STUDIES ON BINDER CREEP, ABRASION LOSS AND DYNAMIC STRIPPING OF POROUS ASPHALT

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STUDIES ON BINDER CREEP, ABRASION LOSS AND DYNAMIC STRIPPING OF POROUS ASPHALT

by

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KAJIAN TERHADAP RAYAPAN PENGIKAT, KEHILANGAN LELASAN DAN PERLUCUTAN DINAMIK ASFALT BERLIANG

oleh

MOHD ROSLI MOHD HASAN

Tesis yang diserahkan untuk

memenuhi keperluan bagi

Ijazah Sarjana Sains

Jun 2011

To my beloved parents, wife, daughter, and son who complete my life with devotion, passion, and desire.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AAPT	Association of Asphalt Paving Technologists
ACV	Aggregate Crushing Value
AL	Abrasion Loss
ANOVA	Analysis of Variance
ARI	Annual Rainfall Intensity
ASTM	American Society for Testing Material
AT	Ambient Temperature
BS	British Standard
BSI	British Standard Institution
DBC	Design Binder Content
DOT	Department of Transportation
DB	Drained Binder
DRI	Danish Road Institute
DSM	Dynamic Stripping Machine
DTC	Inside Drum Temperature Change
FHWA	Federal Highway Administration
FT	Flow Time
FTR	Flow Time Ratio
FTIR	Fourier Transform Infrared Spectroscopy
G_{mb}	Bulk Specific Gravity
G_{mm}	Theoretical Maximum Density
HMA	Hot Mix Asphalt
HPU	Highway Planning Unit
HWTD	Hamburg Wheel-Tracking Device
ICT	Initial Conditioning Temperature
ITS	Indirect Tensile Strength
ITSM	Indirect Tensile Stiffness Modulus
ITSR	Indirect Tensile Strength Ratio
JKR	Jabatan Kerja Raya
k	Coefficient of Permeability
k_R	Coefficient of Permeability Ratio
LAAV	Los Angeles Abrasion Value
MSMA	Manual Saliran Mesra Alam
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
OPC	Ordinary Portland Cement
PA	Porous Asphalt
PAC	Porous Asphalt Concrete
PFC	Porous Friction Course
PSV	Polished Stone Value
R&W	Riedel and Weber
R^2	Coefficient of Determination
SGM	Specimen Geometry Method
SSD	Saturated Surface Dry
STA	Short Term Ageing
STC	Specimen Skin Temperature Change
STOA	Short Term Oven Ageing
TRB	Transportation Research Board
TRL	Transportation Research Laboratory
TU Delft	Delft University of Technology
USM	Universiti Sains Malaysia
XRD	X-Ray Diffraction

KAJIAN TERHADAP RAYAPAN PENGIKAT, KEHILANGAN LELASAN DAN PERLUCUTAN DINAMIK ASFALT BERLIANG

ABSTRAK

Setelah beberapa tahun digunakan, kebolehtelapan asfalt berliang menurun akibat daripada punca utama iaitu penyumbatan. Penyelidikan ini telah menemui satu lagi punca kehilangan kebolehtelapan asfalt berliang iaitu rayapan pengikat. Untuk mengesahkan fenomena ini, sampel disesuaikan pada suhu 15, 20, 30 dan 35°C. Kebolehtelapan beberapa sampel dipantau pada selang masa tertentu sehingga 120 hari menggunakan meterlalap air turus menurun. Selain penyumbatan, masalah utama yang mengehadkan ketahanan dan jangka hayat asfalt berliang adalah jurai. Di makmal, rintangan jurai diuji menggunakan ujian *Cantabro*. Walau bagaimanapun selepas ujian, suhu sampel boleh meningkat atau menurun berbanding suhu penyesuaian awal, bergantung kepada suhu bilik semasa ujian dijalankan. Untuk mengkaji kesan suhu penyesuaian awal dan bilik ke atas kehilangan lelasan dan perubahan suhu, sampel pada awalnya disesuaikan pada suhu 15, 20, 25, 30 dan 35°C dan diuji di USM dan Delft University of Technology (TU Delft), Belanda dengan suhu bilik masing-masing adalah 30 dan 24°C. Seterusnya, sebuah peralatan yang dinamakan *dynamic stripping machine* telah dicipta untuk mensimulasi tindakan air terhadap asfalt berliang secara dinamik dan kajian awal telah dijalankan untuk mengkaji kesan tindakan air secara dinamik terhadap kehilangan mastik. Daripada keputusan keseluruhan ujian, kehilangan kebolehtelapan disebabkan rayapan pengikat lebih ketara berlaku pada sampel yang disesuaikan pada suhu tinggi (30°C dan 35°C). Kemudian, suhu penyesuaian awal dan bilik didapati memberi kesan ke atas kehilangan lelasan dan perubahan suhu asfalt berliang; iaitu nilai kehilangan lelasan yang diperolehi di TU Delft adalah lebih tinggi berbanding nilai kehilangann lelasan di USM. Selanjutnya, kajian telah membuktikan bahawa tindakan air secara dinamik ke atas asfalt berliang mengakibatkan kehilangan mastik serta mempengaruhi kebolehtelapan dan kekuatan tegangan.

