THE EFFECT OF AGGREGATE TYPES ON THE PERFORMANCE OF ASPHALT MIXTURE INCORPORATING SILANE ADDITIVE 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

Kegagalan ikatan di dalam bahan turapan adalah disebabkan mekanisme seperti kegagalan di antara permukaan agregat-asfalt dan kegagalan pada pengikat asphalt itu sendiri. Ia memendekkan hayat campuran asfalt, serta mengakibatkan kegagalan seperti keretakan, pelucutan dan jalan berlubang. Kajian ini ditumpukan kepada jenis agregat dan kesan penambahan surfaktan ‘Zycotherm’ ke dalam campuran asfalt. Suhu pencampuran dan pemadatan bagi campuran asfalt pemalar adalah 160 ℃ dan 150 ℃ masing-masing, manakala, campuran asfalt yang dicampur ‘Zycotherm’ dicampur dan dipadatkan masing-masing pada 145 ℃ dan 125 ℃. Kebolehkhidmatan campuran asfalt diukur menggunakan Indeks kebolehkerjaan, Indeks penyalutan dan Indeks tenaga pemadatan. Manakala kerosakan disebabkan tindakbalas air dan kelembapan dinilai dengan membandingkan sampel yang dikondisi dengan menggunakan Accelerated Lab Vacuum Saturator (ALVS) dan sampel yang kering iaitu tidak dikondisi menggunakan ujian kekuatan tegangan tidak langsung dan ujian Cantabro. Ujian ricih Leutner telah digunakan untuk menguji rintangan ricih dalam campuran asfalt yang dihasilkan menggunakan aggregat yang berbeza. Berdasarkan hasil daripada kajian Indeks kebolehkerjaan dan Indeks penyalutan, campuran asphalt granit mempunyai prestasi yang lebih baik dalam campuran asfalt pada suhu tinggi manakala batu kapur menunjukkan prestasi yang baik dalam penghasilan campuran asfalt pada suhu yang rendah. Merujuk kepada Indeks Coatability, ia boleh disimpulkan bahawa campuran asfalt yang dihasilkan dengan granit mempunyai salutan bitumen yang lebih baik berbanding batu kapur. Prestasi campuran asfalt granit pada suhu tinggi secara umumnya lebih baik berbanding batu kapur. Walaubagaimanapun, campuran asfalt yang ditambah Zycotherm memberikan ketahanan yang lebih baik kepada kelembapan.

ABSTRACT

The bond within asphalt mixture constituents fails in the presence of different mechanism interacting at the interface which results in various forms of distress initiated from the aggregate-asphalt binder surface and cohesive failure within the asphalt binder. It shortens the service life of asphalt mixtures, resulting in failures such as cracking, rutting and potholes. This study concentrates on the aggregates and the effects of adding silane additive to the asphaltic mixture. Mixing and compaction temperatures of 160 ℃ and 150 ℃ respectively was adopted to produce control mixture hot mix asphalt (HMA). While, asphalt mixtures incorporating Zycotherm was mixed and compacted at 145 °C and 125 °C respectively. The serviceability of asphaltic mixture was measured using Workability Index (WI), Coatability Index (CI) and Compaction Energy Index (CEI). Whereas the moisture damage is evaluated by comparing the Accelerated Lab Vacuum Saturator (ALVS) conditioned samples with the dry controlled samples using Indirect Tensile Strength Test (ITS) and Cantabro test. Leutner Shear test was used to test the bonding between aggregates and binder in asphaltic concrete. Based on the test results, it was found that granite is having a better performance in terms its service characteristics at controlled hot mixed asphalt (HMA) whereas limestone is performing well at lower mixing temperature. From the Coatability Index, granite has better binder coating as compared to limestone. The asphalt mixture performance generally favours to the granite at HMA temperature. However, the Zycotherm added asphalt mixture gives a better resistance to moisture and disintegration. In term of the intra-bonding of binder and aggregates, the granite at HMA temperature has the stronger bonds.

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LIST OF ABBREVIATIONS

HMA	Hot Mix Asphalt
WMA	Warm Mix Asphalt
LAAV	Loss Angeles Abrasion Value
ACV	Aggregate Crushing Value
CEI	Compaction Energy Index
ITS	Indirect Tensile Strength
SSA	Specific Surface Area
SMA	Stone Mastic Asphalt
ESAL	Equivalent Single Axle Load
VMA	Voids in Minerals
SFE	Surface Free Energy
AV	Air Voids
SGC	Servopac Gyratory Compactor
KPP	Kamunting Premix Plant
SSD	Saturated Surface Dry
WI	Workability Index
ALVS	Accelerated Lab Vacuum Saturator
SST	Total Surface Area of Mix Design Combined Aggregates
UTM	Universal Testing Machine
CL	Cantabro Loss
VFA	Voids Filled by Asphalt

NOMENCLATURES

$CaCO_3$	Calcium carbonate
H_2O	Water
$Si\text{-}O\text{-}Si$	Siloxane
CO	Carbon monoxide
N	Nitrogen atom
H	Hydrogen atom
G_{mm}	Maximum specific gravity
G_{mb}	Bulk specific gravity
V	Volume of specimen
AV	Air voids
W_b	Amount of binder
P_b	Optimum binder content from mix design
$P_{s\text{-}coarse}$	Percentage of coarse aggregates retained on 10mm
$W_{loose\text{-}ssd}$	SSD weights of the loose mix batch
$W_{agg\text{-}ssd}$	SSD weights of the coarse aggregate fraction
SA_{course}	Surface area of the combined coarse aggregates

CHAPTER 1

INTRODUCTION

1.1 Background

Pavements are generally categorised into two types, namely flexible and rigid. Flexible pavement is prepared using bituminous-treated surface or a relatively thin surface of hot-mix asphalt (HMA). Whereas rigid pavement is made up of concrete with certain arrangement of reinforcement. Aggegates have been used as a main material for the construction of road pavements. This study will be focussing on the effect of aggregate types on the performance of asphalt mixture incorporating surfactant, known as silane additive Zycotherm.

