WATER SENSITIVITY OF WARM POROUS ASPHALT INCORPORATING SASOBIT®

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WATER SENSITIVITY OF WARM POROUS ASPHALT INCORPORATING SASOBIT®

By:

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I wish to dedicate this thesis to my parents, wife, daughters and son who are always proud of me and whom I am proud of.

Without their love and support, I would not be where I am today.

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In the name of Allah S.W.T, the Most Gracious and the Most Merciful

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If you cannot in the long run tell everyone what you have been doing,
Your doing has been worthless.
Attributed to Erwin Schrödinger (1887-1961)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AAPA	Australian Asphalt Pavement Association
AAPT	Association of Asphalt Paving Technologist
ACV	Aggregate Crushing Value
AL	Abrasion Loss
AL R	Abrasion Loss Ratio
ARI	Annual Rainfall Intensity
ASTM	American Society of Testing Material
AT	Ambient Temperature
ATR	Attenuated Total Reflectance
BS	British Standard
BSI	British Standard Institute
CEN	European Committee for Standardization
CT	Computed Tomography
CaO	Calcium Oxide
$CaCO_3$	Calcium Carbonate
$Ca(OH)_2$	Calcium Hydroxide
DBC	Design Binder Content
DOT	Department of Transportation
DB	Drainage Binder
DRI	Danish Road Institute
DASM	Dynamic Asphalt Stripping Machine

DSC	Differential Scanning Calorimetry
DSR	Dynamic Shear Rheometer
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infrared Spectroscopy
GLM	General Linear Model
GSLA	Granulated Synthetic Lightweight Aggregate
HMA	Hot Mix Asphalt
HPU	Highway Planning Unit
ITS	Indirect Tensile Strength
ITSR	Indirect Tensile Strength Ratio
JKR	Jabatan Kerja Raya
LAAV	Los Angeles Abrasion Value
LTA	Long Term Aging
MgO	Magnesium Oxide
MPa	Mega Pascal
NAPA	National Asphalt Pavement Association
Na_2CO_3	Sodium Carbonate
NCAT	National Center for Asphalt Technology
NMAS	Nominal Maximum Aggregate Size
OGFC	Open-Graded Friction Course
OH	hydroxyl
OPC	Ordinary Portland Cement
PA	Porous Asphalt
PAV	Pressure Aging Vessel
PAC	Porous Asphalt Concrete

PG	Performance Grade
PI	Penetration Index
PMB	Polymer Modified Bitumen
PMD	Pavement Modifier
PFC	Porous Friction Course
PSV	Polished Stone Value
RoAM	Raveling of Asphalt Mixes
RV	Rotational Viscosity
PWD	Public Works Department
RAP	Recycle Asphalt Pavement
RTFO	Rolling Thin Film Oven
R&W	Riedel and Weber
SBS	Styrene-Butadiene-Styrene
SEM	Scanning Electron Microscope
SGM	Specimen Geometry Method
SiO_2	Silica
SiOH	Siliceous Hydroxy
SMA	Stone Mastic Asphalt
SSD	Saturated Surface Dry
STA	Short Term Aging
TRB	Transportation Research Board
TRL	Transportation Research Laboratory
TU Delft	Delft University Technology
USM	Universiti Sains Malaysia
UK	United Kingdom

VAI	Viscosity Aging Index
WAL	Wet Abrasion Loss
WMA	Warm Mix Asphalt
XRD	X-Ray Diffraction

LIST OF SYMBOLS

G_{mb}	Bulk Specific Gravity
G_{mm}	Theoretical Maximum Density
k	Coefficient of Permeability
M_a	Mass of the Specimens in Air
G*	Complex Shear Modulus
δ	Phase Angle
dB	decibel
°C	Degree Celsius

SENSITIVITI AIR KE ATAS ASFALT BERLIANG SUAM MENGANDUNGI SASOBIT®

ABSTRAK

Industri asfalt melakukan usaha berterusan untuk mengurangkan penggunaan tenaga dan pencemaran dengan merendahkan suhu pengeluaran asfalt. Ini boleh dicapai dengan menggabungkan bahan tambah asphalt suam yang dikenali sebagai Sasobit®. Dalam kajian ini, sifat reologi bitumen konvensional 60/70 gred penusukan dengan dan tanpa Sasobit® dalam keadaan pengusiaan yang berbeza telah diselidik. Bahan tambah Sasobit® meningkatkan indeks penusukan dan modulus kompleks (G*), walaupun terdapat pengurangan dalam sudut fasa (δ). Peningkatan kandungan Sasobit® sebanyak 3% menurunkan suhu campuran dari 160°C ke 150°C. Peningkatan kandungan Sasobit® sebanyak 1%, 2% dan 3% meningkatkam gred pengikat asas (PG 70) menjadi PG 73, PG 74 dan PG 76, masing-masing. Tiada perubahan suhu campuran yang ketara diperhatikan dengan penambahan Sasobit® sebanyak 3% hingga 4%. Walaubagaimanapun, pengurangan suhu campuran mungkin menghalang kelembapan menyejat sepenuhnya dari permukaan agregat dan memberi kesan ke atas ikatan bitumen lalu menyebabkan bahan lebih mudah terdedah kepada pelucutan. Dua agen anti-pelucutan iaitu kapur terhidrat dan *Pavement Modifier* digunakan untuk mengurangkan kesan kerosakan lembapan ini. *Dynamic Asphalt Stripping Machine (DASM)* yang mensimulasi air hujan telah digunakan untuk menggalakkan pelucutan agregat. Selepas proses pelucutan dinamik, spesimen yang diuji menggunakan ujian kekuatan tegangan tidak langsung dan ujian *Cantabro* menunjukkan kekuatan yang lebih rendah dan pengurangan

rintangan peghancuran akibat pelucutan mastik berbanding kaedah rendaman. Spesimen yang mengandungi campuran *Pavement Modifier* sebagai bahan pengisi meningkatkan rintangan terhadap pelucutan agregat berbanding campuran yang mengandungi kapur terhidrat sebagai bahan pengisi tanpa mengira suhu pemadatan. Berdasarkan kepada Piawaian standard Eropah, campuran yang mengandungi *Pavement Modifier* dan kapur terhidrat boleh di padatkan pada suhu serendah 130°C dan 140°C, masing-masing berbanding 125° C dan 135° C dengan kaedah rendaman dan diuji menggunakan ujian *Cantabro*.