STUDIES ON BINDER CREEP, ABRASION LOSS AND DYNAMIC STRIPPING OF POROUS ASPHALT

ABSTRACT

After several years in service, porous asphalt looses permeability primarily due to clogging. This study presents a phenomenon postulated as binder creep, as another source of permeability loss in porous asphalt. To ascertain the binder creep, samples were separately conditioned at 15°C, 20°C, 30°C and 35°C. Permeability measurements were carried out at regular intervals up to 120 days using a falling head water permeameter. Apart from clogging, the most serious problem that limits porous asphalt durability and service life is ravelling. In the laboratory, resistance to ravelling is evaluated via the Cantabro test. However, after test, the temperature of the disintegrated specimen can be either higher or lower than the initial conditioning temperature, depending on the ambient temperature. To investigate the effects of initial conditioning and ambient temperatures on abrasion loss and specimen temperature changes during the test period, specimens were initially conditioned at 15, 20, 25, 30, 35°C and were tested in USM, Malaysia and Delft University of Technology (TU Delft), the Netherlands where the ambient temperatures were respectively 30 and 24°C. Subsequently, a new machine known as the dynamic stripping machine was developed to simulate the dynamic action of water on porous asphalt. Preliminary evaluations have been conducted to ascertain the effect of flowing water on the occurrences of mastic loss and moisture damage of porous asphalt at different conditioning period. From the overall results, permeability loss attributed to binder creep was more significant on samples conditioned at higher temperatures (30 and 35°C). Then, the initial conditioning and ambient temperatures have significant effects on abrasion loss and temperature changes of porous asphalt. The abrasion loss values obtained from samples tested at TU Delft were higher compared to values tested at USM due to the effects of the specimen temperature changes during the test period. Subsequently, it is proven that dynamic action of water has initiated losses of mastic in this wearing course that affects the permeability and tensile strength of the mixes.

CHAPTER 1

INTRODUCTION

1.1 General

Porous asphalt (PA) is an innovative road surfacing material that provides a safe and comfortable condition for road users especially on high speed roads. PA can reduce traffic noise and is the main reason for its application on European roads especially in the Netherlands where 90% of Dutch motorways are currently paved with this material.

In Malaysia, PA was first tried in 1991 to reduce traffic accidents. Several more field trials were placed after the first one on the toll expressways and federal roads. The first national specifications for PA appeared in the Public Works Department (PWD) updated specifications on flexible pavements in 2008. However, performance evaluation must be carried out on this wearing course to ascertain the efficiency of the mix design. Subsequently, the effects of temperature and moisture must be taken into consideration since both exert a strong influence on the performance and service life of PA in tropical countries such as Malaysia.

1.2 Problem Statement

PA performance is mainly affected by ravelling, clogging and overcompaction by traffic. Ravelling is primarily caused by binder hardening while clogging and traffic overcompaction result in closure and disruption of air voids continuity.

In the field, PA is subjected to abrasive forces from vehicle tyres that could induce ravelling. This abrasive force is commonly simulated in the laboratory by using the Cantabro test. In the Cantabro test, a specimen was subjected to 300 drum rotations and typically, the test took 10 minutes to complete. The European Standard 12697-17 (CEN, 2004) recommends the Cantabro test to be conducted at any temperature between 15^{o}C and 25^{o}C. This test temperature range may suit temperate countries since the European Union regulates ambient temperature at 20$\pm$5^{o}C. For countries in the tropics such as Malaysia, the average ambient temperature in the absence of air-conditioning is about 30^{o}C. However, Malaysian researchers typically carry out the Cantabro test on specimens conditioned at 25^{o}C without giving any regards to the effects of ambient temperature on the abrasion loss values obtained. Many researchers are not aware that subjecting the specimens to 300 drum rotations under Malaysian ambient temperature has caused the specimen skin temperature to increase while it is impossible to maintain the same specimen temperature throughout the test duration. The temperature change will adversely affect the accuracy of the test result because asphalt materials are very sensitive to temperature. Therefore, comparison of abrasion loss values across the globe can be erroneous without specifying the ambient temperature at which the Cantabro test was carried out.

Clogging and traffic overcompaction disrupt air voids continuity and hence result in permeability loss. The possible clogging agents include dust, mud, residual soil deposited from dirty wheels and heavy trucks transporting soil to and from construction sites. Meanwhile, the magnitude and rate of air voids reduction due to traffic overcompaction is more pronounced during its early life especially after the pavement is opened to traffic.

The disruption of air voids continuity in PA is also associated with temperature. In tropical climates, the surface of an asphalt pavement is notably hot during daytime. The heated asphalt binder can migrate downward through the air voids under the influence of asphalt binder self weight and gravitational force for a long period. Over time, more binder creep occurs causing more extensive disruption of air voids continuity in the porous mix. In addition, binder creep accelerates if the mix is subjected to higher temperature.

Long term exposure of PA to water and atmospheric moisture can induce mix deterioration due to stripping. The interaction between water and asphalt mix may cause adhesive and cohesive failures of the asphalt mix. Cohesive failure will affect the bitumen-bitumen interaction while adhesive failure affects the aggregate-bitumen interaction. On the other hand, the function of PA as a drainage mechanism exposes the mixture to the dynamic action of flowing water initiated by rainfall or flowing water through the air voids in the mixes which in turn accelerates the moisture damage. Consequently, the porous mixture may experience mastic loss. This mechanism has been researched hardly and for that reason, a new equipment was needed to simulate the dynamic action of water on the PA.

1.3 Objectives

This study aimed to fulfil the following objectives:

1. To ascertain the reduction of permeability due to binder creep in the PA.
2. To evaluate the effects of the initial conditioning temperature on the abrasion loss of PA.
3. To propose and evaluate a new test to simulate the dynamic action of water on the moisture damage of PA mix.

1.4 Significance of Study

In some region, it has been established that the factors causing permeability loss in PA over time are clogging and voids closure due to traffic overcompaction. However, this study presents binder creep as another source of permeability loss in PA. Binder creep occurs when the binder becomes less viscous due to elevated temperature and migrates downwards with the aid of gravitational force. This will steadily disrupt the air voids continuity and subsequently cause the reduction in permeability over time. From the outcome of this study, researchers would be able to ascertain the occurrence and effects of binder creep in PA.

