nergy **I**ndex
WI	**W**orkability **I**ndex
OPC	**O**rdinary **P**ortland **C**ement
ASTM	**A**merican **S**ociety for **T**esting and **M**aterials
AASHTO	**A**merican **A**ssociation of **S**tate **H**ighway and **T**ransportation **O**fficials

CHAPTER 1

INTRODUCTION

1.1 Background

Asphalt mixture is the most popular paving material used worldwide for asphalt pavement. It is a made of asphalt binder, coarse and fine aggregates, filler and other materials depending on the type of asphalt mixture. Hot mix asphalt (HMA) has been the dominant asphalt mixture type used in the road industry which involves blending of hot aggregates with hot asphalt binder. The typical mixing and compaction temperatures of HMA are 160˚C and 150˚C, respectively. To produce HMA in the asphalt mixing plant at such temperature, a high amount of energy consumption is unavoidable for heating purposes. The elevated temperature is required for the manufacture of HMA to ensure the aggregates are completely dried which enhances the bonding between asphalt binder with aggregates for better coating. In addition, haul distance to deliver the mixture from the mixing plant to site for compaction is taken into consideration so that the mix is laid and compacted at its ideal temperature. Due to the great difference between the ambient temperature and the temperature of the asphalt mixture, the mixture tends to cool down rapidly especially during rainy day at longer haul distance.

Greenhouse gas emissions from the transportation industries has been a problematic issue as it would cause air pollution and eventually global warming that lead to an increase in the earth surface temperature. The transportation industry has been proven as one of the major contributors to greenhouse gas emissions in the United States as it contributed 29% of total greenhouse gas emissions to the atmosphere recorded in 2016 (EPA, 2018). Greenhouse gas emissions from this sector involved primarily fossil fuel from road, rail and air and marine transportation. Figure 1.1 presents the share of greenhouse gas emissions by sector in the United States in 2016.

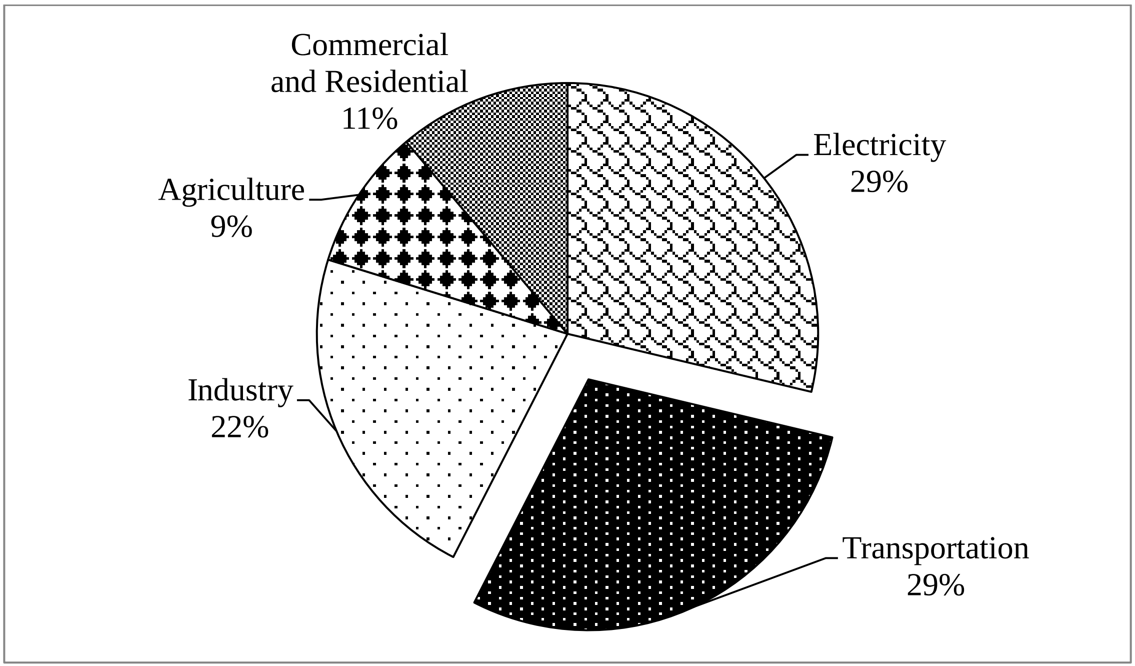

Figure 1.1: Share of the United States Greenhouse Gas Emissions in 2016 (EPA, 2018)

In order to mitigate the issues faced by HMA, various new technologies have been developed to reduce the mixing and compaction temperatures, and these technologies are generally referred to as warm mix asphalt (WMA). The first trial of public road to implement WMA was in Germany using Aspha-min® zeolite system in 1999 (Kumar and Chandra, 2016). WMA is an innovative technology characterized by its lower mixing and compaction temperatures (100˚C to 140˚C) as compared to conventional HMA. WMA is basically produced by adding chemical or other additives into HMA using the conventional asphalt plants and paving machineries. The temperature reduction achieved by WMA through the use of various technologies developed in recent years which can be categorized as organic additives, chemical additives and water-based foaming processes. One of the warm additives used in modifying HMA is Zycotherm which was developed by Zydex Industries from India. Zycotherm is a liquid nano-organosilane warm compaction additive which allows the asphalt mix to be compacted as low as 110˚C. According to Sharanappanavar (2013), Zycotherm offered lower mixing and compaction temperatures, while simultaneously acted as an effective anti-stripping agent to improve moisture resistance of asphalt mix. Rohith and Ranjitha (2013) have proved that Zycotherm is compatible with all unmodified or modified binder without changing the binder properties or affecting the binder grading.