WATER SENSITIVITY OF WARM POROUS ASPHALT INCORPORATING SASOBIT®

ABSTRACT

The asphalt industry is making constant efforts to minimize energy consumption and reduce emissions by lowering asphalt production temperature. This can be achieved by incorporating warm asphalt additive named Sasobit®**.** In this study, rheological properties of a conventional bitumen 60/70 penetration grade with and without Sasobit® at different aging conditions have been investigated. The addition of Sasobit® content increased penetration index and complex modulus (G*), despite reduction in phase angle (δ). By adding 3% Sasobit®, the mixing temperature is decreased from 160°C to 150°C. Meanwhile, adding 1%, 2% and 3% of it increased the PG 70 base binder to PG 73, PG 74 and PG 76, respectively. There was no significant change observed in the mixing temperature from 3% to 4% of Sasobit® addition. However, the reduction of mixing temperatures may prevent moisture from being completely evaporated from the aggregate and so affect the bitumen bond, making the mixture more susceptible to stripping. Two anti-stripping additives, namely hydrated lime and Pavement Modifier (PMD) were used to reduce the destructive effects of moisture. The Dynamic Asphalt Stripping Machine (DASM) that simulate rainfall event was used to enhance stripping. Upon subjected to dynamic stripping, specimens were tested for indirect tensile strength and Cantabro test showed lower strength and less resistance to disintegration due to stripped mastic as compared to immersing condition. Specimen incorporating PMD filler improved resistance to stripping compared to mixes with hydrated lime filler

regardless of compaction temperature. Based on the European standard, mixes incorporating PMD and hydrated lime can be compacted to temperatures as low as 130°C and 140°C, respectively compared to 125°C and 135°C conditioned via water immersion and tested using Cantabro test.

CHAPTER 1

INTRODUCTION

1.1 Preface

The fundamental properties of bituminous mixture influence the stability and durability of asphalt pavement to withstand the destructive effects of dynamic wheel loading. The interaction between air, water and temperature bring about damages that can lead to substantial pavement disintegration. Accumulation of ponding water leads to hydro-planning that causes skidding and affects maneuverability of moving vehicle. Extensive research has been carried out to ensure that the concept of perpetual pavement is a reality. The introduction of porous asphalt (PA) provides effective solution to address some of the engineering related setback experienced by road users. Prolonged pavement life benefits road authorities and road users by ensuring comfortable ride and lower maintenance cost in the long run.

The European Union countries with the best road safety records, such as Sweden, the United Kingdom and the Netherlands, were the first to set quantified targets to reduce the number of victims to derive maximum benefit from potential improvements in road safety (Law et al., 2005). Mo et al., (2011) mentioned that 90% of highways in the Netherlands are made of PA. The quest for comfortable driving experience, traffic noise reduction and improving road safety encourage the wide application of PA on road surfaces. In Malaysia, the earliest PA trial took place in 1991 on the Cheras-Beranang Road aimed at reducing traffic accident. In addition, roads along the Kerinchi Link, Kuala Lumpur also was laid with PA to reduce traffic noise (Hamzah et al., 2002).

The mix design of PA differs from conventional dense asphalt because the former is made up of predominantly coarse aggregate. The mix design must conform to the Malaysian Public Works Department specifications (JKR, 2008) to ensure acceptance by the road authority. The coarse aggregate used should have ample strength to withstand applied loads since PA does not benefit from the cushioning effect of the fine materials. The interconnected air voids provides channel for water to percolate through. According to Elvik and Greibe, (2005), a good PA gradation must have air voids exceeding 20%. The open structure of PA reduces traffic noise, drains water from the road surface and reduces thermal conductivity. Ferguson (2005) describes PA as an innovative road surfacing technology that was initially developed to facilitate rapid removal of surface water during and after a downpour. PA improves driver visibility by reducing splash and spray, eliminates glare from vehicle light for comfortable driving condition.

At the asphalt mixing plant, hot mix asphalt (HMA) is dried and mixed inside a huge rotating drum and heated up to 160°C. Generally, the bitumen-aggregate coating is enhanced at elevated temperature, thus improving mix workability during paving operations. In addition, high temperature mixing in less than 60 seconds, eliminates moisture trapped within the mixes (Hearon and Diefenderfer, 2008; Myers et al., 2000). However, continuous heating at elevated temperatures is not sustainable economically and bad for the environment issues related to greenhouses gases and hazardous chemical emissions, workers exposure to fume and polycyclic aromatic hydrocarbon have become a global concern that merit everyone's attention including asphalt technologists. There must be an alarming awareness in sustainability-related issues including global warming and production of greenhouse gases must be controlled (You and Goh, 2008).