The Cantabro test has been used to evaluate the abrasion loss of PA by subjecting a specimen to 300 drum rotations. However, the skin temperature of the disintegrated specimen after the test can be either higher or lower than the initial conditioning temperature, depending on the magnitude of the initial conditioning and ambient temperatures. The temperature difference between the two will affect the abrasion loss of PA and hence the accuracy of the test results obtained. The Cantabro test was carried out on samples conditioned at varying initial conditioning temperatures separately at two ambient temperatures. The results obtained from the Cantabro test was used to ascertain the effects of different initial conditioning and ambient temperatures on the abrasion loss and temperature change of PA samples as well as to evaluate the effects of temperature difference on the accuracy of the Cantabro test results. The results of this study can be used to propose the temperature to condition and test PA specimens in Malaysia.

The resistance to moisture damage (stripping) was usually evaluated after soaking the samples in water at specified temperatures without considering the dynamic action of flowing water on the asphalt mixtures. Dawson et al. (2009) stated that the action of flowing water has a greater influence on the moisture damage experienced by asphalt mix compared to water in stationary mode. This is because the dynamic action of water on asphalt mix results in loss of asphalt mastic and accelerates moisture damage by subjecting the asphalt samples to stripping and ravelling. In this study, a dynamic stripping machine was designed and fabricated to simulate the dynamic action of water on PA samples, and hence evaluate the effects of flowing water on resistance to stripping.

1.5 Scope of Work

The scope of work covers a study on binder creep, the effects of initial conditioning temperature on abrasion loss as well as moisture sensitivity of PA. A new equipment, known as the dynamic stripping machine was designed and fabricated to simulate the actual mechanism of moisture damage on Malaysian roads to study the resistance to stripping. A preliminary evaluation of the dynamic stripping test result was conducted to ascertain the reliability of the equipment.

Two aggregate gradations, namely JKR gradation (Grading A) and a proposed gradation (Grading B) were evaluated. The JKR gradation was prepared according to the Malaysian specifications for PA specialty mix Grading A (JKR, 2008). While, proposed gradation was developed based on the Dutch PAC 0/16 mixes performance. Crushed granite aggregates from a local source were used in the mix preparation. The asphalt binders used were a conventional bitumen grade 60/70 and a modified PG-76 bitumen.

This study was divided into the following four phases:

1. Phase one involves the preparation and characterisation of raw materials. The specific gravity, abrasion loss, aggregate crushing value, polished stone value, flakiness index and elongation index of the aggregates used were determined. The binders used were tested for their softening point, penetration, specific gravity, ductility and rotational viscosity.

2. Phase two focused on the PA mix design. Initially, the Dutch PA (PAC 0/16) was studied to obtain an overview of its mix properties. Based on the result obtained, the modification of aggregate gradation was carried out by adopting air voids, permeability and indirect tensile strength (ITS) properties as the control parameters. Then, a series of tests to obtain mix properties such as permeability, air voids, abrasion loss and binder drainage were carried out to determine the design binder content.

3. Phase three focused on ascertaining binder creep phenomenon and evaluating the effects of initial conditioning temperature on abrasion loss of PA. The Cantabro test was used to determine the abrasion loss while a falling head permeameter was used in conjunction with the binder creep test.

4. Phase four involved designing and fabrication of the dynamic stripping machine to evaluate mix resistance to stripping.

1.6 Organization of the Thesis

A brief description on binder creep, abrasion loss and moisture damage is presented in the Chapter 1. This chapter outlines the background, problem statement, objectives and scope of work that that needs to be fulfilled. Then, an overview of previous studies related to PA is summarized in Chapter 2.

The description of the materials and test methods used is given in Chapter 3. The properties of the aggregates, asphalt binders and fillers used are evaluated and discussed in this chapter. In addition, details on the specifications used for the experimental works are also included. The handling of materials and methods used for mixture design and testing are crucial to obtain consistent results.

The mix design parameters and the analysis of results are discussed in the Chapter 4. This chapter is divided into three major sections, which are evaluation on the properties of Dutch PA, proposal of a new aggregate gradation and determination of the design binder content. All results associated with the PA mix design are summarized in this chapter.

The experimental results of binder creep and abrasion loss is presented in Chapter 5. The discussion focuses on the permeability loss due to binder creep and the effects of initial conditioning temperatures on the abrasion loss of PA.

Chapter 6 presents a summary of the moisture sensitivity prediction methods from previous studies and description of the newly developed dynamic stripping test equipment. Then, the preliminary evaluation and analysis of the results of the dynamic stripping test is discussed. In addition, statistical interpretation using Pearson Correlation, One-Way and Two-Way Analysis of Variance (ANOVA) are incorporated to support the experimental findings.

The thesis concludes with Chapter 7 which presents the conclusions of current work and recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

PA was initially developed to improve traffic safety. Currently, it is applied due to its noise reduction potential, especially in the developed world. A well designed mix is essential to ensure that PA may perform acceptably with desirable properties from the viewpoint of performance adequacy, longer service life and better resistance to damages induced by traffic loads and the weather.

The performance of asphalt mixtures is mainly affected by temperature and the presence of moisture in the mixes. Meanwhile, asphalt binder is a visco-elastic material and its behaviour depends on temperature and time of loading. The viscous properties give bitumen its ability to flow at high temperature and/or long loading time while the elastic properties cause the bitumen to become brittle at low temperature and/or short loading time. When the bitumen becomes brittle, PA becomes less resistant to abrasive forces and this leads to a surface distress known as ravelling. Hence, changes in temperature of the asphalt mix will influence the behaviour of the asphalt binder which in turn directly affects mix properties.