Lowering the mixing and compaction temperature, the energy consumption to produce asphalt in the plant was trimmed down and the burning fuel savings could be possibly 50% or more (D'Angelo et al., 2008). In terms of environmental aspect and sustainability concern, WMA technologies would eventually reduce the greenhouse gas emissions such as carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), nitrous oxide (NO_x), volatile organic compound (VOC) and dust into the atmosphere. According Hanz et al. (2011), nearly 1 litre of fuel oil and 1 kg of carbon dioxide emission per ton of asphalt mixture produced were decreased for each 10˚C reduction of the asphalt mixture production temperature. In addition, improvement in field compaction even at a lower temperature allows paving season extension and permits longer haul distance as WMA cools down slower due to less difference between asphalt mixture and ambient temperature. Lastly, the welfare of paving workers is assured as WMA provides a cooler working environment and an enormous drop in asphalt fumes. Table 1.1 summarizes the percentage reduction in greenhouse gas emissions by implementing WMA.

Table 1.1: The Percentage Reduction in Greenhouse Gas Emissions by Implementing WMA (Vaitkus, 2009)

Greenhouse Gases	Percentage Reduction (%)
CO_2	30-40
SO_2	35
VOC	50
CO	10-30
NO_x	60-70
Dust	20-25

Despite the advantages of implementing WMA, there are several drawbacks to be highlighted such as: slightly higher cost because there are still reservations to using them; lack of data concerning their long-term performance; greater moisture susceptibility due to lower temperature as well as coating and bonding problems. Due to the relative newness and short life of WMA implementation, there are still doubts and uncertainties to using WMA widely as it is still in the stage of experimentation and in the need of specifications (Chowdhury and Button, 2008).

In addition, the coarse aggregates act as the structural skeleton in asphalt mixture which facilitates the transfer of traffic loads to the underlying base, subbase and subgrade layers. Therefore, the properties of aggregates are the key to excellent pavement performance. Aggregate shape is one of the aggregate characteristics that are known to influence pavement performance. Aggregate particle shape can be described as cubical, flat, elongated and rounded. The presence of flaky and elongated aggregates is undesirable as they tend to break down during mixing, compaction and under traffic load. Hence, aggregate shape must be taken into account in the mix design of asphalt mixture to prevent premature pavement failure.

1.2 Problem Statement

Moisture susceptibility has been reported as one of the primary concerns in WMA. In fact most of HMAs are susceptible to moisture damage as well. However, WMA is more prone to moisture susceptibility due to the lower mixing and compaction temperatures which subsequently cause incomplete drying of aggregates and water entrapped in the aggregate particles. Furthermore, moisture can also infiltrate into the asphalt mixture via intrusion of rainwater, a rising of groundwater table and absorption and adsorption of water vapour. The presence of moisture would shorten the service life of the asphalt mixture and deteriorate the quality of asphalt mix thus results in pavement distresses such as stripping, alligator cracking and raveling.

Sources of failures due to moisture induced damage in asphalt mixture are adhesive failure, cohesive failure and broken aggregate failure. Adhesive failure refers to the bonding failure at the asphalt mortar-aggregates interface. Cohesive failure describes the failure that occurs within the asphalt mortar, while aggregate failure is related to the aggregate degradation or broken aggregates in asphalt mix.

Aggregate shape has been identified as one of the important criteria in the mix design of asphalt pavement. The presence of flat and elongated aggregate particles in asphalt mixture might leads to the breakage or degradation of the aggregate particles during compaction process thus affecting the designed aggregate gradation. High percentage of flaky and elongated aggregates in asphalt mixture makes the mixture harsh and difficult to work with.

In real life, asphalt pavement is not only exposed to moisture damage but also long term aging which in turns increases the stiffness of asphalt mix making it more brittle. Therefore, the road pavements are subjected to simultaneously moisture intrusion and long term aging in reality which would adversely reduce the strength of asphalt pavement. As a result, the phenomenon leads to the formation of several pavement distresses which contribute to the short durability and poor performance of asphalt pavement therefore subsequently increase the maintenance cost in the long run.

1.3 Objectives

The objectives in this study are as follows:

1. To evaluate the moisture susceptibility of asphalt mixture incorporating Zycotherm subjected to simultaneously long term aging and moisture damage.
2. To quantify the percentage adhesive failure and broken aggregates on asphalt mixture using imaging technique.
3. To investigate the aggregate disintegration of normal and geometrically cubical aggregates in asphalt mixture due to compaction and performance tests.