1.2 Problem Statement

The concerns of global warming and emissions of greenhouse gases have led to the development of new technologies in asphalt industries particularly the Warm Mix Asphalt (WMA). WMA can reduce carbon emissions and lower fuel consumption by reducing the mixing and compaction temperatures of asphalt mixes as compared to conventional Hot Mix Asphalt (HMA) (Croteau and Tessier, 2008). Typically, the mixing of WMA ranged from 100°C to 140°C compared to the mixing temperatures of 150°C to 180°C for HMA (Gandhi, 2008a). The technologies incorporated additives to be added into the mixes to reduce mixing temperature without affecting the mix performance. This can be achieved by adding an additive to a binder, one of which is a synthetic wax type called Sasobit®. According to Hurley and Prowell (2005), the addition of Sasobit® does not affect the resilient modulus of an asphalt mix and increase the rutting resistance as measured by the asphalt pavement analyzer. The rutting potential did increase with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder resulting from the lower temperatures as well as from the anti-aging properties of Sasobit®.

However, preparation of mixes at lower temperature gives rise to the problem of stripping. Kim et al., (2012) found that despite their benefits, asphalt mixture prepared using the WMA additives suffered the increasing tendencies to rutting and moisture susceptibility. Due to being heated and dried at lower temperatures, the moisture incompletely dried from the aggregates and possible presence of water in mixtures, which influenced the aggregate-bitumen bonding and potential to stripping. Meanwhile, infiltration of moisture into the asphalt mixture can cause stripping, resulting in weakening the asphalt-aggregate bond and subsequent dislocation of the aggregate, leading to pothole formation (Pinto et al., 2009). D'Angelo et al., (2008) reported that the presence of entrapped water within at the bitumen-aggregate interface causes adhesion failure between water and asphalt mix that affects pavement strength and shortens its design life.

Aksoy et al., (2004) described stripping of PA as a process of weakening or gradual loss of adhesive bond in the presence of moisture between the aggregate surface and bitumen. In addition, the open structure of PA exposes large surface area to the atmosphere and thus enhances binder aging. Kok and Yilmaz, (2008) stated that increased adhesion reduced stripping and increased pavement durability. The resistance to moisture damage in PA was evaluated by initially immersing the specimens in the water at designated temperatures without considering the effects of water flow through the connected macro-pores in the mix. There appears to be a gap in the literature to evaluate the moisture sensitivity of mix due to the dynamic action of flowing water through the internal pore structure. This led to the development of the dynamic asphalt stripping machine that subjected specimens to the dynamic action of flowing water and then computing its water sensitivity.

1.3 Objectives

The study aimed to fulfill the following objectives:

i. To investigate the rheological properties of asphalt binder and its chemical characteristics with respect to its functional group due to oxidation prepared with different Sasobit® contents.

ii. To develop a new aggregate grading for PA based on the Dutch aggregate gradation to suit Malaysian PA practice.

iii. To conduct a comparative study of the effects of different types of anti-stripping additive on aggregate-bitumen bonding, tensile strength, resistance to disintegration and effectiveness to resist stripping.

iv. To develop test procedures to assess aggregate-bitumen bonding due to the presence of water that enables prediction of water induced damages in PA mixes containing different Sasobit® contents at different temperatures.

v. To develop test procedures that enable prediction of water induced damages in PA mixes containing different Sasobit® contents at different compaction temperature using a newly developed Dynamic Asphalt Stripping Machine (DASM).

1.4 Scope of Study

This study focuses on the characterization of warm porous asphalt. For PA specimen, aggregate type granite produced by a local quarry was used. The asphalt binder used was a conventional bitumen grade 60/70, while hydrated lime, PMD and Ordinary Portland cement (OPC) were used as fillers. The material properties must comply to the Malaysian Public Works Department specifications for porous asphalt (JKR, 2008). The aggregate grading used was a modification to the grading used in the Netherlands. The Original Dutch gradations, namely PAC 0/11 and PAC 0/16 were referred to while developing new PA gradation since the Dutch gradation sieve sizes were not compatible with the standard aggregate sizes produced by the local quarries. A series of tests to evaluate PA specimen's air voids, permeability and indirect tensile strength (ITS) were carried out. Binders with stipulated Sasobit® contents were evaluated using the dynamic shear rheometer to investigate rheological behaviours after being conditioned in a rolling thin film oven (RTFO) and pressure aging vessel (PAV) to simulate short-term and long-term aging.

The effectiveness of anti-stripping additives was evaluated through ITS, resistance to disintegration, determination of air voids and permeability tests. The specimens were further analyzed using DASM to evaluate the effectiveness of anti-stripping agent. The DASM was originally developed by Hasan (2011) based on the dynamic action of water on WMA to simulate a rainfall event. A new test procedure was developed to accelerate the stripping process in PA mixes.

1.5 Organization of the Thesis

A general introduction to the research project is presented in Chapter 1. Chapter 2 provides a literature review of recent WMA implementations and technologies globally. This chapter also describes in detail the problems related to moisture induced damages. The methodology used to conduct the research is given in Chapter 3. This chapter also discusses and evaluates the properties of the materials used in accordance to test standards. In addition, detailed explanations on additives used were included in this chapter. Aging conditions, rheological properties of asphalt binder and chemical characteristics due to oxidation were highlighted as well. The PA mix design are discussed in Chapter 4. This chapter highlights the preparation of a new aggregate gradation and design binder content determination for the single layer Dutch PA. Some of the results related to the PA mix design are summarized in this Chapter 5. Chapter 6 discuss the moisture sensitivity of PA. The moisture sensitivity of loosen mixes were reported in this chapter. The acceleration of stripping process using compacted specimens was explained and the explanation of a comparison work between water-immersing method and a newly developed method using DASM are discussed in detail. Chapter 7 highlights the resistance of disintegration of PA. The influence of anti-stripping additives in reducing mixing temperatures and its effects on aggregate bonding are also reported in this chapter. Different sample conditioning methods (using static water and running water) are explained in this chapter as well. The research conclusions and recommendations for future works are outlined in Chapter 8.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Porous asphalt (PA) has been used for the past 60 years to improve surface friction and wet weather driving conditions by allowing rain to drain through its porous matrix. A well-designed PA promoted good mix properties, more durable and caused minimum traffic induced damages during its service life (Nicholls and Carswell, 2001). The production of asphalt mix requires pre-heated aggregates to remove existing moisture. The moisture content should be less than 0.5% before mixing otherwise there is likely to be debonding issues and premature durability problems (Koenders et al., 2000). The bitumen was pre-heated since temperature control is crucial for aggregate coating. The amount of fuel consumed is relatively large due to continuous aggregate heating. Nowadays, modern asphalt plants must consider energy saving and environmental awareness to minimise the effects of global warming. Increased consumed energy cost, global warming and a more stringent environmental regulation had resulted in a global interest in warm mix asphalt technology, commonly abbreviated as WMA (Hurley and Prowell, 2005).