Two types of aggregates were evaluated, namely granite and limestone. Limestone aggregates are not conventionally used for preparing the asphaltic concrete mixture in Malaysia. However, all the relevant aggregate properties tests were carried out to check its suitability for mixing before it is used as a component of asphaltic concrete. Despite comparing the aggregate type, silane additive Zycotherm with 0.1 % by mass of binder is used in the asphalt mix to reduce the surface tension during the mixing which will directly reduce the viscosity of the mixture that acquire low temperature to mix the asphaltic concrete.

Each type of aggregate is further compared with two mixing conditions. The HMA samples were prepared at the conventional Hot Mix Asphalt (HMA) temperature, whereby the samples were mixed at 160 ℃ and then compacted at 150 ℃. Additionally, samples incorporating Zycotherm were mixed and compacted at 145 ℃ and 125 ℃, respectively.

The main concern of this research is to study the effect of aggregate types on the performance of asphaltic mixture when subjectes to moisture degradation. Moisture degradation in asphaltis concrete resulting in pavement distresses such as cracking, raveling, rutting and potholes. Moisture degradation of asphalt mixture can be related to three mechanisms. First, the loss of cohesion within the asphalt binder which occurs due the rupture of bond between asphalt molecules. Next, the adhesive failure within the asphalt binder and aggregate happen due to the rupture of bond between molecules between different phases. Lastly, the degradation due to the nature of the materials involved, the hydrophobic binder and hydrophilic aggregates. Binder generally act as an impermeable surface for the water to pass through it. Water tend to be absorbed by the hydrophilic aggregate when there are ruptures within the asphalt film, hence weaken the aggregate-asphalt bonding, consequently damaging the pavement.

1.2 Problem Statement

The bond between asphalt-aggregate constituents fails in the presence of different mechanism interacting at the interface which results in various forms of distress initiated from the material interphase and cohesive failure within the asphalt binder. It shortens the service life of asphalt mixtures, resulting in failures. Workability of asphalt mixtures is a property that describes the ease with which the mixture can be mixed, placed and compacted. Coatability of asphalt mixtures is defined as the degree of coating of the aggregates by the asphalt binder. In general, workability and coatability of aggregates in asphaltic concrete are affected by the viscosity of asphalt binder used for the mixture production. Prior to enhancing the service characteristics of asphalt mixture, surfactant has been used to reduce the surface tension of binder, improves bonding between materials and structural integrity. In order to understand the interaction between materials and mixture performance, experimental works have been performed in the laboratory.

1.3 Objectives

To achieve the aim stated above, the following objectives were drawn up.

1. To evaluate the effect of Zycotherm on the service characteristics of asphalt mixtures.
2. To evaluate the performance of asphalt mixtures prepared using different aggregate types.
3. To correlate the performance of asphalt mixture with the aggregate properties.

1.4 Scope of Work

Experimental approach was implemented in this study. Aggregate properties of limestone and granite collected from quarries located in Perlis and Penang respectively were tested. Few tests to determine the aggregate properties were carried out namely specific gravity, water absorption, flakiness and elongation index and aggregate crushing value (ACV). A surfactant namely Zycotherm at 0.1 % mass composition based on the mass of asphalt binder used to allow the production of asphalt mixture at lower temperature. Then, service characteristics of asphalt mixtures prepared using granite and limestone were compared in term of its workability, coatability and compactability. Mixing and compaction temperatures of 160 °C and 150 °C respectively was adopted to produce control mixture of hot mix asphalt (HMA). While, asphalt mixtures incorporating Zycotherm was mixed and compacted at 145 °C and 125 °C respectively. Test on workability and coatability index was carried out to compare the different types of aggregates performance stated above by manipulating the control mixture hot mix asphalt temperature and the temperature of asphalt mixtures incorporating Zycotherm.

Compaction energy index (CEI) was determined by using mixtures prepared from granite and limestone at two different compaction temperatures. For mixture properties, test on moisture damage was carried out and evaluated using Indirect Tensile Strength test (ITS) and Cantabro test. The samples prepared with 7 % air voids in it. Leutner shear test has been performed on 4% air voids samples to determine the shear strength of samples.

1.5 Significance of Study

With the addition of 0.1 % Zycotherm by mass of binder, the coatability of aggregate and as well as the workability and compactability of the mixture enhance both granite and limestone aggregates. Use of surfactant also increase the mixture workability during production of asphalt mixture at lower temperature, hence ease the placement and compaction of asphaltic concrete mixture. Strong coating bonds between aggregate-asphalt binders promise the strength of pavement and reduces the chances of aggregates stripped off from the pavement. These could thus enhance the asphalt mixture performance and prolong the pavement service life.