1.4 Scope of Work

This research concentrates on the combined effects of long term aging and moisture damage on asphalt mixture incorporating cubical aggregates with Zycotherm. The asphalt mixture was prepared in accordance to JKR mixture type AC 14. Ordinary Portland Cement (OPC) was used as the filler and asphalt binder grade 80/100 was used for mixing. Zycotherm acted as warm mix additives as well as anti-stripping agent to produce WMA at 140˚C and conventional HMA was mixed at 160˚C. All specimens were compacted to 7±1% air voids at 150˚C for HMA and 140˚C for WMA, respectively. After compaction, the specimens were subjected to ultraviolet light for five days at 85˚C to simulate long term aging and moisture conditioning of three freeze-thaw cycles in accordance to ASTM D4867 (ASTM, 2006). Unconditioned specimens were prepared as the control sets in this study. These specimens were neither subjected to long term aging nor moisture conditioning.

Two performance tests were conducted namely; Semi-Circular Bending test (SCB) and Leutner shear test to evaluate the mixture tensile and shear strengths, respectively. Imaging technique was performed to identify the percentage of adhesive failure, cohesive failure and broken aggregate on the fracture surface of asphalt mixture after subjected to SCB and Leutner shear tests. Analysis on the broken aggregates was carried out to determine the factor that contributes to failure in terms of the orientation of the broken aggregates as well as the aggregate shape. Lastly, the extent of aggregate degradation in the asphalt mixture due to the effect of gyratory compaction and performance tests was studied and compared with the original aggregate gradation for JKR mixture type AC 14.

Analysis of data enables results such as Workability Index (WI), Compaction Energy Index (CEI), fracture energy, maximum tensile and shear stresses at failure, tensile and shear strength ratios, image analysis and aggregate degradation of the asphalt mix could be obtained. At the end of the study, the moisture susceptibility of HMA and WMA could be identified after subjected to moisture conditioning and long term aging which reflect the real life situation faced by asphalt pavements in the field.

1.5 Justification of Study

Sustainable pavement is the one that achieves its specific engineering goals to meet basic human needs, use resources effectively and preserve the surrounding ecosystem. To reduce the greenhouse gas concentration in the atmosphere as mentioned by the Kyoto Protocol, WMA is a sustainable alternative to replace HMA in the future. The benefits of WMA have been well established among the local authorities, researchers and pavement industries such as significant reduction of asphalt fumes and carbon emission, decrease in energy consumption, improved warm compaction, longer haul distance as well as enhanced working environment for paving workers. From the past studies, WMA has been proven to perform as well as if not better than HMA. However, WMA is not extensively implemented due to some doubts and uncertainties. One of the main concerns is the moisture susceptibility of WMA due to lower mixing and compaction temperatures.

External water and moisture entrapped in the aggregate particles are the main contributors of moisture intrusion in asphalt mixture which would eventually induced damage. Asphalt pavement is subjected to simultaneously moisture damage and long term aging during its service life which eventually results in stripping and increase of the pavement stiffness. Stripping describes the physical separation of the asphalt mortar and aggregate formed by the loss of adhesion between asphalt mortar and aggregate surface primarily due to the action of water. Three distress modes that are caused by stripping include fracture, distortion and disintegration which subsequently lead to alligator cracking, shoving and raveling, respectively. Aged pavement would have lower strength and poor performance as it becomes brittle.

To dissipate the doubts on the implementation of WMA, it is therefore important to evaluate the moisture susceptibility of WMA as well as HMA to improve the mix design in the future. From the results analysis, the sources of failure due to moisture induced damage such as adhesive failure, cohesive failure and aggregate failure could be identified and quantified. The effects of aggregate shape in asphalt mixture were emphasized in this study as well where normal shaped aggregates and geometrically cubical shaped aggregates were tested. In addition, the asphalt mixture was investigated under the combined effects of long term aging and moisture damage to simulate the real life condition. The outcome could be taken as a reference for future mix design in implementing WMA to mitigate moisture susceptibility therefore providing high quality of sustainable asphalt pavement that could help to reduce carbon footprint. The findings can also prove the benefits of utilizing geometrically cubical aggregate in asphalt mixture to enhance the strength of asphalt pavement.

1.6 Dissertation Outline

This dissertation is divided into five chapters. Chapter one presents an overview of HMA and WMA followed by problem statement, objectives, scope of works and justification of the study. Chapter two summarizes the literature review on HMA and WMA, warm additive, performance tests, imaging technique as well as analysis on broken aggregates. Previous studies on moisture sensitivity tests, effects of long term aging and moisture damage on asphalt mixture and sources of failure due to moisture damage are elaborated in this chapter.

Chapter three explains the raw materials used which include asphalt binder, aggregate type and warm mix additives for WMA. In this chapter, the variables and test parameters for the specimens are mentioned as well. Sample preparation methods, moisture conditioning methods and performance tests namely; SCB and Leutner shear tests with the respective standards are listed in this chapter. Imaging technique, analysis on the broken aggregates and analysis on aggregate degradation are included in the chapter.