Unfortunately, PA aged faster due to continuous exposure to severe climate and traffic that resulted in a shorter service life. The aging of the binder is a major contributor to poor performance of PA pavement layers. Loss of aggregate particles from the surface occurred if the adhesion between aggregate and bituminous cohesion is lost (Mallick et al., 2000). However, during the production of warm asphalt mixes, lower mixing temperatures caused incomplete elimination of aggregate surface moisture. In tropical countries like Malaysia, frequent heavy rainfall exposed the PA structures to water induced damages. Increased air voids had exposed pores structure to running water that eroded the binder film, washing the particles and eventually affecting mix properties (Hasan, 2011). Therefore, anti stripping additive namely hydrated lime; is used in asphalt mixes to increase the adhesion and improved the bond strength between asphalt binder and aggregates. The increased adhesion helps to reduce stripping potential, resulted in a more durable pavement. (Kok and Yilmaz, 2008).

2.2 Porous Asphalt

PA is widely used for water drainage and noise reduction to improve traffic safety and driving comfort. The wet weather driving conditions has been improved since the water drained through the porous structure, avoiding standing water on the road surfaces. Typically, PA consists of coarse aggregate with small amount of sand and filler, thus creating a more open texture and a permeable structure with good permeability. It is a mixed combination of a bituminous binder, high proportion of coarse aggregates and limited amount of fine and filler with air void in excess of 20% (Ferguson, 2005; Barrett, 2008). According to Alvarez et al., (2011), in the United States of America, PA is known as permeable friction course (PFC) or new generation open-graded friction course (OGFC). In Europe, the mix is termed and identified as PA. A schematic illustration of pore matrix in both dense-graded and PA are shown in Figure 2.1.

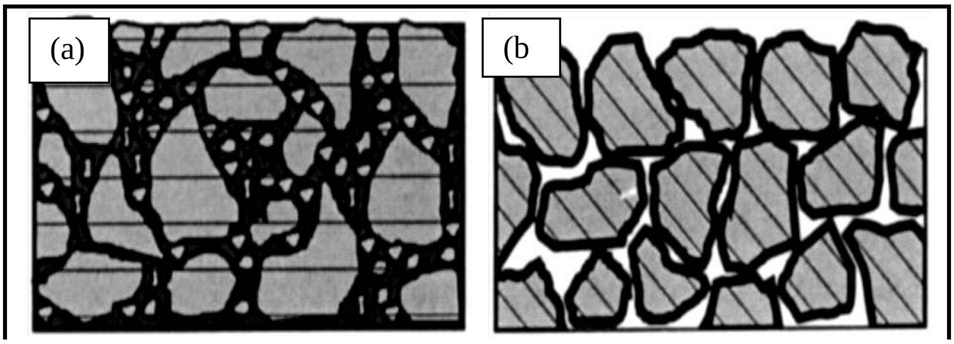

Figure 2.1: Schematic illustration of air void in (a) Dense-Graded and (b) Porous Asphalt (Chen et al., 2004)

A high quality aggregate is used to ensure proper stone-on-stone contact and created channels of connected air void. Hunt et al., (2002) and Barrett, (2008) found that permeable pavement has been proven to decrease surface runoff and substantially lower peak discharge. It acted as a filter for the storm water. The suspended solids and other particulate pollutants were retained as the water flows through the pores.

2.2.1 Mix Design

PA mixture design includes the determination of minimum and maximum binder content required and modification of the aggregate grading. The larger maximum aggregate size and lower fine aggregate used, resulted in mixes that are prone to abrasion loss. Meanwhile, the adequate affinity between the binder and aggregate also improves resistance to disintegration. Thus, the use of modified binder and quality filler is important. Hamzah et al., (2004) proposed an aggregate gradation designed based on the packing behaviour of dry aggregate mass to develop mixes with high air voids and good drainage. Sufficient air void in asphalt mixture is very critical to ensure the drainage capacity in PA pavement. While the shape of the aggregate particles and bitumen content do contribute, the aggregate gradation of asphalt mixture is an important factor affecting the air void (Liu and Cao, 2009).

The Federal Highway Administration (FHWA) introduced an aggregate grading chart to determine the densest aggregate packing for dense mix. This was obtained by a gradation drawn on a 0.45 power chart as a straight line from the origin to the nominal maximum aggregate size, and desired for a low air void content (Robert et al. (1996). In contrast, Cabrera and Hamzah (1996) adopted the aggregate packing theory and proposed a gradation for PA based on the concept of ‘designing to a target porosity', while Takahashi and Partl (2001) used the wet-packing method. The air void in asphalt mixtures is fundamental in the mix design and is greatly influenced by the amount of coarse aggregate. According to McDaniel and Coree **(**2003), the aggregate sizes used in the Europe ranges from 6.0 mm to 14.0 mm to produce higher air void and reduced traffic noise. Suresha et al., (2009a) found that larger-sized aggregate grading provides superior performance than finer graded mixes in terms of hydraulic-conductivity. Less than 20% of aggregate passing a 4.75 mm sieve is crucial to achieve coarse aggregate stone-on-stone for better permeability.