Premature failure can be reduced by providing a proper bonding and structural integrity in the asphaltic concrete. A thorough coating is needed to lower the possibility of premature damage that induced by moisture and bonding between materials. In this study, service characteristics in terms of coatability, workability and compactability, as well as mechanical performance of asphalt mixture are emphasized to prolong the service life of pavement. The relationship between aggregate properties and mixture performance that has been established provide a better understanding on the bituminous materials behavior under tropical climate condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Aggregates are the main component of bituminous mix design. Hot binder which act as a binding agent is introduced to preheat aggregates to produce asphalt mixture. Concerning the failure in asphaltic concrete which mainly caused by the moisture induced damage, bond between asphalt-aggregate constituents fails in the presence of different mechanism interacting at the interface which results in various forms of distress initiated from the aggregate surface and cohesive failure within the asphalt binder. Mohd Hasan et al., (2015) stated that moisture damage can be reduced by incorporating additives that act as an anti-stripping to the asphalt mixture. By incorporating additives in the asphalt mixture, the mixing and compaction temperature can be reduced by about 30 °C. The temperature decreases due to the reduction in surface tension in between the molecules of binder that reduces the viscosity of binder. Hence, less heat thus fuel is required to heat the binder and to produce asphalt mixture.

2.2 Aggregates

Aggregates are the product of rocks that have been crushed and screened. The important aggregate qualities for asphalt are durability and angularity which determined by the number of crushed faces on the aggerates. Aggregate varies from different sizes and has its own mass composition in mix design.

Mineral composition of aggregates determines the physical characteristic and the behaviour towards pavement material. The knowledge of quarry rock's mineral properties guide the suitability of chosen aggregate. Aggregates that are hydrophilic (water-loving) tend to strip more readily since water replaces the asphalt film more easily over each particle. Freshly crushed aggregates with many broken ionic bonds tend to strip more easily. Table 2.1 shows the comparison of mineral properties of aggregates in terms of hardness, resistance to stripping, surface texture and crushed shape.

Table 2.1: Mineral Properties of Aggregates (Brown et al., 2009)

Rock Type	**Hardness, Toughness**	**Resistance to Stripping**	**Surface Texture**	**Crushed Shape**
Igneous				
Granite	Fair	Fair	Fair	Fair
Syenite	Good	Fair	Fair	Fair
Diorite	Good	Fair	Fair	Good
Basalt (trap rock)	Good	Good	Good	Good
Diabase (trap rock)	Good	Good	Good	Good
Gabbro (trap rock)	Good	Good	Good	Good
Sedimentary				
Limestone	Poor	Good	Good	Fair
Sandstone	Fair	Good	Good	Good
Chert	Good	Fair	Poor	Good
Shale	Poor	Poor	Fair	Fair
Metamorphic				
Gneiss	Fair	Fair	Good	Good
Schist	Fair	Fair	Good	Fair
Slate	Good	Fair	Fair	Fair
Quartzite	Good	Fair	Good	Good
Marble	Poor	Good	Fair	Fair
Serpentine	Good	Fair	Fair	Fair

Since the relationship between mineral properties and physical properties are complex that making it difficult to predict how an aggregate source will behave based on mineral properties alone, chemical properties of aggregates are taken into consideration. Aggregate surface chemistry can determine how well an asphalt cement binder will adhere to an aggregate surface. Physical properties of aggregates also important as they have the direct effect on the performance of aggregates. Gradation and size, toughness and abrasion resistance, moisture content and specific gravity are the commonly measured physical aggregate properties (Pavia Systems, 2012).

2.2.1 Granite

Granite is the most commonly found aggregates in Malaysia where it is made up of crushed hard rock of granular structure. Granite which originates from igneous rock has good properties that make it the most popular building materials. In terms of its technical characteristics granite is solid (grades 800-1200) and highly solid (grades 1,400-1,600), frost resistant (grades 300-400), of the first class in terms of radionuclidity (A (eff) <370 nBq/kg). There is no radionuclide content, harmful components and additives indicators in granite (Lafarge Building better cities, 2017).

According to Yi-qiu et al., (2010), granite is an acidic aggregate and its surface microstructure has large texture depth. It is also highly resistant to wear. All these characteristics ensure the texture depth and skid resistance of the road surface, which ideal coarse aggregates should have. However, there is limiting factor for the interaction of granite and asphalt that exhibit formation of the structure of asphalt mixtures. The adhesion or bonding between granite and asphalt is insufficient to provide good moisture stability to the asphalt-aggregate mixtures in pavements.

Alex et al., (2015) found that granite has the highest internal pores among the basalt, granite, greywacke and limestone aggregates. Surface characteristics such as porosity, specific surface area (SSA), and surface free energy are key physico-chemical properties of aggregates that influence their adhesion to other materials. In terms of water absorption, granite shows the maximum moisture uptake with highest specific gravity value. Poor performance of the granite bonds can be attributed to the marginal moisture diffusion and transport properties as well as the mineralogical composition of the aggregate. Furthermore, the relatively high porosity of the poorly performing granite bonds is a key factor influencing the sensitivity to moisture of aggregate-mastic bonds.

2.2.2 Limestone

Limestone originated from sedimentary rock and mainly composed of calcite which is known as calcium carbonate ($CaCO_3$). It is also one of the main type of aggregate used in road construction. Limestone is widely used to produce crushed stone in the United States where it holds about 65.8 % of US crushed stone rock types (Geology.com, 2005).

According to McNally (1998), typical compressive strength of limestone ranges from 50 to 150 MPa, stronger than most high strength concrete but weaker than ingenious rocks. Moderate strength of limestones is used for roadbase construction as they are well graded. Limestone is rarely acceptable for surfacing aggregate because of its susceptibility to breakdown under repeated loading and its tendency to polish under traffic.