Chapter four analyzes the laboratory test results of each specimen after conditioning and testing. The results such as WI, CEI, fracture energy, maximum tensile and shear stresses at failure, tensile and shear strength ratios, image analysis and broken aggregate orientation and shapes are determined after analysis. Comparison between aggregate gradation of recovered normal and cubical aggregates after compaction and performance tests with the original aggregate gradation AC 14 are conducted to evaluate the aggregate degradation due to the effects of compaction and performance tests. Lastly, chapter five concludes the results and the findings of this study with some recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

WMA has been developed as one of the sustainable asphalt pavement initiatives by reducing the energy consumption and carbon emissions associated with asphalt production via warm mix and warm compaction technologies. However, the entrapped water in the aggregate particles may not be completely dried due to lower production temperature which potentially induces moisture damage. Thus, the performance of WMA as well as HMA due to the adverse effect of moisture is a major issue among the researchers for years. Due to the moisture ingression in the asphalt mixture, the structural integrity and the stiffness of the asphalt pavement would be eventually reduced. Such moisture intrusion facilitates pavement distress modes such as raveling, alligator cracking, rutting and fatigue (Sengoz and Agar, 2007 and Caro et al., 2008).

In reality, the asphalt pavement is subjected to simultaneously long term aging and moisture damage. Unfortunately, not much research is done on the combined effects of long term aging and moisture damage on asphalt mixture. This research will therefore focus on the evaluation of the combined effects of long term aging and moisture damage on asphalt mixture.

2.2 Hot Mix Asphalt

Hot mix asphalt is a mixture of coarse and fine aggregates with asphalt binder which is mixed, placed and compacted at elevated temperature. The typical mixing and compaction temperatures of HMA are 160˚C and 150˚C, respectively. Therefore, the production of HMA implies high energy consumption and generation of harmful greenhouse gas emissions and asphalt fumes which eventually contribute to environmental contamination (Goh, 2012). Figure 2.1 visualizes the typical mixing temperature range for asphalt mixtures.

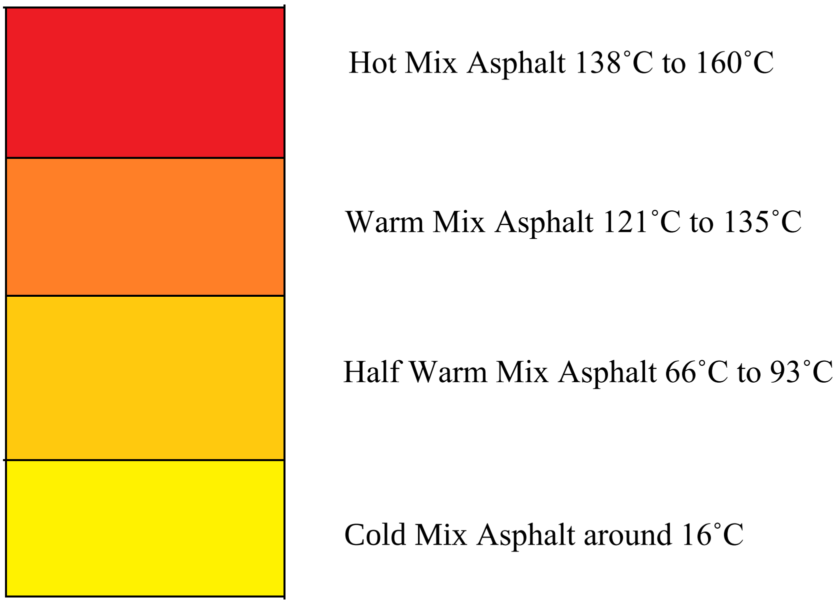

Figure 2.1: Typical Mixing Temperature Range for Asphalt Mixtures (Goh, 2012)

2.3 Warm Mix Asphalt

Further to the increasing environmental awareness over the years, many countries have agreed on the national targets for reduction of greenhouse gas emissions stipulated in the Kyoto Protocol to improve global climate. Among others, this has led to the development and implementation of WMA as an effort to reduce energy requirement and greenhouse gas generation during pavement construction for environmental concern. WMA is one of the potential technologies to be implemented by the local authorities in supporting green and sustainable development by replacing HMA. WMA is mixed, transported and compacted at a temperature lower than HMA. Typical temperature reduction ranges from 20˚C to 40˚C. WMA technologies aim to have at least equivalent if not better performance than HMA in terms of strength and durability (Kristjansdottir, 2006).

2.3.1 Warm Mix Technologies

There are three categories of WMA technologies namely; foaming process, organic additive and chemical additive. Foaming process technology can be further divided into two groups which are water containing and water-based. For foaming process achieved by water containing, zeolite is injected into asphalt mixture during the mixing process. Foaming processes technology for water based was conducted by spraying water into hot asphalt binder or by mixing the wet sand into asphalt mixture (Rubio et al., 2012; Capitão et al., 2012). When water was added in the hot bitumen, a large volume of foam is generated which temporarily increased volume of binder and reduces mixture viscosity. Thereby, it subsequently increased workability of the mixture and enhance aggregate coating at lower temperature (Barthel et al., 2004). According to Smith (2007), the quantity of water added shall be just enough to produce foaming effect as too much water would cause stripping problems.

Addition of organic additives is basically adding waxes into the mixture such as synthesis wax, fatty acid amides and Montan wax. The asphalt viscosity decreased significantly when the temperature was slightly higher than the melting point of the organic additive and the wax melts (Zaumanis, 2010). When the additive cools and crystallizes, it forms a uniform network structure in the binder which enhances the stiffness of the binder. Therefore, the asphalt mixture can be mixed and placed at lower temperature. It was concluded that different blends containing a range of synthetic wax contents should be selected to maximize the temperature reduction, the fatigue or the rut resistance, without compromising the other properties of the mixture (Silva et al., 2010).

