FUNCTIONAL PERFORMANCE AND MICROSTRUCTURAL PROPERTIES OF POROUS ASPHALT SUBJECTED TO CLOGGING

MOHD ZUL HANIF BIN MAHMUD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
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DEDICATION

In the name of Allah, the Most Beneficent, the Most Merciful. This thesis is dedicated to my family and friends who are always support and believe in me.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Beneficent, the Most Merciful. Alhamdullilah. First and foremost, I would like to express my deepest gratitude to my main supervisor, Dr. Norhidayah binti Abdul Hassan, for her contributions, criticism, guidance, encouragement and understanding in completing this thesis. This has motivated me to complete this thesis. I would like to express my sincere appreciations to my co-supervisors, Professor Dr. Mohd Rosli Hainin and Mr. Che Ros Ismail for their encouragements, advice and guidance in helping me to complete this thesis.

Getting through this journey has its ups and downs, and I have indeed many people to thank for their time to listen, understand and advice throughout this years. I would like to thank my colleagues (Dr. Chang, Dr. Ibrahim, Dr. Naqiuddin, Dr. Idham, Dr. Izzul, Dr. Khairil, Mr. Azri Samsudin, Dr. Syahriza, Dr. Euniza, Dr. Nurul, Mdm. Azah, Yaya, Fatin Izzati, Fazira and Naqibah) who help to build a joyful environment. Special thanks go to numerous laboratory staffs from Universiti Teknologi Malaysia, Universiti Teknologi Petronas, and Universiti Tun Hussein Onn Malaysia who have assisted in conducting this research.

I would like to thank my parents, sibling, uncle and auntie particularly to Bibi Sygena Nebi for their prayers and sacrifices in reaching one of my goal. Thank you in making this dream possible. Last but not least, special thanks to the Ministry of Education Malaysia in for funding this study through MyBrain15 scholarship.

ABSTRACT

Porous asphalt is designed with high air voids that increases the voids interconnectivity to improve permeability and sound absorption. However, after few years in service, these functional performances become ineffective due to clogging. Due to high air voids, debris and dust from moving vehicles and surface runoff tend to clog the voids structure. This research investigates the effect of clogging on the functional performances and microstructural of porous asphalt. Initially, a comprehensive laboratory procedure with different variables (cycles, materials, concentrations) was established to characterise the clogging potential. Then, the changes in voids properties due to internal clogging were investigated using X-ray Computed Tomography scanner and imaging technique for microstructural characterisation. Detailed image analysis procedure was developed and verified with the volumetric properties of the mix. The functional performances such as permeability, sound absorption and skid resistance of the porous asphalt were then evaluated under various clogging conditions. Based on the microstructure analysis, repeated clogging cycles have densified the top region of porous asphalt and changed the air voids structure as well as the voids interconnectivity. This has caused reduction in water permeability as more time is needed for water to permeate through the voids channel. The results also suggest clogging phenomenon reduces the sound absorbing capabilities in the porous structure particularly at high frequency due to excessive energy attenuation. For frictional performance, deposition of clogging particles on the pavement surface has changed the properties of the macro and micro-texture as indicated by the difference in British Pendulum Number (BPN) under dry and wet conditions. Overall, these results suggest that clogging phenomenon is an important factor affecting the functional performance and microstructure of porous asphalt.