Akacem et al., (2016) suggested a way to use the low performance limestone aggregate in asphalt pavement. The addition of sand dunes improves the skid resistance of asphalt concrete made with limestones aggregates. There is an increase in the level of performance of asphaltic mix containing sand.

2.3 Technologies Used to Reduce the Asphalt Mixture Production Temperature

2.3.1 Foaming Techniques

Namutebi et al., (2011) stated that foamed bitumen which produced from the foaming process consists of bubbles of hot bitumen encapsulating steam. It is produced when small quantities of cold water of 2-3 % by weight of bitumen are injected into hot bitumen at about 150 °C to 180 °C under certain pressure. The exchange of heat energy occurs between bitumen and water which leads to steam formation. Thus, the steam forced under pressure into the bitumen continuum forming bubbles that forming foamed bitumen.

Martins (2010) suggested that the evaporation and expansion which encapsulate in binder produces large volume of foam. This foaming action increases the volume of binder and lower the viscosity that allows good coating and workability with aggragates. Enough water must be added to cause the foaming action where over addition of water will cause the anti-stripping problem.

Namutebi et al., (2011) stated that increase in bitumen temperatures causes more thermal energy being made available to convert water into steam and thus binder viscosity reduces. As the thermal energy increases, the formation of foam with many bitumen bubbles encapsulating steam also increases, leads to larger volume of the foam produced and thus high expansion ratio values.

The foaming process can be divided into two, namely water-containing and water based. According to European Asphalt Pavement Association (2015), water based is the direct method to inject a small controlled amount of water to hot bitumen. This can be done by the using the foaming nozzles that resulting in large and temporary increase in the effective volume of binder. During compaction, some of the vapour remains in the bitumen that reducing the effective viscosity and thus aiding the compaction process. The amount of water which is insignificant reverts to normal upon cooling.

Moore (2007) stated that WAM-Foam process (water-based foam) is a joint venture between Shell International Petroleum and Koko Veidekke (Norway's largest asphalt-mix producer). Two separate binder components in the WAM-Foam process which are lower-viscosity soft binder and higher-viscosity hard binder. The soft binder is mixed with aggregate at temperature 110 °C. Then, the hard binder added with steam injection that forms the foam as it with the pre-coated aggregate.

According to U.S. Department of Transportation (2016), there are two separate components in mixing stage of WAM-Foam At first stage, soft binder is mixed with aggregates at 110 °C. Hard binder is mixed into the pre-coated aggregates in the form of foam. Injecting cold water into the hot binder causes the rapid evaporation and thus producing large volume of foam. The final stage produces the combination of hard and soft binder.

Zaumanis (2010) stated water containing is an indirect foaming technique that uses mineral as the source of foaming water. Zeolite mineral which is the hydrophilic mineral contains about 21 % of crystalline water that released when temperature increases to 85 °C. When the additive is added to the mixture simultaneously with the binder, water is released as a fine mist. The foaming effect creates expansion in volume and improve the workability of asphalt mix.

Aspha-Min which categorised in water containing foaming technique is a product of Eurovia Service GmBH Bottrop, Germany and available as very fine powder form. You and Goh (2008) stated that Aspha-Min synthetic zeolite that has been hydro-thermally crystallised and holds water about 21 % by mass. Water is released in the temperature range of 85-182 °C. The addition of Aspha-Min to binder during mixing resulting in a fine water spray created. Thus, binder expand in terms of its volume that results in asphalt foam which allowing a workable and good aggregate coating at lower temperature.

According to Porras-Alvarado (2011), Advera® is an aluminosilicate or hydrated free flowing powdered zeolite that is white to grey in colour. It is added at a rate of 0.3 % by total weight of mixture and a reduction in the asphalt mixtures production temperatures of 50-70 °F is observed. In a continuous drum asphalt plant, Advera® powder is usually blown through the fiber port which is located just after the entry point of the binder so that the zeolite is encapsulated in the binder when it begins to release its internal moisture and does not get caught in the exhaust air stream. The dispersion of zeolite is improved when the Advera® powder and the asphalt binder under-go thorough mixing in the mixing box. Whereas in batch plant, the Advera® can be either manually added to the pug mill using melt bags or automatically added using a weigh bucket.

U.S. Department of Transportation (2016) stated Advera WMA is a product developed by PQ Corporation, Malvern, PA. The synthetic zeolite that has 18-21 per cent of water entrapped in crystalline structure. Water is released above 99 °C in hot binder that creates foaming of binder in mix. As the water released, it causes the increase in binder volume with the workability of binder and mix enhanced.

2.3.2 Chemical Additives

According to Milton and Joy (2012), surfactant is being used in chemical industry which having diverse products in automobiles, pharmaceuticals and detergents. A contraction of the term surface-active agent, it is a substance that when present at low concentration has a property of adsorbing onto the surfaces or interfaces and altering the interfacial free energies of those surfaces or interfaces. The minimum amount of work required to create the interface is called the interfacial free energy which measured in term of energy per unit area of the boundary of the difference phases. The surface tension is a measure of difference in nature of the two phases meeting at the surface. Greater difference accounts for the higher surface tension between them.

Milton and Joy (2012) elaborated surfactants at low concentration adsorbs all or some of the surfaces in the system and changing the work required to expand the surfaces significantly. Molecules at a surface have higher potential energy than the interior because much work is done to bring an interior molecule to surface.