Chemical additives are added in virgin asphalt binder before pouring bitumen into the asphalt mixer. It is basically an innovation through a combination of emulsification agents, surfactants, polymers, and additives in order to improve coating, mixture workability, and compaction, as well as adhesion promoters (anti-stripping agents). Water in this emulsion evaporates as steam when mixing with aggregate and improves the coating of aggregate by the asphalt (Rubio et al., 2012).

Zycotherm is an odourless additive developed by Zydex Industries from India. It can be used to modify HMA into WMA based on warm compaction technology. Usage of Zycotherm for WMA can reduce the mixing and compaction temperatures. Different types of warm additives are summarized in Table 2.1.

Table 2.1: Examples of Existing and Potential Warm Mix Technologies (Goh, 2012)

Foaming Additive		
WMA Technology	Company	Recommended Additive/Usage
Aspha-min®	Eurovia and MHI	0.3% by total mass of mixture
ADVERA® WMA	PQ Corporation	0.25% by total mass of mixture
WMA-foam®	Kolo Veidekke Shell Bitument	No additive. It is a two component binder system that introduces a soft and hard foamed binder at different stages during plant production.
LEA®	LEA-CO	0.2-0.5% by weight of binder
LEAB®	BAM	0.1% by weight of binder
Organic Additive		
WMA Technology	Company	Recommended Additive/ Usage
Sasobit®	Sasol	0.8-3.0% by weight of asphalt
Asphaltan-B®	Romonta	2.5% by weight of asphalt
Licomont BS 100®	Clariant	3% by weight of asphalt mixture

Table 2.1: Continued

Chemical Package		
WMA Technology	Company	Recommended Additive/ Usage
CECABASE RT®	Arkema Group	0.2-0.4% by weight of asphalt
Evotherm®	Meadwestvaco Asphalt Innovations	Generally pumped right off a tanker truck to the asphalt line using a single pair of heated valves and check valves to allow for recirculation.
Rediset WMX®	Akzo Nobel	2% by weight of mixture

2.3.2 Advantages of Warm Mix Asphalt

A number of benefits have been identified as driving the development of WMA. In terms of environmental concern and sustainable development, energy consumption and carbon dioxide emissions are trimmed down. At temperatures below 80 ℃, there are nearly no emissions from the bitumen; even at about 150 ℃, emissions are only about 1 mg/h. However, significant emissions were recorded at 180 ℃ (D’ Angelo et al., 2008). According to D’ Angelo et al. (2008), burner fuel savings with WMA typically range 20% to 35% and the levels could be higher if the burner is allowed to run at lower settings.

Implementing WMA properly would be able to bring paving benefits such as paving in cooler temperatures while desired density can be achieved, hauling the mix for longer distance while remaining mixture workability to be placed and compacted, enhancing compaction even with manual handling as well as opening to traffic in a short period of time (D’ Angelo et al., 2008).

Lowering of mixing and compaction temperatures of WMA reduces the emission of fume is beneficial for the paving workers by providing a cooler and less odour working environment (Kristjansdottir, 2006). For paving works in tunnel, worker exposure to fumes is significant thus WMA is desirable for this application.

2.4 Warm Mix Asphalt Additive

WMA can be modified from HMA by adding suitable warm mix asphalt additives through warm mixing and warm compaction technologies. Example of warm mixing additives include Aspha-min, Sasobit, Cecabase and Rediset while, example of warm compaction additive is Zycotherm.

2.4.1 Zycotherm

Zycotherm is a warm compaction additive developed by Zydex Industries, Gujarat, India. It is an odourless liquid nano-organosilane chemical additive. In addition to lowering of mixing and compaction temperatures, Zycotherm serves as an effective anti-stripping agent to increase moisture resistance. In addition, it is compatible with all types of modified and unmodified bitumen such as polymer modified binder and crumb rubber modified binder (Rohith and Ranjitha, 2013). Usage of Zycotherm is effective at 0.1% by weight of binder for most asphalt binders.

In Malaysia, most of the asphalt mixtures are produced using granite aggregates especially wearing course. However, granites are hydrophilic (water-loving), while bitumen is hydrophobic. Therefore, mixing granite with conventional bitumen will result in poor bonding between aggregates and asphalt binder which subsequently leads to premature moisture damage particularly in wet condition. By providing unique and strong chemical bonding between aggregate surface and bitumen, Zycotherm provides significant moisture resistance, improves coating of bitumen on aggregates and allows lower temperature for mixing and compaction (Hasan et al., 2017).

The addition of Zycotherm in asphalt mix has significantly lowered the mixing and compaction temperatures without compromising the quality. Furthermore, the warm mix asphalt with Zycotherm has proven to perform better than hot mix asphalt in water sensitivity test as well as Marshall stability test (Raveesh and Manjunath, 2017). Hasan et al. (2017), Mirzababei (2016) and Raveesh and Manjunath (2017) demonstrated that warm mix asphalt with addition of Zycotherm significantly enhanced the moisture susceptibility of asphalt mixtures as shown in Figures 2.2 and 2.3. Mirzababaei (2016) carried out Fourier Transformed Infrared Spectroscopy (FTIR) test which proved that Si-O link in Zycotherm turns into Si-OH bond when it is exposed to moisture. Si-OH silanoles on the aggregate surface produces Si-O-Si film structure which is a hydrophobic layer and that layer prevents water ingression and formation of H-bonds on the asphalt binder and aggregate interface. Ibrahim and Mehan (2015) showed that asphalt mixtures with Zycotherm have better resistance to moisture induced damage as well as improved resistance to rutting, fatigue and low temperature cracking.