2.2 Porous Asphalt

The term “porous asphalt” arises from the nature of the aggregate grading, which is made up of more than 80% of coarse aggregate fraction. Other terms used for PA are gap graded asphalt, permeable asphalt and open-graded friction course.

Despite the various terminologies, the main objective of PA as stated by Ruiz (1997) is to attain a large amount of continuous air voids which permits quick evacuation of water from the road surface.

PA is a totally different mix compared to the conventional water proofing wearing course (Nielsen, 2006). PA has received acceptance globally because it improved safe driving conditions at wet weather and subsequently reduced the number of accidents. However, its short service life compared to conventional dense mix has limited its application. Hence, it is important to look into the advantages and disadvantages of PA from previous studies.

2.2.1 Advantages of PA

According to Alvarez et al. (2006), PA offers safety improvements as well as economy and environmental benefits.

2.2.1.1 Safety Improvements.

Alvarez et al. (2006) stated that PA was initially used to improve the traffic safety especially in wet conditions. A poor drainage system in asphalt pavement, mostly caused by some permanent deformation in the driving tracks, resulted in vehicles experiencing hydroplaning due to ponding water on the road surface. This hazardous situation led to the loss of control during braking and steering while driving. Lefebvre (1993) discovered that the severity of hydroplaning depended primarily on the amount of rain and the drainage capacity of the road, apart from the driving speed and to a certain extend the tyre profile. The presence of continuous air voids in a PA wearing course allows water to pass through the mix and eliminates ponding water which in turn will improve the skid resistance of the road surface and subsequently increase road safety.

Roseen et al. (2009) conducted an evaluation on the skid resistance of PA, Dense-Mix Asphalt (DMA), Pervious Concrete (PC) and Standard Asphalt Reference (SR) pavements with the British Pendulum Tester during and after storm events. Additionally, different pavement conditions were evaluated, including dry, wet, snow, slush, compacted snow (c. snow), and ice-covered pavement. The data were grouped by pavement type and analyzed statistically to determine median skid resistance values for each type of surface layer. PA exhibited higher median skid resistance values compared to other mixes except under ice-covered condition as displayed in Figure 2.1.

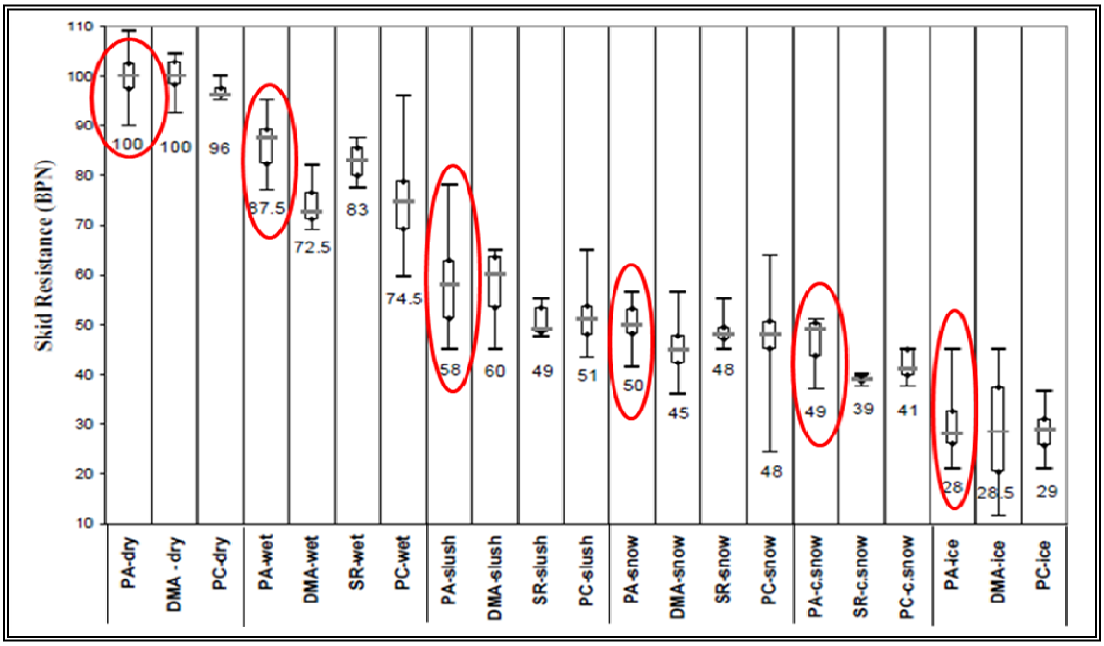

Figure 2.1: Skid Resistance for All Pavements and Winter Surface Conditions (07 - 08) [Median Skid Resistance Value Displayed Under Each Group] (Roseen et al., 2009).

Khalid and Perez (1996) reported that splash and spray of water contributed to the reduction in visibility especially during night driving. Splash and spray was respectively caused by rolling tyres on the wet surface and ponding water on the pavement. Splash and spray differed in terms of the density and size of the airborne water particles. The water particles in splash had higher density and were larger in size if compared to droplets in spray. The application of a PA wearing course could drastically reduced the splash and spray of water particles and provided better visibility while driving in wet conditioned as shown in Figure 2.2.

Figure 2.2: Splash and Spray Generated by Dense Asphalt (Right)
(Coldraine ® Porous Asphalt, 1991).

Tappeiner (1993) stated that PA was used to reduce glare. Glare was generated by reflection of the vehicle headlight on the wet pavement surface. The application of PA improved the visibility of road marking especially during the night. Khalid and Perez (1996) mentioned that without the presence of water sheets on the road surface, it reduced the rate of glare reflected from other vehicle lights.