ABSTRAK

Asfalt berliang direka bentuk dengan lompang udara yang tinggi bagi meningkatkan sambungan antara lompang untuk menambahbaik kebolehtelapan dan penyerapan bunyi. Walau bagaimanapun, selepas beberapa tahun digunakan, prestasi fungsian ini menjadi tidak efektif kerana masalah penyumbatan. Disebabkan oleh kandungan lompang udara yang tinggi, kotoran dan habuk daripada kenderaan yang bergerak dan air larian permukaan mendorong struktur lompang udara menjadi tersumbat. Kajian ini menyelidik kesan tersumbat terhadap prestasi fungsian dan mikrostruktur asfalt berliang. Diperingkat awal, satu prosedur makmal yang komprehensif dengan pembolehubah yang berbeza (kitaran, bahan, kepekatan) telah dibangunkan untuk mencirikan potensi tersumbat. Seterusnya, perubahan ciri-ciri lompang udara disebabkan oleh tersumbat dalaman dikaji dengan menggunakan pengimbas sinar-x tomografi berkomputer dan teknik pengimejan untuk pencirian mikrostruktur. Prosedur analisis imej telah dilaksanakan secara terperinci dan disahkan dengan ciri-ciri volumetrik campuran. Prestasi fungsian seperti kebolehtelapan, penyerapan bunyi dan rintangan gelinciran bagi asfalt berliang kemudiannya dinilai di bawah pelbagai keadaan tersumbat. Berdasarkan analisis mikrostruktur, kitaran tersumbat berulang telah memadatkan kawasan atas asfalt berliang dan menukar struktur lompang udara serta sambungan antara lompang. Ini telah menyebabkan pengurangan kebolehtelapan air kerana lebih banyak masa yang diperlukan untuk air meresap melalui saluran lompang. Keputusan ini juga mencadangkan fenomena penyumbatan akan mengurangkan keupayaan penyerapan bunyi dalam struktur berliang terutama pada frekuensi yang tinggi disebabkan oleh kehilangan tenaga yang berlebihan. Untuk prestasi geseran, pengumpulan zarah tersumbat di permukaan turapan mengubah sifat makro dan mikro-tekstur seperti yang ditunjukkan oleh perbezaan dalam *British Pendulum Number* (BPN) di bawah keadaan kering dan basah. Secara keseluruhan, keputusan ini mencadangkan bahawa fenomena penyumbatan merupakan satu faktor penting mempengaruhi prestasi fungsian dan mikrostruktur asfalt berliang.

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LIST OF ABBREVIATIONS

2D	-	Two Dimensional
3D	-	Three Dimensional
AASTHO	-	American Association of State Highway and Transportation Officials
AUS	-	Australia
ASTM	-	American Society for Testing and Materials
BPN	-	British Pendulum Number
BPT	-	British Pendulum Tester
BS	-	British Standard
BSI	-	British Standards Institution
CT	-	Computer Tomography
DBC	-	Design Bitumen Content
DFT	-	Dynamic Friction Tester
DIP	-	Digital Image Processing
DOT	-	Department of Transportation
EMA	-	Ethylene Methacrylate
FESEM	-	Field Emission Scanning Electron Microscopy
FHWA	-	Federal Highway Administration
HMB	-	Highly Modified Bitumen
JKR	-	Jabatan Kerja Raya
MY	-	Malaysia
NCAT	-	National Center for Asphalt Technology
NMAS	-	Nominal Maximum Aggregate Size
NMB	-	Non-Modified Bitumen
OGFC	-	Open-Graded Friction Course
PMB	-	Polymer-modified Bitumen
PG 76	-	Performance Graded Asphalt Binder 76
SAA	-	Sound Absorption Average
SBS	-	Styrene Butadiene Styrene
SD	-	Standard Deviation

SG	-	Singapore
SN	-	Skid Number
SPL	-	Sound Pressure Level
t/NMAS	-	Lift Thickness over Nominal Maximum Aggregate Size
TIFF	-	Tagged Image File Format
TRL	-	Transport Research Laboratory
UK	-	United Kingdom
USA	-	United States of America
USCS	-	Unified Soil Classification System

LIST OF SYMBOLS

α	-	Absorption Ratio
F	-	Friction
G_{ma}	-	Apparent Specific Gravity
G_{mb}	-	Bulk Specific Gravity
G_{mm}	-	Theoretical Maximum Specific Gravity
k	-	Coefficient of Permeability
k_{20}	-	Coefficient of Permeability at 20°C
k_h	-	Horizontal Coefficient of Permeability
k_v	-	Vertical Coefficient of Permeability
R_S	-	Air Flow Resistivity
μ	-	Coefficient of Friction
U	-	Discharge Time
Z_n	-	Acoustic Impedance

CHAPTER 1

INTRODUCTION

1.1 Background

Porous asphalt has been used in the road construction industry for decades. It was commercialised in 1960s, where initially the aim was to reduce hydroplaning and spray on highway especially during heavy rainfall conditions (Morgan, 2006). As more research was conducted on porous asphalt, it was shown that porous asphalt is not only permeable but it can also provide additional benefits to road users such as reducing traffic noise, good surface friction, visibility under wet condition and self-cleansing ability (Gołebiewski, Makarewicz, Nowak et al, 2003; Kandhal and Mallick, 1998; Rungruangvirojn and Kanitpong, 2010, Hamzah, Abdullah, Voskuilen et al, 2012). However, there are issues related to functional and structural performance that could severely affect its service life (Alvarez, Martin, Estakhri et al, 2006; Poulikakos and Partl, 2012).

