UNIVERSITY MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Tamalkhani Bin Syammaun

Registration/Metric No: KGA100012

Name of Degree: Master of Engineering Science

Title of Project Paper/Research Report/Dissertation/Thesis (‘this Work’):

“Effect of oil palm fiber on some physical properties of porous asphalt”

Field of Study: Highway Pavement

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya (“UM”), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate’s Signature Date

Subscribed and solemnly declared before,

Witness’s Signature Date

Name:
Designation:

ABSTRACT

The use of waste fibers has been developing in many ways to increase the performance properties of asphalt mixture. Efforts to create a green technology which is more environmentally friendly that can produce economic value is also a consideration in the utilization of waste materials. The objective of this study is to evaluate the effect of oil palm fiber (OPF) on some physical properties of porous asphalt. Using OPF as the alternative, an additive in porous asphalt is one of the potential paths to improving the service properties of porous asphalt. In this study, five different contents of fiber (1%, 2%, 3%, 4% and 5%) were used by weight of bitumen. Several laboratory tests, namely drain down, air void, air abrasion loss, water abrasion loss, resilient modulus and permeability were conducted to compare and determine the specimen's performance. The performances of porous asphalt with respect to OPF additives were analysed and validated using standard statistical techniques such as regression analysis and analysis of variance (ANOVA).

In general, the results showed that the addition of OPF has a significant effect on the properties of porous asphalt. With regard to the drain-down test, the mix with 2% to 5% OPF content performed better at 4%, 4.5% and 5% binder content. However, adding more OPF to the mixture increased the air void content. The specimens containing 2% and 3% fiber in both conditions (air abrasion and water abrasion) showed lower abrasion loss than the control specimens (no fiber). For any particular binder, the coefficient of permeability decreases as the binder content increases. In reference to the results of resilient modulus, the value increased between 2% and 3% OPF content, but the higher OPF content in the mixture decreased the indirect tensile value. From the observations, it was evident that the addition of OPF has the potential to improve performance of asphalt pavements and prevent binder drain down. It is also a

continuation in creating a better environment and an alternative way in which to re-use waste materials.

ABSTRAK

Penyelidikan berkaitan kegunaan serat buangan telah dibangunkan dengan meningkatnya tujuan bagi memperbaiki pencapaian campuran asfalt. Usaha untuk menggunakan teknologi hijau yang lebih mesra alam yang boleh memperbaiki nilai ekonomi perlu dipertimbangkan dalam memanfaatkan bahan buangan. Objektif kajian ini ialah untuk menilai kesan serat kelapa sawit (OPF) ke atas sifat-sifat asfalt berliang. Penggunaan OPF sebagai bahan tambah di dalam asfalt berliang adalah usaha untuk meningkatkan sifat-sifat perkhidmatan asfalt berliang. Di dalam kajian ini, lima serat yang berbeza peratusan (1%, 2%, 3%, 4% dan 5%) berdasarkan berat bitumen telah digunakan. Beberapa ujian iaitu lebihan aliran, rongga udara, ketahanan lelasan, modulus elastik dan ketelapan telah dijalankan untuk menyiasat dan menentukan pencapaian spesimen. Prestasi asfalt berliang dengan bahan tambah OPF telah dianalisis dan disahkan menggunakan teknik-teknik statistik iaitu analisis regresi dan analisis varian (ANOVA).