2.2.1.2 Economic Benefits.

Khalid and Perez (1996) and Khalid and Walsh (1996) indicated in their studies that the use of this material resulted in a significant reduction in fuel consumption due to enhanced smoothness. Higher saving was reported when comparing PA to mixtures with greater roughness. The improvement of pavement surface macro texture resulted in the reduction of tyre wear due to the reduction in tyre-pavement interface contact stress. Newcomb and Scofield (2004) stated, when comparing the noise reduction of PA and a noise barrier on a unit cost basis, PA is 2.5 to 4.5 times more efficient.

2.2.1.3 Environmental Benefits.

One of the benefits of PA mixtures is the significant noise reduction if compared to dense asphalt because of their good sound absorption potential. Huber (2000) reported that measurements in most European countries had shown that the application of PA could reduce noise level by approximately 3 dB(A) for passenger car vehicles travelling at 80km/hr compared to the corresponding noise level from a reference dense asphalt wearing course. Bendtsen (1996) indicated that the noise level measurements achieved reductions of up to 6 dB(A) with the two-layer PA surfacing used in the Netherlands. Kandhal (2004) stated that a decrease of 14 dB(A) was recorded in Texas when asphalt-rubber open grade friction course was used to overlay an existing continuously reinforced concrete pavement (CRCP).

Golebiewski et al., (2003) conducted a study to measure the sound exposure level of a vehicle travelling at different velocities on dense asphalt and PA; the noise from the PA was less compared to noise produced when the vehicles passing the dense asphalt at different velocities as depicted in Figure 2.3. In the study, Two-Way analysis of variance (ANOVA) was used to analyze the data and the study revealed that there were significant different annoyances for both surfaces and three velocities as indicated by the $F(2, 966) = 6.79$ and $p\text{-value} < 0.0012$. The noise from the PA was less annoying than the noise from the dense asphalt at all vehicle speeds as shown in Figure 2.4. In this study, twenty-seven university students served for the subjective evaluations. All subjects had normal hearing with the inclusion criterion 15 dB above the ISO zero thresholds. The subjects listened to the recorded drive-by noises of individual vehicles and were asked to judge the annoyance of each sound.

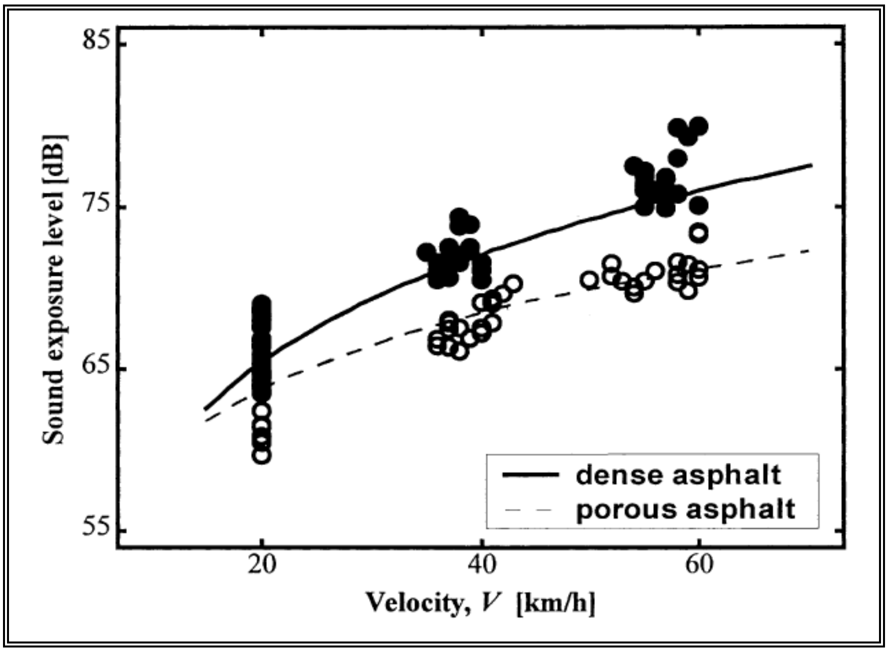

Figure 2.3: Sound Exposure Level of Dense and Porous Asphalt at Different Velocities (Golebiewski et al., 2003).

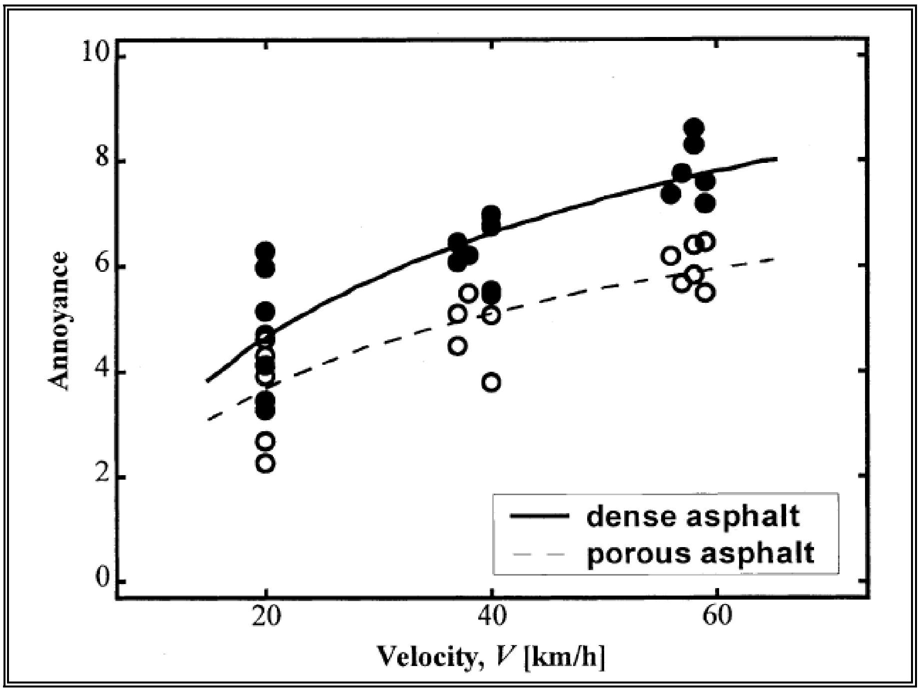

Figure 2.4: The Average Annoyances versus Vehicle Speed (Golebiewski et al., 2003).