According to Putman and Kline (2012), the performance of porous asphalt can be categorised into two main criteria that are functional and structural performance. The functional performance can be described as the ability of the pavement to remain permeable, absorb traffic noise and offer high skid resistance, while the structural performance is referred to low structural strength due to the high design voids content in the pavement. The open structure of the porous asphalt could expedite aging problem due to the direct exposure of weathering effects such as heat, air and water. Additionally, some adhesion loss might occur that results in ravelling and stripping problem within the pavement. As a result, many studies have been conducted to improve the structural performance through modification of aggregate gradations and bitumen quality as well as adding fibre to the mix (Mallick, Kandhal, Cooley et al, 2000; Liu and Cao, 2009; Mo, Huurman, Woldekidan et al, 2010).

On the other hand, researchers have stated that functional performance loss in porous asphalt occurs due to blockage of interconnected air voids as a result of road debris and post-compaction effect under traffic loads (binder creep). Therefore, insufficient amount of interconnected air voids in the porous asphalt layer will reduce the efficiency of the functional performance as well as its service life (Krol, Khan. & Andrew, 2017).

In Malaysia, porous asphalt is constructed with great challenges for the road industries particularly in dealing with climate conditions, cost and maintenance. Among all of the issues highlighted, clogging problem can be a major disadvantage and discouragement to the industry as it reduces and shortens the effective pavement service life. This is due to lack of maintenance in cleaning the porous surface and low structural strength, making the pavement ineffective in its years of service life. One of the preferred solutions by the authorities is to resurface the pavement with conventional dense graded asphalt due to budget constraint. Higher maintenance and construction cost discourages the authorities from the wide spread use of porous asphalt except for unique road conditions. Therefore, collective and continuous studies by researchers on the clogging issue from different perspectives should be undertaken to provide better understanding and improve the properties of porous asphalt (Suresha, Varghese & Ravi, 2010; Hamzah, Samat, Joon et al, 2004; Kandhal and Mallick, 1998).

1.2 Problem Statement

Apart from all the aforementioned benefits, porous asphalt is struggling with short service life (approximately 3 to 4 years) due to clogging problem. Although the structural performance of porous asphalt is still remained in good condition after few years in service, the functional performance has sometimes reached its limit and has become dysfunctional. As a result, the authorities requested to resurface the road with dense graded mixture due to maintenance cost. The maintenance issue of porous asphalt is closely associated with its significant loss in functional performance due to excessive clogging effect. Clogging phenomenon does not only affect the permeability, but also the acoustic properties and the skid resistance of the road surface. Therefore, the clogging issue is of great concern among researchers as clogged porous asphalt reduces the dimension of the interconnected air voids channel and thus limits the water flow and noise absorption through the internal structure of the surface layer. On the other hand, the presence of excessive clogging materials on the surface will reduce the macro and micro-texture causing reduction in the surface friction.

According to Poulikako and Partl (2012), the issues related to deterioration of functional performance and service life of porous asphalt are mainly due to its microstructural properties as it could further define the volumetric changes in porous asphalt. For example, the air voids characteristics within the porous asphalt play a major role in providing the desired voids connectivity. Currently, there have been limited studies on the characterisation of microstructural properties of porous asphalt mixture and its correlation with the functional performance. This is important in order to evaluate the volumetric changes due to the presence of clogging materials and its effect towards permeability, noise absorption and surface friction of porous asphalt. Fortunately, with the advancement of imaging technology, it is possible to non-destructively capture the internal structure of the asphalt mixture including porous asphalt. This study took the initiative to monitor the changes in volumetric and microstructural properties of the porous asphalt under various clogging variables subjected to different functional performance tests. Additionally, a set of laboratory procedure to simulate the clogging conditions was developed in this study.

1.3 Aim and Objectives

The aim of this research was to investigate the effect of clogging on functional performance and microstructural properties of porous asphalt. The objectives were as follows:-

i. To examine the clogging materials properties and establish laboratory clogging procedures;

ii. To establish the imaging procedure and evaluate the effect of clogging on the air voids properties of porous asphalt; and

iii. To evaluate the functional performance of porous asphalt in terms of permeability, sound absorption and skid resistance when subjected to different clogging variables.

1.4 Research Framework

For this research, the operational framework was divided into three phases as shown in Figure 1.1. The first phase was mainly focused on the literature reviews of the related topics and some preliminary works undertaken to justify the aim and objectives. The reviews cover porous asphalt overview, its functional performance (permeability, sound absorption characteristics and surface friction), clogging phenomenon, and imaging techniques for microstructural characterisation.