According to Zydex Industries (2014), silane additive Zycotherm (surfactant) is an odour-free additive that increases moisture resistance and lowers mixing and compaction temperatures up to 80 °C. It is an advance generation silane additive with multiple benefits. Its 3C nanotechnology which are the chemical bonding, complete coating and consistent compaction gives pavements an extended life cycle. The bitumen binder sprayed and coated over the water loving aggregates forms weak physical bonds which fails in the moist condition and resulting in stripping and potholes. Zycotherm chemically modifies the aggregates surface form the water loving to bitumen loving which gives a strong bonding of bitumen on aggregates.

From Zydex Industries (2014), Zycotherm modified binder achieves complete coating faster as due to the improved wetting. Helping to saturate the finest pore and crevices of aggregates surface, the fines are completely coated in the mixing time of 45-60 seconds and ensure the pinhole free surface. With this, stripping and oxidative effect at aggregates can be avoided as the binder interface due to the elimination of air interface at the aggregates surface. Consistent compaction is achieved through the cooler hot mixes where the mixing temperature is reduced by 10-15 °C. The compaction temperature is further reduced by 35-40 °C.

Mirzababaei (2016) stated that Zycotherm which is the silane-based technology, creates a molecular level hydrophobic zone which is water-repellent. Organofunctional silanes couple an organic and inorganic phase through covalent bonding. This bonding is very renitent against moisture conditions as inorganic part of the couple, hydrogen bond with the hydroxylated agent on surface of the stones while the organic part is condensed in the procedure of hydrolysis in the presence of water and transformed into hydrophobic siloxanes in the bitumen. Hydrogen bond collapses when temperature increases which resulting in the production of H_2O and a covalently bonded metallosiloxane. Therefore, cross-linked siloxane (Si-O-Si) film structure produced over the surface. The hydrophobic layer is shown in Figure 2.1. The properties of Zycotherm is illustrated in Table 2.2.

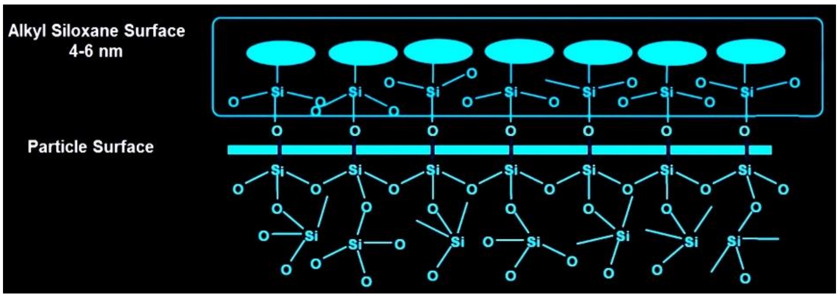

Figure 2.1: Cross-Linked Siloxane Film Structure of Aggregate Surface (Mirzababaei, 2016)

Table 2.2: Properties of Zycotherm (Mirzababaei, 2016)

Properties	**Test result**
Specific gravity (g/cm^3)	0.97
Form	Liquid
Colour	Pale yellow
Odour	Odour free
Flash point	80 °C
Explosive point	Not reported
Freezing point	5 °C

Frigio and Canestrari (2016) evaluated that the presence of the chemical additive improves the compactability properties of the porous asphalt mixtures at reduced production temperature. This is due to the presence of emulsification agents, surfactants, polymer and additives within the chemical additive that helps improving coating, mixture workability and compactability. The use of chemical additives ensures moisture susceptibility as the chemical additive contains adhesion promoters and surfactants that improve the water sensitivity of the asphalt mixture. The chemical additive is the only additive that gives adequate performance in both dry and wet conditions, with acceptable water damage resistance.

Punith et al., (2012) stated that Evotherm H5 is a modified tall oil fatty acid polyamine condensate water. It exists in viscous liquid state, amber (dark) in colour and gives out fishy amine like smell. Evotherm H5 has boiling point is more than water and soluble in water.

Al-Qadi et al., (2014) stated that Evotherm 3G which was developed by Mead Westvaco Asphalt Innovations in Charleston, South Carolina, is a water-free chemical package containing surfactant and an antistripping agent. Chemical additive technology and a "Dispersed Asphalt Technology" (DAT) delivery system are used in the production of Evotherm. This additive helps in improving the aggregate coating, mixture workability and compaction. Evotherm 3G lower the asphalt mixing temperatures by 33–45 °C when typical dosage of 0.4–0.7 % by weight of the binder is fed to the asphalt mixture.

Ghabchi et al., (2013) stated that the use of Evotherm additive shows significant improvement in the work of adhesion with all types of aggregates. Higher work of adhesion indicates stronger bond between asphalt mix components that leads to durable and a less moisture susceptible mixture. Addition of Evotherm results in a lower work of debonding which is more favorable to reduce the moisture susceptibility of the system.

Hamzah et al., (2015) stated that Rediset is a poly functional additive based on fatty amine surfactants and olyethylenes. This additive contains a long chain aliphatic hydrocarbon structure and amine group which chemically reacts with aggregate surfaces. Rediset can be mixed easily with hot asphalt binder at 85 °C without high-shear mixer. There are two parts of mechanism in the temperature reduction. First, the surfactant part reduces the surface tension of asphalt binder. This will reduce the interfacial frictions between thin film of asphalt binder and aggregate and thus improves the wettability of aggregate by asphalt binder. Next, the organic part that reduces the viscosity of asphalt binder and provides a lubricating effect for easier coating and compaction. Chemical additive act at the microscopic interface of the asphalt binders.