Khalid and Perez (1996) found that higher driver comfort levels could also be achieved by using PA since noise reduction was perceived not only from the outside but also from the inside of the vehicle. In addition, PA could be considered as an environmentally friendly product because crumb rubber from old tyres could be used as additive in asphalt binder to produce this type of mixture. Chowdhury et al. (2006) demonstrated that fibre from the tyre recycling process could be satisfactorily incorporated in PA mixtures.

Pagotto et al. (2000) discovered that PA also improved the quality of runoff water where heavy metal loads discharged into the environment were reduced by 20% and 74% for copper and plumbum (lead), respectively. Moreover, 87% of solids were retained, while 90% of hydrocarbons were intercepted. In addition, Roseen et al. (2007) reported that the percentage of pollutants filtered through PA from storm water contained 99% of suspended solids, 38% phosphorus, 96% zinc and 99% petroleum hydrocarbons from diesels were higher.

2.2.2 Disadvantages of PA

The main disadvantages related to the use of PA are high construction cost, low structural strength, clogging, ageing resulting in ravelling and stripping.

2.2.2.1 High Construction Cost

PA is more expensive to construct compared to conventional asphalt mix due to the requirement for high quality aggregate, the use of modified binder and more stringent construction quality control. According to Huber (2000), the cost per ton of PA in the United States was 10% to 80% higher than dense asphalt. When unmodified asphalt was incorporated into the mixture, the extra cost was within the range of 6% to 38%. The cost of PA containing modified asphalt was 50% to 80% higher than the cost of dense asphalt containing unmodified binder. However the use of modified binder provided similar life expectancies for PA compared to dense asphalt.

2.2.2.2 Low Structural Strength

According to Khalid and Walsh (1996), open graded friction course (OGFC) and PA were typically considered to have low structural contribution. Van Heystaeten and Moraux (1990) discovered that the moduli of PA prepared with 80/100 pen grade binder were 73% to 79% lower than the moduli from conventional wearing course. However, Bolzan et al. (2001) and Poulikakos et al. (2003) indicated that PA and dense asphalt were structurally comparable.

2.2.2.3 Clogging

Ever since its inception, PA has a low popularity due to its short service life. Birgisson et al. (2006) attributed this to premature clogging of the air voids which led to ineffective drainage of surface water. Alvarez et al. (2006) stated that another major concern for this material was loss of its noise reduction capacity due to the clogging of air voids.

Gharabaghy and Csink (2006) revealed that adhesion failure was also related to the clogging of air voids in PA because of the deterioration of the mortar with time as shown in Figure 2.5. The figure showed an accumulation of grains from the sand range partly stuck together with bitumen particles on their surfaces. The grains also partly appeared clean and completely free of bitumen. It is also noticeable from a consideration of the micrographs that very fine cracks occurred in the mastic surrounding the air voids. The mastic film on the chipping grains around the air voids was irregular in thickness and in some cases there was only a very thin coating on the grain surface. Areas of bitumen at different stages of ageing were also identifiable by difference of colours where those in black indicated aged and brittle bitumen, while brown colour signified functional and elastic bitumen.