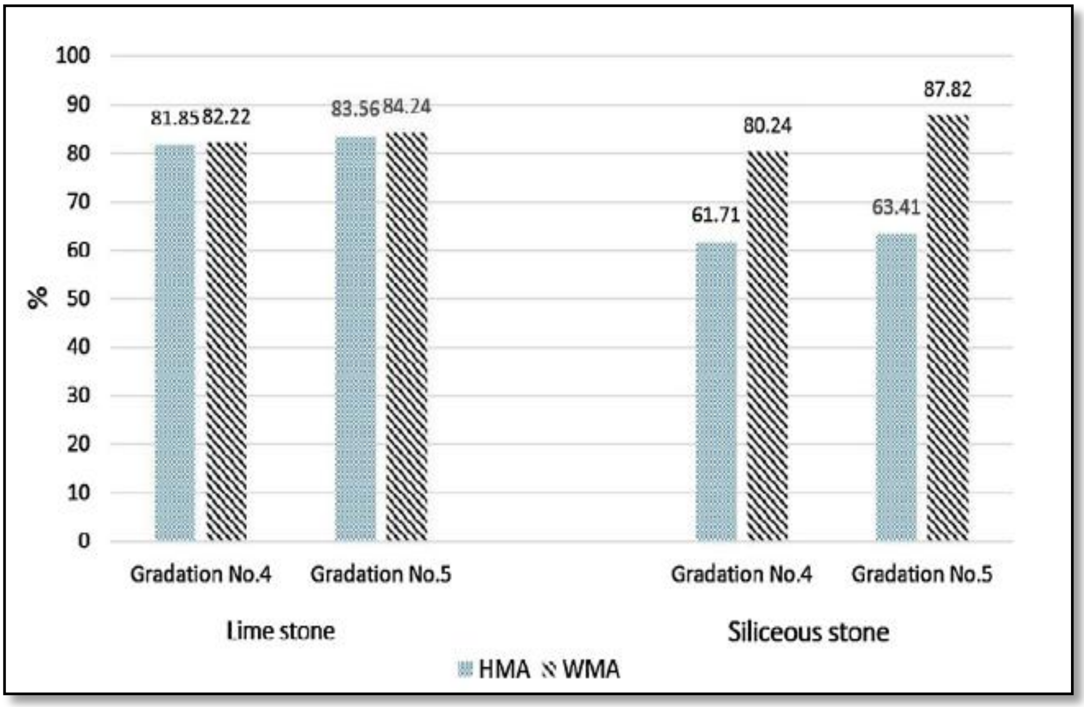

Figure 2.2: Marshall Stability Ratio (Mirzababaei, 2016)

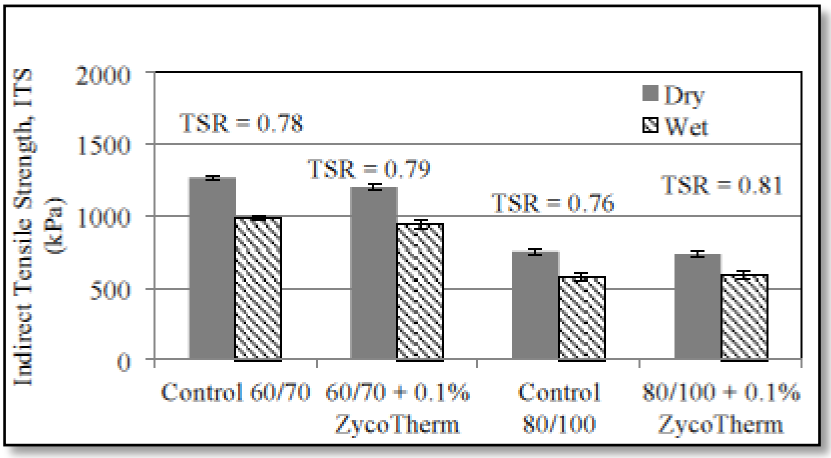

Figure 2.3: Moisture Susceptibility Test Results (Hasan et al., 2017)

2.5 Moisture Susceptibility of Asphalt Mixture

Moisture damage has been identified as one of the main issues in asphalt mixtures since the 1900s. Moisture damage is a complex phenomenon that involves thermodynamic, chemical, physical and mechanical processes. The steps involved in moisture damage mechanism are moisture transport and response of the system. Moisture transport describes the process of moisture infiltrates the asphalt mixture either in liquid or vapour form and reaches the aggregate and asphalt binder interface, while response of the system explains the change in internal structure of the asphalt mix which eventually causes reduction in load carrying capacity (Caro et al., 2008). Although moisture ingression in asphalt does not initiate the pavement distresses, it exacerbates their severity and extent.