The optimum binder content also has a significant effect on PA performance. Lower bitumen content caused incomplete coating of aggregates. A rapid oxidation might occurred due to thinner bitumen film and eventually caused ravelling. In contrast, excess bitumen content led to binder drainage (Whiteoak, 1990). According to Hamzah et al., (2010a), decreased binder content in PA mixes, increased air void and decreased the resistance to abrasion, which resulted in lesser adhesion between aggregate particles. A thin binder coating is inadequate to prevent particles from being dislodged by traffic. It also aged more rapidly, thus aggravating the raveling problem. Therefore, the gradation and design binder content is a primary consideration in asphalt mix design and affects the mixture properties of PA (Hasan, 2005).

2.2.2 Advantages of Porous Asphalt

PA pavement with high air void and good permeability provides some benefits. The environmental and safety benefits of PA includes storm water management, water quality and improved safety for road users. Cooley et al., (2009) reported that the performance of PA is divided into two separate categories: service life and performance life. Service life is defined as the length of time a PA maintained its frictional properties and smoothness, while performance life is defined as the length of time the PA maintained its beneficial properties.

2.2.2.1 Improve Skid Resistance

The resistance to skidding of a road surface is one of the highway safety requirements that must be considered in pavement design to provide a safe travelling surface. Kane et al., (2010) stated that skid resistance depends directly on the friction between road surface and tire tread, which is influenced by the road surface texture. According to Fwa et al., (2003), skid resistance was governed by the properties of the aggregate in the wearing course of the surface layer, which involved the aggregate spacing, or gap width between aggregates. The friction was enhanced by the macrostructure of the pavement surface and PA has higher macrotexture than dense graded mixtures (Huber, 2000). However, the macrostructure is the overall pavement surface texture that provided drainage for water and had dominant frictional property contribution at higher speeds (McDaniel and Coree, 2003). Ahammed and Tighe, (2009) reported that skidding has contributed up to 35% of wet weather accidents. Skid resistance is a function of microstructure and macrostructure as shown in Figure 2.2.

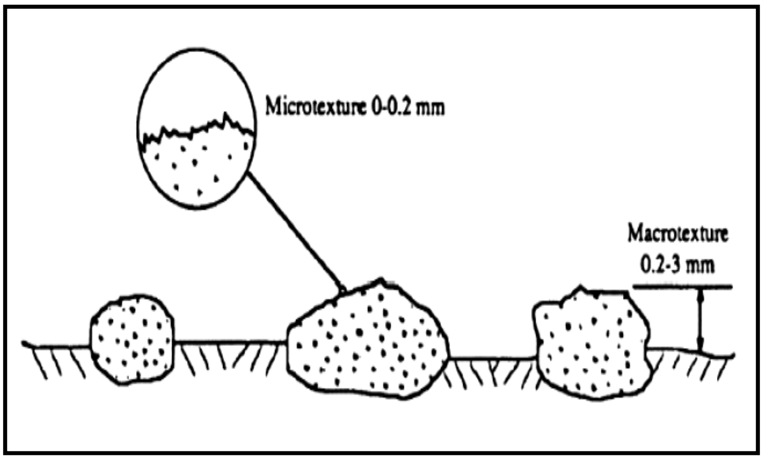

Figure 2.2: Illustration of microtexture and macrotexture of a road surface (Tighe et. al., 2000)

A recent study by the North Carolina Department of Transportation (DOT) found that crashes decreased significantly with an increased in pavement macrotexture. Pavement macrotexture less than 3.0 mm was found to be the most appropriate in providing safe and efficient transportation to road users (Pulugurtha et al., 2008).

2.2.2.2 Reduction of Splash and Spray

Use of PA improved visibility by reducing splashing and spraying from passing vehicles (Tan et al., 1997). On impermeable surfacing, accumulated water on wet surface created splash and sprays. Yager et al., (2009) has summarised the phenomenon of splash and spray as follows: “Splash tends to be relatively large droplets which move in ballistic trajectories and are associated with deep water or low speeds. Spray is composed of the smaller droplets, which tend to be suspended in the air and are associated with shallow water or high speeds". Rungruangvirojn and Kanitpong, (2009) measured the visibility loss due to splash and spray between PA, Stone Mastic Asphalt (SMA) and conventional asphalt pavement. The researchers found that pavement surface type was significantly affecting the visibility loss due to splash and spray. The visibility loss of PA and SMA was 1.4 times lower than conventional pavement. At high-speed (80 km/h), PA reduced the visibility by 28% compared to 55% and 30% for dense graded mix and SMA, respectively. In the United Kingdom, Nicholls (1999) found that compared to dense asphalt, spray was reduced by 95% initially and even after 8 years by 66% when utilising PA.

2.2.2.3 Reduction of Hydroplaning Potential

Hydroplaning is a phenomenon whereby the tires of moving vehicle were partially or completely separated from the road surface by a layer or film of water (Yager et al., 2009). Hydroplaning occurs when the tyres hit the ponding water at high speed. This hazardous situation led to the loss of control during steering, braking and accelerating while driving during wet weather. The situation is extremely hazardous as the driver loses steering and braking control, and any slight differential drag between the two wheel paths could cause the vehicle to spin (Glennon, 2006). Unfortunately, the phenomena gets worse as the dirt and oil flew to the top of the water causing slippery road due to not only water but also even more slippery surface of oil and dirt. There are three main factors that cause hydroplaning namely speed, tread depth and water depth. The ability of PA drainage, remain in continous the vehicle contact tyre with the surface of pavement, and thus reduces the possibility of aquaplaning. The more worn the tyres are and the shallow the tread, the more likely the vehicle is to hydroplane. In addition, as the water gets deeper, the vehicle loose traction sooner (Yager et al., 2009). Thus, the application of PA that functions to prevent ponding water on road surface has reduced hydroplaning potential.