Sampath (2010) stated that Rediset^{TM} WMX enhance the adhesion between asphalt and aggregates. The surfactants improve the wetting ability of the asphalt binder for better coating with the aggregates, and the organic additives provide a reduction of the viscosity of the binder and a lubricating effect for easier coating and compaction of asphalt mixtures. Rediset^{TM} WMX supplied in a pellet form that can be added at a dosage rate of 1.5 % to 2.5 % by weight to asphalt mixture. Typical dosage of 2 % by weight of asphalt improves the cohesive strength of the asphalt and reduces the rutting and moisture sensitivity of the final pavement.

According to Al-Qadi et al. (2014), Rediset LQ-1106, developed by AkzoNobel Surface Chemistry LLC, allows reduction in mixing and paving temperatures and provides a built-in anti-stripping effect. Reduction by 15–30 °C can be achieved when a typical dosage of 0.5–1.0 % by weight of binder added to asphalt mixture.

According to Rondón et al., (2016), Cecabase RT® which developed by the Ceca Arkema Group (France) is generally added in proportions of 0.2–0.5 % of asphalt binder weight and mixed for 15 minutes. It can be found in liquid form that is directly injected into the asphalt mixture. This additive is very environmental friendly as its active surface agents are composed of at least 50 % renewable raw materials of vegetable origin. Same as Rediset, the use of Cecabase RT® lowers asphalt binder viscosity and compaction temperatures.

2.3.3 Organic Additives

Sampath (2010) suggested that organic additives are used to reduce the viscosity of binder to achieve a reduction in mixing temperature. Decrease in viscosity above the melting point of wax make it possible to produce asphaltic concrete mixture at lower temperature. The stiffness of binder and the asphalt resistance against deformation increases after the wax crystalize. The melting point of wax should be higher than the service temperature and the wax should minimize the embrittlement of asphalt in low temperature.

Sampath (2010) further stated that Sasobit is a Fischer-Tropsch (FT) wax produced from the coal gasification process and is typically added at the rate of 1.5 % by weight of asphalt. Production of Sasobit using FT process using natural gas converts the carbon-monoxide atoms into a mixture of hydrocarbons having molecular chain lengths from 1 to 100 carbon atoms or greater. There exists a difference between the generic paraffin wax and the FT wax where Sasobit® has a much longer chain length (40 to 115 carbon atoms) and thus has a melting point around 99 °C compared to 20 to 45 carbon atoms and a melting point of 50 °C to 80 °C for generic paraffin wax.

Akpolat and Kök, (2015) stated that Sasobit modified mixture of bitumen (2 % by weight of binder) reported to possess the same workability characteristics as that of the hot mixture at a temperature that is 30 °C lower than that of the hot mixture. Sasobit reduces the rate of aging in bitumen over time. Mixture prepared using Sasobit exhibit higher stiffness, a higher dynamic modulus rutting parameter, and a higher fatigue cracking parameter than that of the other asphalt mix types. Sasobit able to solve the workability problems in crumb rubber modified mixture.

U.S. Department of Transportation (2016) evaluated that Asphaltan B® which is a product of Romonta GmbH, Amsdorf, Germany, a mixture of substances based on

Montan wax constituents and higher molecular weight hydrocarbons. Addition of 2-4 % of Asphaltan B® either to the asphalt mixing plant or directly at the binder producer resulting in the decrement of asphalt mixture production temperature. Similar to FT waxes, it acts as an "asphalt flow improver" and increased compactability and resistance to rutting.

2.4 Application of Anti-Stripping to Reduce Moisture Susceptibility

According to Raquel et al., (2016), moisture damage is defined as the loss of stiffness and strength due to moisture exposure under the mechanical loading and manifests itself in a phenomenon known as stripping. The due reduction in pavement strength resulting in other distresses such as rutting, fatigue cracking and raveling.

Raquel et al., (2016) stated that moisture can degrade asphalt mixture in three mechanisms. The very first is the loss of cohesion within the asphalt binder. Rupture of bonds between molecules in asphalt film is the main reason for this failure. Adhesive failure occurs between aggregates and asphalt which is so called stripping. The last mechanism is known as degradation (fracture) of aggregates. Apart from that, water that present in the mixture also affect the performance of the mix and the compacted sample which causing the damage.

According to Xu and Wang (2016), as the asphalt binder is hydrophobic in nature, water gives certain impacts on the bonding between asphalt and aggregates. The energy associated with the displacement of asphalt by water is addressed as the work of debonding. A negative value for the work of debonding indicates that no eternal energy is required to separate the asphalt–aggregate interface. This indicates that there exists a thermodynamic potential for water to disrupt the asphalt–aggregate interface.

Moisture damage in HMA as stated by Amelian et al., (2014) is the main concern in the durability of flexible pavement. Moisture susceptibility is an HMA mixture's tendency toward stripping. Moisture susceptibility of HMA is determined using retained indirect tensile strength test as an indicator. According to Mohd Hasan et al., (2015), the test indicated that moist aggregate is more likely to strip and fail due to moisture damage. Higher production temperature of the HMA has resulted in a stiffer mixture and allowed for more water to be dissipated during mixing.

According to Mohd Hasan et al., (2015), moisture damage in WMA can be due to incomplete expulsion of moisture in aggregates due to its lower production temperature. This increases the damage including to stripping. Due to improper burner adjustment, there is a possibility of damage in WMA as there is un-combusted fuel which resulting in higher rutting potential in the field and higher levels of carbon monoxide (CO) release during the production.

Nazirizad et al., (2015) stated stripping which is the common distress in pavement occur due the destruction of bond between aggregates particles and bitumen. The main reason for stripping is the traffic loading which worsen the moisture damaged pavements. Anti-stripping agent increases the resistance to moisture damage. It is evident that some additives can improve the stiffness and resistance to rutting.