According to Hicks (1991), moisture damage maybe associated with two mechanisms namely; loss of adhesion and loss of cohesion. Loss of adhesion is due to water present at the interface between asphalt binder and aggregates which subsequently stripping away the asphalt film. Loss of cohesion is due to the softening of asphalt mortar in the presence of moisture. Accordng to McGennis et al. (1984), there are two theories that explained the phenomenon of softening or loss of cohesion of asphalt mix. The first theory assumes that certain reactions occur causing the asphalt cement to degrade to lower viscosity. The second theory states that asphalt mortar and mineral filler are the primarily important materials to bind larger aggregate particles. Therefore, the overall binding effect is diminished when the asphalt mortar and mineral filler is stripped away leading to loss of cohesion in the mixture. However, a third mechanism in which moisture degrades the asphalt mixture has been recognized namely aggregate degradation (Copeland et al., 2007).

Moisture damage is influenced by several factors such as asphalt concrete characteristics, environmental factors and construction practices. Asphalt concrete characteristics include the nature of aggregate, the nature of the asphalt cement and the type of mixture. In order to better resist moisture damage, clean aggregates with rough surface texture and low surface moisture are desirable. In terms of environmental factors, climate and traffic conditions affect the moisture damage the most. Asphalt mixture is highly susceptible to moisture damage when simultaneously subjected to extreme weather condition with freeze-thaw action and heavy traffic volume. The quality of compaction and weather conditions during paving works are the construction factors that would accelerate moisture damage in asphalt mixture as they are related to the control of air voids (Hicks, 1991).

There are several contributing mechanisms of moisture damage identified from past studies: detachment, spontaneous emulsification, displacement, pore pressure-induced damage, hydraulic scour, dispersion of the mastic, film rupture and desorption of the mastic (Taylor and Khosla, 1983; Kringos et al., 2007; Caro et al., 2008). Moisture damage mechanisms are described as follows:

- Detachment is the separation of an asphalt film from an aggregate surface by a thin layer of water, with no obvious break in the asphalt film. Where stripping by detachment has occurred, the asphalt film can be peeled easily from the aggregate, indicating a complete loss of adhesion (Taylor and Khosla, 1983).
- Spontaneous emulsification describes the combination of water and asphalt to form an inverted emulsion where asphalt represents the continuous phase and water represents the discontinuous phase thus eventually leading to stripping (Taylor and Khosla, 1983).
- Displacement occurs due to the intrusion of moisture into the aggregate surface through a break in asphalt film. This may be caused by improper coating on aggregates or by film rupture at the sharp edge of aggregates due to traffic loading (Taylor and Khosla, 1983).
- Stripping by pore pressure occurs via free circulation of water in high voids mix thus water might be entrapped in the asphalt mix under traffic loading. High excess pore pressure built up causing the stripping of asphalt film (Taylor and Khosla, 1983).
- Hydraulic scour is only applicable on the surface course due to the action of vehicle tyres on saturated pavement surface. When vehicles travel on the road, the water is being pressed into the pavement and followed by sucking away of the pavement which continuously becomes a compression-tension cycle thus asphalt film stripped off from the aggregates (Taylor and Khosla, 1983).
- Dispersion of the mastics occurs as a result of the weakening of cohesion in asphalt binder due to long-term diffusion periods and loss of material in the presence of flow (Kringos et al., 2007).

- Film rupture is the rupture in the mastic or aggregates which subsequently deteriorates the structure integrity of material and generates new path for moisture transport due to the microcracks (Caro et al., 2008).
- Desorption of the mastics is basically the washing away of the outer layers of mastics due to the presence of moisture flow (Kringos et al., 2007).

2.6 Aggregate Shape Characteristics

Aggregates are the primary material in pavement construction where approximately 90% of asphalt mix by volume consists of coarse and fine aggregates. Aggregate shape has significant effect on the performance and strength of asphalt pavement. Aggregate characteristics such as particle size, shape, and texture affect the performance and service ability of hot-mix asphalt pavement (Brown et al., 1989; Kandhal et al., 1992) Particle shape can be described as cubical, flat, elongated and rounded.

According to Hamzah et al. (2010), geometrically cubical aggregates possessed a high degree of homogeneity with visible edges and corner faces compared to normal shaped aggregate particles. The research showed that dense packing and lesser air voids can be achieved by utilizing geometrically cubical aggregate in asphalt mixture. In addition, the density, stability and air voids for asphalt mixture incorporated geometrically cubical aggregates were significantly higher than those of the other Marshall properties. In the study, flakiness and elongation indices of normal aggregate Cubical particles possessed the best rutting resistance over the other shapes. Hamzah et al. (2014b) showed that the increasing percentage of cubical aggregates in asphalt mixture enhanced the indirect tensile strength of asphalt mixture as presented in Figure

2.4. Flaky and/or elongated aggregate in an asphalt mixture resulted in a lower resistance to shear deformation (Chen et al., 2005).