2.2.2.4 Reduction the Effects of Light Reflections

Another advantage of PA is its ability to reduce glare (Subagio et. al., 2005). On an ordinary road, during rainy day thin water film will form on the road surface. Glare is generated by the reflection of vehicle headlight on the wet pavement surface. The use of PA reduced the headlight glare from reflection on wet surfaces by providing a dry riding surface (Tan et. al., 1997). Figure 2.3 shows the reduction of light reflection using PA.

Figure 2.3: Light reflection on porous and dense asphalt (Barrett and Shaw, 2007)

In addition, visibility is impeded by the presence of fog; high winds can make controlling a vehicle difficult, especially when the vehicle is high-sided in crosswinds; and slippery road surfaces increase the likelihood of skidding (Edwards, 2002).

2.2.2.5 Reduction of Road Noise

Hanson et al., (2005) showed that the modification of pavement surface type using porous surfacing such as PA has succeeded to reduce noise. In European countries, where stricter environmental regulation related to traffic noise, the implementation of PA offers a big potential to reduce traffic noise. The reduction of noise generation is beneficial for the environment and provides comfort for the drivers (Elvik and Greibe, 2005). Nicholls et al., (2002) mentioned that the noise generated from vehicle tyres on a rigid pavement was 5 dB (A) to 7 dB (A) higher than on asphalt roads. In Malaysia, traffic noise is not given due consideration in the past. However, recently, noise started to become an issue, particularly on expressways traversing near the residential in urban areas notably the capital city of Kuala Lumpur (Hamzah, 2007). A study by Golebiewski et al., (2003) proved that at different velocities, the noise level generated from the PA was less compared to the noise produced when vehicles move on dense asphalt. The reduction of noise level decreases by 3%, 5.6% and 6.7% at vehicle speeds of 20 km/h, 40 km/h and 60 km/h, respectively. They found that the noise from the PA was less annoying than the noise from the dense asphalt at all vehicle speeds, change of the road surface, from dense to porous surface, leads to the reduction of traffic noise. As depicted in Figure 2.4, the difference in noise levels produced on both road surfaces are more significant at higher velocity. The change from dense to porous road surfaces has led to reduction of drive by noise annoyance for velocities between 20 km/h to 60 km/h.

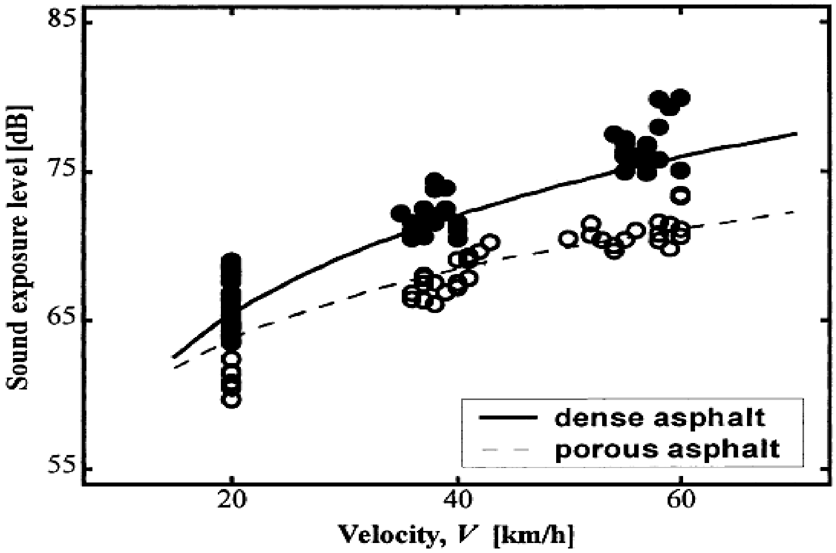

Figure 2.4: Sound exposure level of porous and dense asphalt at V = 20, 40, 60 km/h, respectively (Golebiewski et al., 2003)

PA is quieter because its texture is made up of holes rather than lumps. Particularly, noise is generated by tyre vibration and the movement of air particles in the tread patterns. The air void at the road surface reduced noise generated from tyre-pavement contact. Thereby, the aggregate's pores in the PA retarding the ability of the sound waves to travel long distances intercept sound waves and mainly absorbs it (Braga and Connolly, 2010).

2.2.3 Disadvantages of Porous Asphalt

Despite its environmental benefits, PA can suffer from problems, which can affect both its performance and service life. Some of the disadvantages of PA are summarised in the following sections.

2.2.3.1 Clogging

Major problem with PA is clogging, which causes air voids closure. When air voids closed up, mix permeability is reduced and may reach a point where it ceased to inhibit ponding water. Huber, (2000) found that PA ageing is one of the factors that reduce the ability to transmit water through the connected air void. The debris collecting in the pores plugs the mix and loss of voids due to traffic loading or traffic densification hence reducing the permeability of PA. In addition, when sand or de-icing material is used especially in northern climates, debris collected in pores is not flushed out by the action of the traffic, thus after several years, levels the PA drainage performance to conventional pavement. Cleaning methods including vacuum vehicles with hydraulic water jets had been developed to maintain the advantages of PA (Schaus, 2007). Nevertheless, in Europe, urban environment success has been reported using a novel double layer PA that provided the benefit to resist surface clogging (Van Bochove, (1996). Huber, (2000) suggested that additional resistance to clogging can be achieved by increasing the air void to 20 % or more.