2.4.1 Hydrated Lime

According to Gorkem and Sengoz, (2009), hydrated lime is a solid type antistripping agent that added to the HMA to react with aggregates and hence strengthens the bond between bitumen and the aggregate interface. Lime reacts with highly polar molecules to resist the water soluble-soap formation which promote stripping. The polar molecules form insoluble salts that would not attract water anymore. The performance of hydrated lime which make an asphalt mixture stiffer, tougher and resistant to rutting reflects its performance as active mineral filler.

Gorkem and Sengoz, (2009) further stated that hydrated lime can be introduced to the asphalt mixture in few different methods. The methods are by adding lime slurry to dry or wet aggregates; dry lime to wet aggregate; dry lime to dry aggregate; dry lime to bitumen; and quicklime slurry to dry or wet aggregate. Among the five methods, the most commonly used is the dry hydrated lime to wet aggregates. Dry hydrated lime can be added to wet aggregate that contain 3-5 % of water or also by adding to dry aggregates and then sprayed with water. The limestones which added to wet aggregates enhances good coating and treatment with poor aggregates.

According to Al-Khateeb et al., (2013), hydrated lime tends to reduce stripping and moisture sensitivity of asphaltic concrete. Hydrated lime in HMA improve moisture damage, reduce oxidative aging, improve mechanical properties, and improve resistance to fatigue and rutting. Lime reduces stripping of aggregates from asphaltic concrete which acts as a mineral filler to stiffen the asphalt binder and HMA that reduces rutting. Three test procedures were compared for evaluating the moisture sensitivity of HMA mixtures and concluded that with the addition of lime and after multiple cycles of freeze-thaw moisture conditioning, all asphalt mixtures demonstrated an enhanced ability to retain the original measured properties.

Al-Tameemi et al., (2016) studied the performance of asphalt concrete modified with hydrated lime. Addition of hydrated lime to asphalt mixture improve the capability to resist the deformation. Hydrated lime improves the mechanical behaviour by increasing the stability of the mixture evident from 2.5 and 3 % hydrated lime content that has the highest number of load repetitions before failing. The addition of 2 to 2.5 % hydrated lime displays the most effective improvement on the Marshall properties.

2.4.2 AD-here® HP Plus

According to Hossain et al., (2011), AD-here® HP Plus liquid anti-stripping agent used by Oklahoma Department of Transportation can be added with binders at different stages. AD-here® HP Plus is an organic compound with a functional group containing a Nitrogen (N) atom with a lone pair (valance electron) and at least one Hydrogen (H) atom replaced with an alkyl or aryl group (hydrocarbons). It is a surfactant with a lyophobic amine group which is highly surface active. The molecules of "head" groups of this surfactant tend to diffuse through the lyophilic surface of the binder, while the lyophilic hydrocarbon chain ("tail" group) remain in the asphalt binder. This anti-stripping agent resist the action of water as they act as bridge between the asphalt binder and the aggregate surface.

2.4.3 Fly ash

Suheibani (1986) stated that fly ash is a fine material resulting from furnaced-burned bituminous coal. Fly ash has low specific gravity, averagely about 2.4 g/cm^3. They are relatively uniform grain-sized. It has a shade grey colour. Fly ash has been widely used as filler for asphalt mixture and has the ability to increase the resistance of asphalt mixes towards moisture damage. It is also possible to use fly ash up to 30 % by volume as a substitute for part of asphalt cement in bituminous base course, resulting in the improvement of mixture characteristic. Addition up to 6 % of fly ash lower VMA value and reduce the asphalt requirement compared to portland cement and hydrated lime. Fly ash having particles size in the range of 1-44 micron is the best asphalt extender as the coarser particles tend to create more voids among aggregates while the fine tend to stiffen mixes and produce less workable mixes which after compaction possess more voids. According to this study, medium size fly ash (1-44 micron) is reasonable to replace with the asphalt volume.

Celik (2008) stated that usage of fly ash in asphalt mixture improve the resilient modulus characteristics and resistance to stripping. The addition of fly ash did not significantly reduce field performance of asphalt concrete mixture in terms of rut depth and present serviceability index but increased the amount of surface cracking on the pavement. Celik also investigated fine aggregate replacement with fly ash in hot-mix asphalt concrete mixtures. Fly ash in amounts of 5, 6, 7 and 8 % by total aggregate weight was added as an additive to asphalt concrete mixtures. The effect of fly ash is very significant on the stability properties of HMA where 5 % of fly ash shows highest stability for asphalt mixture. Fly ash has higher optimal content than other filler as higher additive ratio obtained for the lower optimal asphalt content which favours the low cost production of asphaltic concrete.

2.4.4 Zycosoil

Arabani et al., (2012) stated the physical properties of Zycosoil, where it as a pale yellow solid at room temperature. Having a flashing point at 80 °C, its viscosity is 0.2–0.8 Pa·s at 25 °C. Zycosoil is a water-soluble reactive organosilicon compound that designed to improve the adhesion between bitumen and aggregates in hot mixed asphalt. It is typically added at about 0.5 % of asphalt binder by weight. Micromechanism effect of Zycosoil on the rate of stripping of aggregate assessed through Dynamic Modulus test.

Zycosoil cause an increase in the value of ratio of the dynamic modulus values for wet or dry condition. This can be explained by the mechanism Zycosoil where most of asphalt mixture is acidic. Due to the acidic nature, presence of water in that system causes the aggregates to have a tendency to strip from asphalt binder and stick to water.