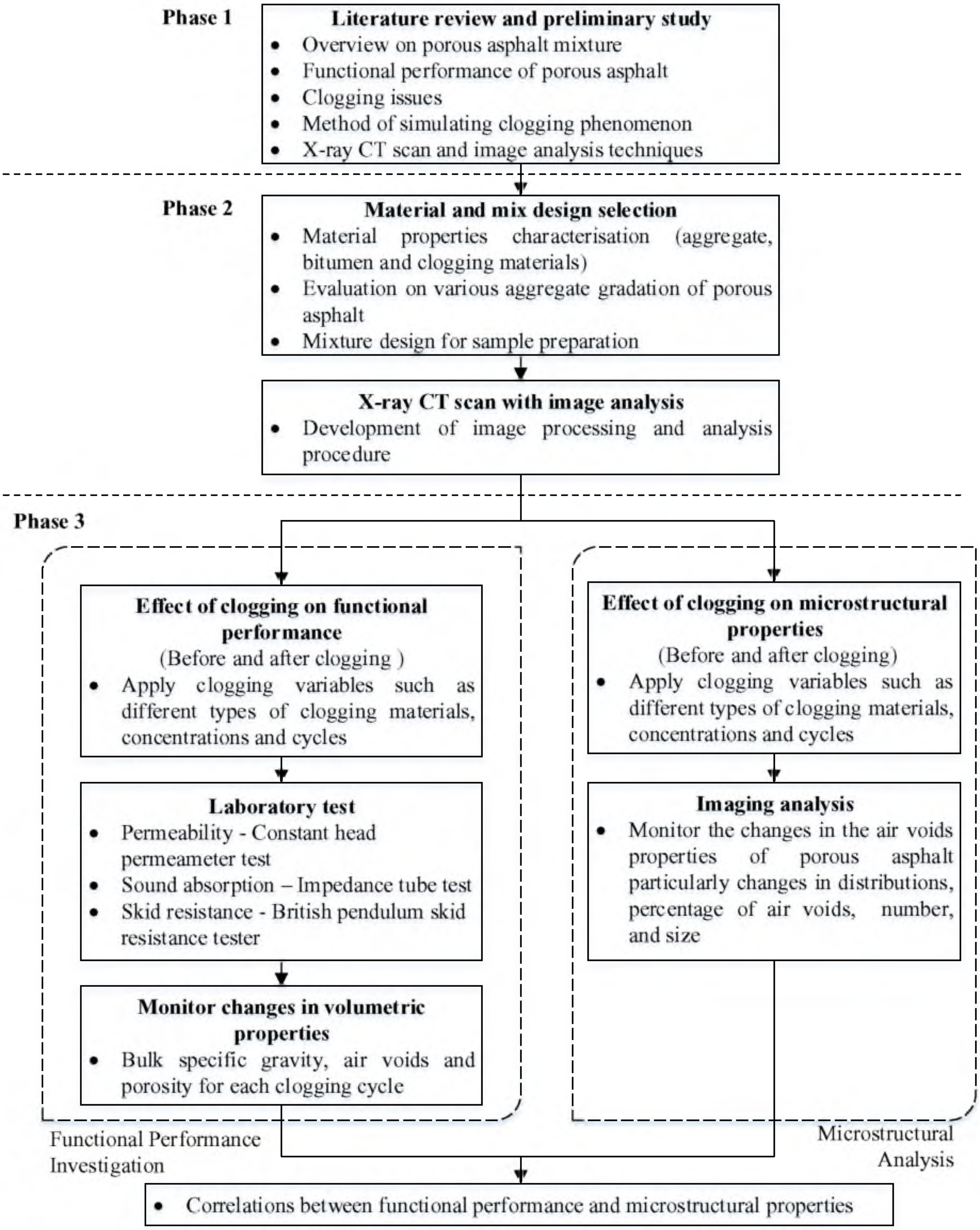

Figure 1. 1 Research framework

The second phase involves materials and mix design selection. These investigations are basically divided into four tasks. The first task involved material properties characterisation for aggregate, bitumen and clogging materials. The clogging materials properties were also characterised at the microscopic scale using Field Emission Scanning Electron Microscopy (FESEM) and its physical properties including gradation, specific gravity, and plasticity index. The second task involves the evaluation of different aggregate gradations of porous asphalt used in different countries that are from Australia, Malaysia, Singapore and the United States of America. Several laboratory tests along with imaging technique were conducted to determine the most performed gradation to be used in this study. The third task involved the preparation of the compacted sample and the fourth task involved the development of imaging technique for further analysis.