Secara amnya, keputusan menunjukkan penambahan serat kelapa sawit memberikan kesan yang signifikan ke atas sifat-sifat asfalt berliang. Untuk ujian lebihan aliran, campuran serat kelapa sawit sebanyak 2% ke 5% menunjukkan prestasi yang lebih baik untuk kandungan bitumen 4%, 4.5% dan 5%. Walau bagaimanapun, penambahan lebih banyak serat kelapa sawit ke atas campuran meningkatkan kandungan udara. Spesimen-spesimen yang mengandungi serat kelapa sawit sebanyak 2% dan 3% menunjukkan nilai ketahanan lelasan berbanding specimen kawalan. Untuk sebarang pengikat, pekali ketelapan meningkat dengan peningkatan kandungan pengikat. Keputusan untuk modulus elastik menunjukkan peningkatan di antara 2% ke 3% kandungan OPF. Namun begitu, peratusan tinggi serat kelapa sawit di dalam campuran mengurangkan nilai modulus elastik. Daripada pemerhatian, penambahan serat kelapa sawit mempunyai

potensi untuk meningkatkan prestasi turapan berasfalt dan mencegah lebihan aliran pengikat. Ia juga adalah kesinambungan untuk menjadikan alam sekitar lebih baik dan sebagai alternatif dalam menggunakan semula bahan buangan.

ACKNOWLEDGEMENTS

This thesis was prepared and conducted at the Department of Civil Engineering, University of Malaya in Malaysia. I would like to convey greatest appreciation to the thesis supervisor Professor Mohamed Rehan Karim, for invaluable advice and comment throughout this thesis.

This thesis could not have been made possible without the support of many people. I am grateful to all my colleagues at the department for their support. I also like to express my sincere appreciation to Mr. Khairul, technician of highway laboratory.

Finally I would like to express my great appreciation to my parents H. Syammaun Raden and Hj. Cut Nurul Rabiah, my sisters Nurmiati S.Pd, Sabriati Amd.Keb, and Ns. Hariani Fitri for their love, concern, patience and understanding.

Kuala Lumpur, 2013

Tamalkhani

LIST OF CONTENTS

Appendices

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

ACR	Acrylic Polymer Modified Bitumen
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BC	Binder Content
BS	British Standard
EFB	Empty Fruit Bunches
EDX	Energy-Dispersive X-ray
FFB	Fresh Fruit Bunch
ITS	Indirect Tensile Strength
MPOB	Malaysian Palm Oil Board
OBC	Optimum Binder Content
OGBM	Open Graded Bituminous Mixes
OGFCs	Open Graded Friction Courses
OPF	Oil Palm Fiber
PERS	Porous Elastic Road Surface
PWD	Malaysia Public Work Department
REAM	Road Engineering Association of Malaysia
SBS	Styrene Butadiene Styrene
SEM	Scanning Electron Microscope
SIRIM	Standards and Industrial Research Institute of Malaysia
SMA	Stone Mastic Asphalt
UMMATA	Universal Material Testing Apparatus

CHAPTER 1

INTRODUCTION

1.1 General

Pavement is an element of infrastructure which plays a crucial role in supporting the riding quality of the road user. Ideally, the service of pavement must be efficient and geared towards supporting the user with comfort, safety, and environmental friendliness. Unfortunately, various pavement distresses can be found in asphalt pavement thus affecting its performance and serviceability. In this case, maintenance and rehabilitation of pavement would be the technical recommendations, although these measures may be extremely costly. Improvements to the asphalt pavement can usually be made by improving the properties of the binder and/or improving the properties and gradation of the aggregates as well as improving the properties of the mix. Hence, the asphalt mixture should be modified using certain techniques in order to facilitate their further application.

In recent years, many of the earlier researchers have had a growing interest in incorporating fiber as reinforcements in asphalt mixture. Fiber-modified is one of the promising proposals for increasing the performance asphalt mixture and providing low cost by re-using waste materials. Several types of fiber are available for use in asphalt mixture, such as polyester fiber, cellulous fiber, glass fiber and mineral fiber (Mahrez & Karim, 2010). However, research is limited when it comes to the utilisation of oil palm fiber (OPF) in porous asphalt pavement.

Malaysia is a major country in the production of oil palm, which began more than 80 years ago. Standards and Industrial Research Institute of Malaysia [SIRIM] (2009) reported that there are 26.2 million tons of oil palm fronds, 7.0 million tons of oil palm trunks, and 23% of empty fruit bunch (EFB) per ton of fresh fruit bunch (FFB) processed in the oil palm mill. The utilisation of oil palm fiber in the bituminous binder is expected to fulfil the pavement construction demand at a lower production price whilst still preserving the quality.