Addition of additives to asphalt mixture causes an increase the asphalt-binder acidic property and the asphalt moisture sensitivity. Polar by nature (water soluble), Zycosoil converts to the polar hydrophilic surface, reacts with the silanol groups and condenses to form a siloxane bond (the strongest naturally occurring bond). Thus, the silanol surface has been converted at the nano level to chemically bonded siloxane with the pendant alkyl group. This alkyl group is now compatible with asphalt (i.e., maltene and improves wetting), by reducing interfacial surface tension to yield pinhole-free surface and allow air to be released completely, forming a tightly bonded layer on the interface. Addition of Zycosoil into asphalt binders modified with WMA additives causes the surface energy of adhesion between aggregate and asphalt in dry condition to increase.

Use of additives causes an increase in the adhesion Surface Free Energy (SFE) between asphalt-binder modified with additives and aggregates in the presence of water. Thus, the energy released in Zycosoil modified mixtures are lower than other mixtures, decreasing stripping.

2.5 Mixture Properties of Asphalt Mixture

2.5.1 Resistance to Moisture Damage

Assis et al., (2017) studied on the mixture properties of limestone and granite by the following proportions. C1 represents the granite aggregate asphalt mixture with granite crushed dust, while C2 stands for the granite aggregate asphalt mixture with limestone crushed dust. The ITS value of C2 was higher than that of C1. Tensile strength ratio of C2 mix was higher than C1 mix. The granite adhesion with asphalt binder was harmed by the presence of water. The composition of limestone in C2 mix show better resistance against moisture.

According to Xu et al., (2017), moisture damage of granite and limestone aggregate asphalt mixture is evaluated using the ratio of dynamic modulus test. the higher value of ratio indicates better resistance to moisture damage. Mixtures made from limestone shows better resistance to moisture damage than the mixtures made from granite. The main reason is that the adhesion between asphalt and granite is weak. It is stated that limestone which is an alkaline aggregate show better resistance to moisture as compared to granite which is as acidic aggregate.

2.5.2 Resistance to Disintegration

According to Mirzababaei, (2016), the use of Zycotherm in asphalt mixture increase the fracture energy ratio (FER). The ratio indicates the cracking performance of bituminous mixtures. The FER value of limestone aggregate asphalt mixture is higher than that of granite aggregate asphalt mixture in HMA. The adhesion and cohesion between binder and aggregate in the mixtures containing Zycotherm is higher, implies that more energy is desired to breakdown the bonds at the onset of binder and aggregate. Hence, it can be concluded that Zycotherm improves the adhesion between these two phases.

Nazirizad et al., (2015) stated that the addition of limestone as filler improves the stripping of aggregates from the specimen. The amount of coating was maximised in hydrated lime treated mixture which indicates better adhesive properties of this material.

CHAPTER 3

METHODOLOGY

3.1 Overview

Experimental approach is implemented in this study. Aggregate properties of limestone and granite collected from quarries located in Perlis and Penang respectively were tested. Limestone was supplied by PENS Industries Sdn. Bhd., while granite was obtained from Kuad Sdn. Bhd. Aggregate properties tests were carried out, namely specific gravity, water absorption, flakiness and elongation and aggregate crushing value (ACV). A surfactant namely Zycotherm at 0.1 % mass composition based on the mass of asphalt binder is used for low temperate asphalt production. Then, service characteristics of asphalt mixtures prepared using granite and limestone were compared in term of its workability, coatability and compactability. Test on workability index and coatability index were carried out to compare the performance of asphalt mixture with different types of aggregates by manipulating the asphalt temperature. CEI was evaluated to determine the amount of energy required for compaction. Tests on mixture performance were evaluated to determine the moisture susceptibility of asphalt mixture namely indirect tensile strength test (ITS) and Cantabro test. Control samples (HMA) and ALVS conditioned sample were prepared to determine the moisture resistance of samples in each condition of asphalt mixture. Then, Leutner shear test were used to measure the bond condition between asphalt samples.

3.2 Determination of Air Voids

Air voids (AV) can be stated as the total volume of small pockets of air between the coated aggregate particles throughout a compacted asphaltic concrete. Air voids is determined from Equation 3.1.

$$AV = 100 \text{ X } (1 - \frac{G_{mb}}{G_{mm}}) \tag{3.1}$$

Where G_{mb} is the theoretical maximum specific gravity and G_{mm} is the bulk specific gravity.

3.2.1 Theoretical Maximum Specific Gravity

Theoretical maximum specific gravity (G_{mm}) of asphalt mixture is the specific gravity of aggregates and asphalt binder excluding the air voids. Theoretical maximum specific gravity is needed to calculate the percentage air voids in each sample. This testing was performed in at least two specimens at the estimated optimum asphalt content.

Aggregates of 1000 g from Asphaltic Concrete Wearing (ACW) 14 gradation was batched and loose asphaltic mixture were produced. The loose mix then cooled by stirring for 15 minutes once and put in 25 °C temperature to avoid the aggregates stick together and form a clump of asphalt. The cooled loose sample was then inserted into pycnometer and some distilled water was poured until two-third of pycnometer is covered. The jar was put into the equipment called vacuum saturator for rice method as shown in Figure 3.1 to remove all the air voids in the loose asphalt mixes. The condition for this test was achieved at vacuum and zero pressure. The jar containing loose asphalt mix was taken out and distilled water was poured into the jar until reached the line on pycnometer and weighed. The calculation of maximum specific gravity is as shown in Equation 3.2.