2.2.3.2 Shorter Life Span

Huber (2000) claimed that OGFC has been used in the United States since 1944 the least. The pavement life ranged from 7 years to 13 years, which is less than typical dense pavement. In addition, the pavement deteriorates very rapidly, just in a matter of months after it reached its design life. Herrington et al., (2005) highlighted that the average lifetime for PA in New Zealand is 10.5 years, which is lower compared with that of dense mixes for 16 years. The shorter life is due to factors such as binder content and type, aggregate gradation, traffic volume and climate.

The most critical factors in the performance of bituminous mixes are due to the tendency of the binder film on the surface of the aggregate to be continuously exposed to the effects of oxygen, sunlight and water. When the bitumen becomes too hard and brittle, the aggregate striped from the asphalt mix. However, the adoption of modified binder to counter the tendency to ravel has lengthens the life span of PA (Huber, 2000). The service life of PA and other pavement as summarized in Table 2.1.

Table 2.1: Porous asphalt and other pavement service life (Alvarez et al., 2006)

Country	Type of Mixture	Service lift (Years)
United States (Arizona)	Rubber Modified OGFC	13
United States (Wyoming)	OGFC	15
United States (TxDOT)	OGFC	6 to 8
United Kingdom	PA	7 to 10
Demark	PA	7
France	PA	8 to 12

2.2.3.3 Aging and Stripping

Birgisson et al., (2006) mentioned that, the open nature of PA allowed faster oxidation and binder embitterment, which rapidly increased the stiffness of the binder over time. According to Poulikakos and Partl (2009), the open structure of PA exposed a large binder surface area to the oxidative effect of air, led to rapid aging of the binder. In addition, water ingress may lead to moisture damage of the bitumen aggregate bond and structural distress of the compounds, which in turn stripping of the road surface layer.

Stripping, amongst other moisture damage distresses, is commonly believed to be caused by water induced loss of adhesion between asphalt binders and aggregates (Gorkem and Sengoz, 2009). Abo-Qudais and Al-Shweily, (2007), stated that the stripping might cause different types of distress such as ravelling, rutting, shoving and cracking. According to Jahromi (2008), moisture damage can be classified with two mechanisms, loss of adhesion due to water in between the asphalt binder and the aggregate and stripping away the binder film and loss of cohesion due to softening of asphalt binder mixtures mastic. Zeng and Ksaibati (2003) found that moisture caused damages to asphalt mixture, weakening of the bond between the asphalt and aggregate and consequently enhanced premature deterioration of asphalt pavement.

2.2.3.4 Ravelling and Low Resistance to Disintegration

The faster oxidation and binder embrittlement of PA compared to the conventional mixes lead to ravelling under traffic shearing stresses, making it rough and undulate (Herrington et. al., 2005). Huber, (2000) stressed that PA pavements typically failed by ravelling and disintegration when the asphalt binder aged and became brittle. In turn, aggregate particles are dislodged and pavement experience ravelling. Unfortunately, rapid ravelling process caused the entire pavement layer to disintegrate in a matter of weeks. Sasana et al., (2002) studied the quality of PA using local materials in Indonesia. They found problems such as aggregate loss due to ravelling and plastic deformation related with rutting. Sometimes ravelling occurred when the pavement is only 6 to 8 years old. Low resistance to disintegration means PA cannot withstand high turning force (Huber, 2000).

2.2.3.5 High Construction Cost

Construction costs of PA is more expensive compared to conventional asphalt mix due to the requirement for high quality aggregates and the use of modified binder to consider the field performance. Huber, (2000) stated that the cost per ton of PA in the United States is between 10% to 80% higher than the cost of dense asphalt. According to Nielsen (2006), when unmodified asphalt is incorporated into the mixture, the extra cost is in the range of 6% to 38%. The cost of PA containing modified asphalt is 50% to 80% higher than the cost of dense asphalt containing unmodified binder. Katman et al., (2005a) also agreed that the materials and construction costs of PA are higher than conventional asphalt mixtures. However, the researchers insisted that cost benefit analyses and practical experience has proved that the benefits of PA compensate the extra construction costs.

2.2.3.6 Low Stability

According to Woodside et al., (1999), another drawback of PA is the low pavement strength. It is a known fact that the proportion of fines in an aggregate gradation affects mix stability. Nelson (2006) stated that in order to achieve a high percentage of voids the fine aggregate content is lowered and the mortar content must be drastically reduced compared to dense asphalt mixes. Generally, mixtures with lower fine contents will exhibit lower stability and vice versa. Meanwhile, higher coarse aggregate content implicates higher permeability but reduction in strength and lacking in durability. Further, Woodside et al., (1999) mentioned that in PA the source of stability is from aggregate interlock, enhanced by the stability of the coarser aggregate matrix. However, the stability value of PA is lower than that of dense asphalt, but increases as the gradation becomes less open by integrating more fines. In fact, PA wearing courses have a low structural strength compared to conventional pavement.

2.3 Laboratory Evaluation of Porous Asphalt

Mixture density and corresponding total air voids are the main parameters for PA mix design and evaluation. Therefore, Marshall compaction at 50 blows per face is extensively used for mix design of PA mixtures. However, Suresha et al., (2009b) recommended compaction at 35 blows per face for mix design of PA. A compaction level of 75 blows per face was suggested to assess the over-compaction mixture response. These recommendations were based on a macroscopic evaluation of density, aggregate breakdown and stone-on-stone contact and widely practice for open graded friction courses (OGFC) mix design and evaluation in the United States (Watson et al., 2003; Suresha et al., 2009c).