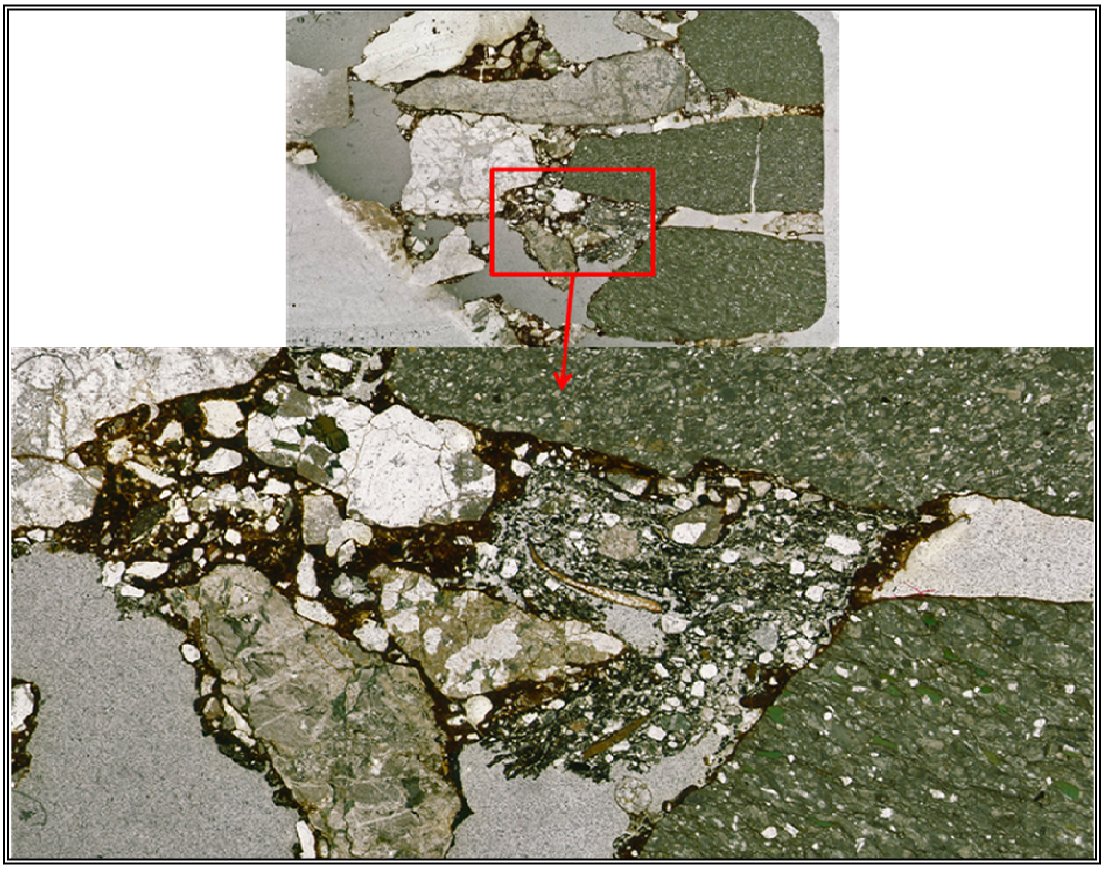

Figure 2.5: Destroyed Black Bitumen with Some Loose Sand at the Centre, Brown Intact Bitumen between the Chipping Grains (Gharabaghy and Csink, 2006).

Gharabaghy and Csink (2006) noted that during cutting off the drilled core discs for the preparation of specimens, water from the cutting machine was partly mixed with sandy material. Then, the drilled core discs were therefore heated carefully at approximately 90°C, and divided into two halves vertically. From the visual observation, loose sand particles were found in different intensities in the tested drilled cores as shown in Figure 2.6.

Figure 2.6: IPG 095, A 8, Right Wheel Track, 1995, class M: Top Section Scarcely Filled With Sand, While Bottom Section Heavily Filled With Sand (Gharabaghy and Csink, 2006).

Alvarez et al. (2006) stated that a wide range of service lives had been reported from various countries and that different approach had been adopted to deal with the reduction of air voids. In Spain, Khalid and Perez (1996) reported that PA with air voids less than 20% retained its drainage capacity for 9 years when subjected to medium traffic. However, clogging occurred in the mixture after 2 years when subjected to heavy traffic. In Britain, the reduction in noise and permeability and some increment in splash and spray were also recognized. Based on these situations, some integrated strategies had been implemented to improve the characteristics of the mixture and increase the service life of this road surfacing material. For example, high pressure cleaning equipment (Figure 2.7) is used in Denmark to clean the PA two times a year to maintain the drainage capacity (Nielsen et al., 2005). On the contrary, these practices have not been implemented in the United States, while in the Netherlands; only the road shoulder is cleaned twice a year. The material on the trafficked lane can perform its own self-cleaning caused by the suction generated by rolling tyres at high speed in rainy conditions. So the weather is also important.

An air voids content higher than 20% would ensure adequate drainage capacity for the entire service life in the majority of the cases (Tappeiner, 1993).

Figure 2.7: High Pressure Cleaning Equipment On The Øster Søgade Test Sections In Copenhagen, Denmark. (Bendtsen and Raaberg, 2007).

2.2.2.4 Ageing and Stripping

Birgisson et al. (2006) mentioned that, as a result of the open structure of PA, the binder was likely to undergo accelerated ageing due to oxidation which in turn rapidly increased the stiffness of the binder over time. In addition, water ingress may lead to stripping of the road surface layer, which affected the cohesive properties as well as the adhesion to the underlying base course and hence impairing the load transfer characteristic of the structure. According to Gharabaghy and Csink (2006), ageing was a major factor that caused embrittlement of the mastic. The mastic became brittle and at the same time permeable. Consequently, the transfer of stresses in the asphalt matrix was weakened and this led to ravelling by the abrasive action of traffic.

Hagos (2008) stated that ageing of the binder (bituminous mortar) was believed as a major contributor to poor performance of PA. Furthermore, ageing was known to change the characteristics of bituminous materials such as stiffness, strength, fracture, toughness, and relaxation.The cohesive strength of PA was influenced by the ageing of the bituminous mortar, which results in hardening of the binding material due to climatic factors, such as interaction with the environment (oxidation) which was a complex process involving the effects of temperature, exposure to UV radiation, and water/rain. Ageing results in hardening of the binder resulting in brittle behaviour of the material at low temperatures. Significant ageing took place during short term ageing where the binder was subject to high temperature during production of the asphalt mixture. During the short term ageing of the bitumen, both oxidation and volatilization processes took place. The hardening of the binder during the service period of the pavement (long term ageing) was mainly due to oxidation. The long term ageing process of an asphalt pavement depended on the prevailing environmental conditions and the type and origin of the binder. The ageing process was influenced by the type of asphalt mixture; for example, a higher rate of ageing was expected in a PA mixture compared to dense asphalt. Hagos (2008) revealed that the ageing of bitumen as a result of environmental effects was regarded a major factor contributing to cohesive failure and lower service life of PA. Damage to the cohesive properties of the binding material or mortar was induced when certain stress/strain levels of the mortar were exceeded. Tensile, compression, shear or a combination of these factors was imposed by the actions of the environment and/or traffic loading. The resistance to ravelling (durability) of PA in terms of cohesive failure depended on the ability of the binding material to resist the accumulation of damage due to such stresses (fatigue) and its ability to heal.

Hamzah (2005) stated that rapid hardening of binder occurred when a higher proportion of the bitumen film coating the aggregate was exposed to the effects of weathering. This problem can be mitigated by designing for a thicker binder film. However, this had the adverse effect that the mix permeability was reduced.