The third phase focused on the effect on clogging towards the functional performance and microstructural properties of porous asphalt mixture. Various clogging variables were considered including different clogging agents, concentrations, and clogging cycles. Hence, a set of performance tests (for evaluating permeability, sound absorption and skid resistance) and volumetric properties tests (for measuring bulk specific gravity, air void content and porosity) were conducted repeatedly after each clogging cycle. The properties of the clogged samples were continuously monitored and x-rayed at every clogging cycle. Finally the functional performance and microstructure properties of the porous asphalt were correlated for further discussion.

1.5 Scope of Study

The initial stage of the investigation evaluates different porous asphalt mixture gradations that were used in Australia, Malaysia, Singapore and the United States of America (nominal maximum aggregate size range between 12.5 to 14 mm). The Design Bitumen Content (DBC) of these porous asphalt gradations were evaluated using Jabatan Kerja Raya (JKR) Malaysia standard specification for road works (Jabatan Kerja Raya, 2008). The bitumen used in this study was Performance Graded

Asphalt Binder 76 (PG76) and the samples were compacted using gyratory compactor. The selection of suitable gradation were based on two main criteria that are the performance of the porous asphalt mixture (permeability, durability and resilient properties) and air voids homogeneity. Next, the clogging phenomenon was simulated by conditioning the porous asphalt samples at various clogging variables such as the clogging agent (clayey and sandy materials), clogging concentrations and clogging cycle (five repeated cycles). Within the cycle interval, the samples were subjected to functional performance tests such as permeability, sound absorption and skid resistance as well as the X-ray CT scanning. This study utilised two imaging software packages for the microstructure properties analysis such as ImageJ and Avizo. The X-ray CT scanning was conducted at Universiti Teknologi Petronas with the capacity of 225 kV. The impedance tube test was performed at Universiti Tun Hussien Onn Malaysia and the remaining tests were conducted at Universiti Teknologi Malaysia.

1.6 Significance and Contribution to Knowledge

Porous asphalt offers numerous benefits to the road users. The ability of the pavement surfacing to be permeable, mitigate traffic noise and provide better skid resistance improves the driving conditions to the road users. However, clogging issue, which reduces its service life, has become one of the main challenges of this type of pavement. In the early stage of the life span, porous asphalt is able to self-clean its internal structure. However, as the pavement was subjected to regular clogging cycles by dirt and organic debris over the years, the clogging particles will start to settle and harden within the pores structure, making it difficult to be cleaned and function as it was designed.

Numerous researchers have been performed to evaluate the functional performance of porous asphalt such as permeability, sound absorption and skid resistance. However, not much emphasis has been placed previously on the internal porous structure properties and in correlating these properties with the functional performance. Hence, this investigation is significant for the fact that any changes in the internal structure at the macro and micro-level due to the clogging problem can determine the efficiency of the porous asphalt to perform under severe condition.

As for the internal structure, the assessment is quite difficult and complex. For a clogged porous asphalt, an additional consideration should be given to the presence of clogging materials in the composite asphalt mixture together with the aggregates, mastic and bitumen. By using an industrial X-ray CT scanner together with imaging technique, the technology has managed to capture and analyse the complexity of the porous structure down to the micro-level without destructing the sample. This enables the assessment of clogging within the internal structure to be made at multiple clogging cycles by repeatedly scanning the samples. Therefore through this research, intensive efforts were made in providing insight into the continuous effect and severity of different clogging variables within the porous structure associated with the functional performance from the microstructural perspective.

1.7 Thesis Outline

This thesis consists of six main chapters. Chapter 1 describes the background of study, problem statement, aim and objectives, research framework, scope of study as well as the contribution of the study.

Chapter 2 provides comprehensive literature review on numerous related topics. It introduces an overview of porous asphalt that covers the history, mixture design and field application. Detailed explanations on the functional performance of porous asphalt were also provided that include permeability, sound absorption and skid resistance. The review also explains the clogging phenomenon such as clogging mechanism and laboratory clogging methods used by previous studies. Detailed reviews on digital image and X-ray CT scan are presented in this chapter.

Chapter 3 presents the details of mixture design and preliminary investigation. The explanation covers the materials characterisation (aggregates, bitumen, and clogging materials), compacted sample preparations, and laboratory tests for

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