2.3.1 Permeability of Porous Asphalt

Hydraulic-conductivity or permeability is one of the major indicators to measure the drainage capability of PA mixes. According to Alvarez et al., (2006), the common approach to determine the drainage capability of PA is by measuring the time taken for the discharge of a specific water volume. In general, the permeability of PA mixtures is controlled by the size and interconnection of the air void. Hamzah (1995) studied the PA permeameter of saturated asphalt samples using a falling-head permeameter by recording the interval of time taken to reach a known change in head across the specimen. Fwa et al., (2001) used an automatic field hydraulic parameter device to determine in-situ field permeability. The most common approach for mix design is to consider minimum targeted air voids and measurement of permeability on laboratory compacted specimens. The National Center of Asphalt Technology (NCAT) and ASTM D7064 (ASTM, 2005) procedures recommended a minimum permeability value equivalent to 0.116 cm/s (Alvarez et al., 2011).

2.3.2 Relationship Between Air Voids and Permeability

The permeability of PA mix is controlled by the shape and size distribution of aggregates, and interconnection of the air void (Liu and Cao, 2009). According to Tarefder et al., (2005), the grain-size distribution influenced the air void in mix and considered as a key factor that affected the water accessibility of an asphalt mixture. The pore space of the PA formed as an interconnected air void that promoted permeability and isolated air void that discouraged permeability. Figure 2.5 shows the relationship between the connected air void and coefficient of permeability *(k)*.

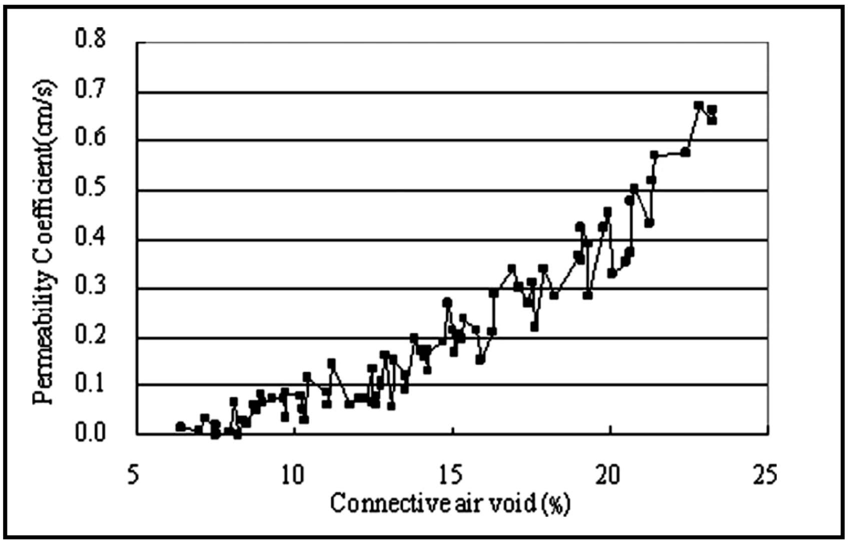

Figure 2.5: Relation between connective void and permeability coefficient (Liu and Cao, 2009)

Hamzah et al., (2012b) stated that the high-interconnected air void confers its vast benefits compared to the traditional dense mix, which include the prevention of hydroplaning and reduction of splash and spray. Sufficient air void is indispensable to ensure the drainage capacity of PA. Kayhanian et al., (2012) studied the field permeability measurement of OGFC pavements in parking lots in California. In their study, the results produced from the computed tomography (CT) scanning images on OGFC core samples confirmed the air void and the permeability measured using the NCAT field permeameter. The core samples with higher air void recorded a higher permeability. However, the permeability measurements were unable to distinguish the differences in existing air void at different sample depths. The permeability results indicated that higher porosity has higher permeability. The high correlation between these two parameters was confirmed by measuring the coefficient of permeability and air void in core specimens of OGFC as shown in Figure 2.6.

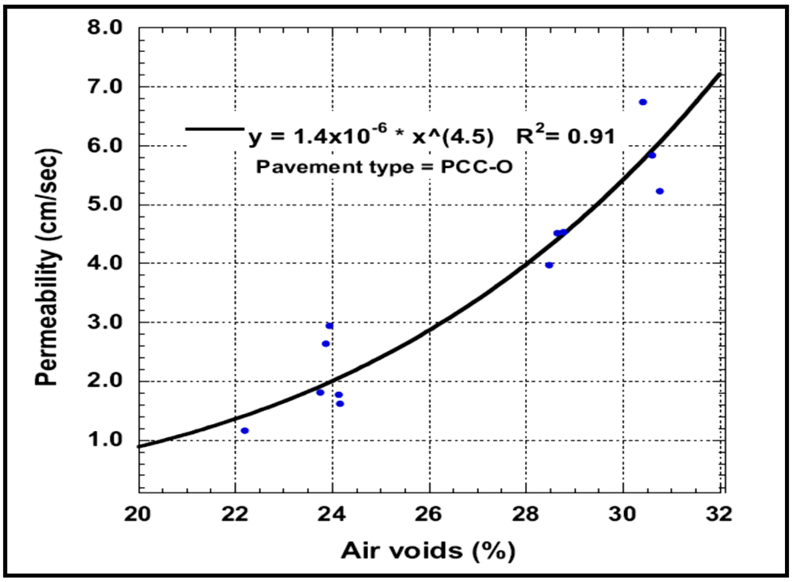

Figure 2.6: Relationship between permeability and air void of OGFC specimens (Kayhanian et al., 2012)