2.3 Overview of PA Mixture Design

The uniqueness of PA lies in the presence of connected quite large air voids in the mixture that makes PA different from conventional dense asphalt. Unlike dense asphalt mix design, the binder content of PA cannot be optimized using stability and flow values obtained from the Marshall Stability test. The method to determine the design binder content for a PA should include the limiting requirements for the maximum and minimum binder contents. According to Ruiz (1997), the minimum binder content ensures that the mix achieved an adequate resistance to disintegration, retarded oxidation and less susceptible to moisture damage. Meanwhile, the maximum binder content must satisfy the requirement to produce a highly permeable mix and prevent binder drainage during storage and transportation (Nielsen, 2006).

In Europe, Ruiz (1997) stated that the PA mixture design varied with the applied mechanical test. A European agreement was never reached and different procedures were adopted by different countries. In some countries, the binder drainage, water sensitivity and particle loss tests were used to determine the design binder content as shown in Table 2.1. Compaction of an asphalt mix with the Marshall hammer was the normal approach to compact PA. However, the gyratory compactor is now specified in European countries.

Nielsen (2006) mentioned that the normal test used to determine the lower binder content limit of PA mixture was the Cantabro test. This test was carried out by rotating the Marshall sample in a Los Angeles steel drum without steel balls. According to Kiggundu and Roberts (1988), the Cantabro test was also used by Minnesota Departments of Transportation (DOT) to determine the moisture susceptibility of an asphalt mix in the Cold Water Abrasion Test. The amount of abrasion loss was expressed as a percentage of the original weight of the set of 50mm x 50mm compacted briquettes and must not exceed 25%. To carry out the test, the specimens were firstly conditioned in an oven at 60^{o}C for 24 hours and then immersed in a water bath at 48.9^{o}C for 6 days. Next, the specimens were allowed to cool down to room temperature prior to cooling at 0.8^{o}C for one hour. Lastly, each of the specimens was then tumbled at 0.8^{o}C for 1000 revolutions in 34.5 minutes.

Several agencies in the United States use the mix design procedure proposed by NCAT in 2002 (Kandhal, 2002) and modified in 2004 (Watson et al., 2003; 2004). The common feature of these mix design procedures relies on the evaluation of volumetric properties such as total air voids content as the main parameter to define the design binder content. An assessment of mix durability via Cantabro test, moisture susceptibility, binder drainage, and stone-on-stone contact was also included in the mix design procedure (Alvarez et al., 2010). Nevertheless, the limiting parameters may vary depending on the road authorities or countries as shown in Table 2.1.

Table 2.1: Limiting Values in PA Mix Design.

Country or Centre	**Design Properties**				
	Permeability	**Air voids (%)**	**Binder Drainage (%)**	**Abrasion loss (%)**	**ITSR**
NCAT (USA)	*>0.116 cm/s	*>18	*<0.3	*<20 at 25^{o}C	*Min ITS Ratio 80%
TxDOT (USA)	NA	*18-22	*<0.2	*<20 at 25^{o}C	NA
Denmark (DRI)	*0.15-0.50cm/s	*>26	NA	NA	NA
Netherlands	NA	*>20	NA	NA	NA
Australia	NA	*TypeI (>20) *TypeII(20-25)	*<0.3	*Type I (<25) *Type II (<20)	NA
Belgium	NA	*> 21 ¥16-18	NA	*<20 at 18^{o}C	NA
Switzerland	NA	*18 – 22	NA	NA	*ITS Ratio 70-80%
British	*0.12/s-0.40/s	¥>20	NA	NA	NA
Spain	NA	*,¥>20	NA	*,¥<25 at 25^{o}C	NA
Italy	NA	*,¥18-23	NA	*,¥<25 at 20^{o}C	NA
South Africa	NA	*>22	NA	*<25 at 25^{o}C	NA
Georgia	NA	¥10-20	¥<0.3	NA	NA
Other (Khalid and Perez)	*>0.029 cm/s	*>16	*<0.3	*<25 at 20^{o}C	NA

*Alvarez et al., 2006; ¥Birgisson et al., 2006 (NA = Data Not Available)

2.4 Application of PA

According to Colwill et al. (1985), the use of PA was initiated in the United Kingdom by the then ruling Air Ministry due to aquaplaning and skidding problems faced by fast moving aircraft traffic. Collaboration with the Transportation Research Laboratory (TRL) to overcome these difficulties resulted in a material for the construction of a road surfacing known as airfield friction course (Szatkowski and Brown, 1977).

Ferguson (2005) mentioned, as an extension to this development, that PA was applied on roads to provide safe driving conditions and improved skid resistance. In wet weather, driving was difficult and dangerous when the pavement was slippery. The wheel and pavement could be separated by the sheets of water that accumulated on the pavement surface. Mallick et al. (2000) stated that another advantage of PA was that this wearing course had good macro texture for fast moving traffic. The United States of America had some of the earliest initial experienced with open mixes. Open Graded Friction Course (OGFC) had been used since 1950 in different parts of the United States to improve the surface frictional resistance of asphalt pavements.

According to Smith (1992), the Federal Highway Administration (FHWA) developed a mix design procedure for OGFC in 1974, which was used by the DOTs of several states. Some states reported good performance while others ceased using OGFC due to unacceptable performance and lack of adequate durability. According to FHWA (1980), PA was applied as a mechanism to reduce traffic noise in residential areas within 33 to 66 meters from moderately travelled roads and 180 meters from heavily trafficked freeways. In European countries where stricter environmental regulations related to traffic noise were imposed, PA surfacing offers a big potential to reduce traffic noise at the source, the contact between tire and surface layer (Van Bochove, 1996).

The first application of PA in the Netherlands was in 1972. The significant potential of this material to improve road safety coupled with the favourable experience gained during the trials led to the establishment of a working group to