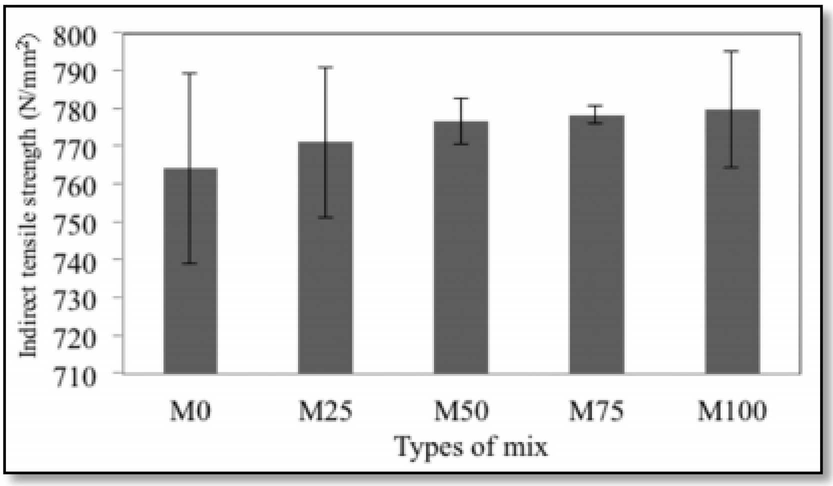

Figure 2.4: Indirect Tensile Strength Test Results (Hamzah et al., 2014)

The normal shaped aggregates consist of flaky and elongated aggregate particles which are undesirable. Several design procedures specifications therefore limit the percentage of flat and elongated aggregate allowed in the asphalt mixture. According to Vavrik et al. (1999), increased levels of flat and elongated particles lead to increased air voids in gyratory compacted HMA samples. A high amount of flat and elongated aggregates would lead to more breakdown and fracture of aggregate particles during compaction.

2.7 Long Term Aging

The exposure of asphalt pavements to various factors during production and service life leads to short term aging and long term aging problems. According to Androjić (2006), internal variables that affect the aging of asphalt pavement are: properties of materials, asphalt mixtures, binders, air voids content and thickness of binder around the aggregate. Temperature of the asphalt mix, external weather conditions and long term exposure of asphalt surface to weather conditions are the external variables. There are several mechanisms of asphalt aging namely; volatilization, oxidation and steric hardening (Androjić, 2016).

According to Bell et al. (1994), specimens were oven aged at 135˚C and 85˚C or 100˚C to simulate short term and long term aging, respectively. Long Term Oven Aging (LTOA) protocols on compacted specimens at 60˚C for two weeks and at 85˚C for five days were suggested to simulate field aging of approximately 9600 and 17,500 Cumulative Degree Days (CDD) values (Yin et al., 2017). In the study, field aging of 9600 CDD value was equivalent to 7 months in-service in warmer climates and 12 months in-service in colder climates. In addition, field aging of 17,500 CDD value was equivalent to 12 months in-service in warmer climates and 23 months in-service for colder climates.

2.8 Leutner Shear Test

Bond strength is an important parameter to evaluate the binder resistance to moisture damage. According to Copeland (2007), bond strength is defined as the mean tensile strength at failure. The strength and durability of asphalt pavement are affected by the bonding between the asphalt layers. Inadequate bonding between asphalt layers may cause the asphalt pavement to be affected by corrugation, slippage and traverse cracking which normally occurs at acceleration or deceleration and turning zone. Several tests can be used to evaluate the bonding strength between asphalt layers, the shearing test is the most often used in practical. The Leutner shear test is normally used to determine the quality of bonding between pavement layers without normal stress in the specimen (Vaitkus et al., 2012). The different methods used to determine the bond strength of asphalt layers are shown in Figure 2.5.

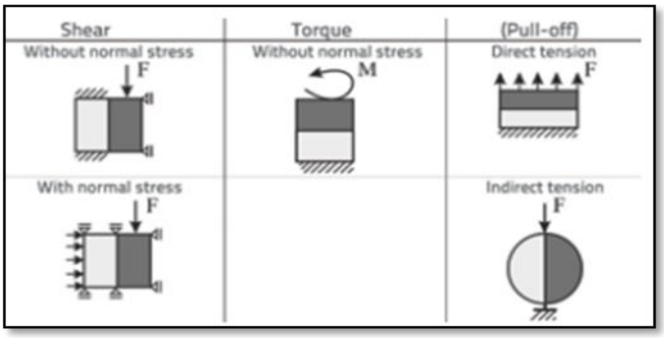

Figure 2.5: Methods Used to Determine Bond Strength of Asphalt Layers (Vaitkus, 2012)

The shear test procedures derive from shear testing in soil mechanics and the devices evaluate the strength interface performance forcing failure in the interlayer zone. Uzan developed the first device which consisted of a shear mould divided into two parts (Uzan et al., 1978). A frame applied the vertical load at a constant rate 2.5mm/min and four deflectometers measured the displacements. A graph of shear stress versus displacement was plotted for analysis purpose. In the late 1970s, Collop developed Leutner shear test to determine the asphalt layer bonding strength (Collop, 2003). The test was performed on 150 mm diameter cores consisting at least two layers taken either from a pavement or fabricated in the laboratory. A shear displacement rate of 50mm/min across the interface of a cylindrical core was applied and the shear force was obtained. Leutner shear test arrangement has advantage of simplicity but it has non-uniform interface shear stresses. Some other devices of the same type with respective plots are summarized in Figure 2.6.