The addition of oil palm fiber as an additive is expected to improve performance of OPF-modified porous asphalt. The utilisation of waste material re-use in bituminous mixes is one of the many techniques in asphalt mixture or industries due to its ability to enhance performance and solve waste problems (Ahmadinia et al., 2011). Based on these facts, it would be important to conduct an experimental laboratory study to investigate the use of this fiber in porous asphalt mixtures according to Malaysia's condition.

1.2 Objective of Research

The main objective of this study was to evaluate the effect of oil palm fiber on the mixture and to determine the contribution of the various fiber contents of oil palm fiber on porous asphalt. The aim this study was also to use OPF in its natural form in bituminous mixes with the primary goal of helping to increase binder film thickness around aggregates without excessive binder drainage. Due to the fact that oil palm fiber may be considered as waste material, its successful utilisation in pavement mixes helps to address the issue of waste management and environmental conservation. Throughout this study, the optimum fiber was determined based on the laboratory test. This study also looks assessed the performance and possibility of using oil palm fiber as an additive in porous asphalt.

The specific objectives of this study can be derived as follows:

1. To evaluate the use of OPF as reinforcement on properties of porous asphalt mixture.
2. To determine the effects of OPF on durability and drainability using different percentage of OPF and binder.
3. To examine the resilient modulus of porous asphalt mixture by adding OPF as compared to the control specimen.
4. To study the relationship between the performances of porous asphalt mixture with respect to OPF reinforcement.

1.3 Scope of Work

The scope of work can be further refined as below:

1. Porous asphalt grading-B and conventional bitumen penetration-grade 80/100 were used.
2. In the first phase, the binder and oil palm fiber was designed and prepared. Bituminous binders with five contents, i.e. 4%, 4.5%, 5%, 5.5%, 6% were used by weight of aggregate and the oil palm fiber as an additive with 1%, 2%, 3%, 4% and 5% by weight of bitumen.
3. In the second phase, the physical properties of aggregate were evaluated using tests of flakiness index, elongation index, impact value, loss angeles value, soundness, and aggregate crushing value.
4. The third phase involved the conduction of certain physical tests on the bituminous binder, such as penetration test, softening point, flash and fire point test, ductility test and viscosity test.

v. In the fifth phase, the specimens were prepared and tested to evaluate air void, cantabro on air cured specimen, cantabro on water cured specimen, binder drain down, falling heard permeability and indirect tensile modulus.

1.4 Thesis Organisation

This thesis is organised as follows:

Chapter 1: This chapter presents a general introduction to the research, objectives and scope of work.

Chapter 2: Provides a literature review which examines the various past studies undertaken using fiber as an additive in asphalt mixtures and other related research.

Chapter 3: Reviews the selection of material and provides a detailed summary of the laboratory testing method. The methodology included aggregate test and also binder tests such as the penetration test, softening test, flash and fire point test, ductility test and viscosity test. The methodology used for porous asphalt is also detailed, including air void test, cantabro on air cured specimen test, cantabro on water cured specimen test, binder drain down test, falling heard permeability test and indirect tensile modulus test.

Chapter 4: Presents the results and discussion obtained from the laboratory investigation. The data was proposed based on a regression analysis and ANOVA to establish the relationship of mix performance and OPF parameter.

Chapter 5: Consists of conclusions and recommendations which were derived from previous chapters and analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter consists of a review of past investigations related to porous asphalt and the use of fiber as reinforcement in asphalt mixture. Pavement deformation problems around the world have led to new developments of mix design and the use of modified binders. Porous asphalt is considered as one of the potential method for providing safer facility. It has been introduced on a wide scale for road surfaces where rainfall is abundant. The choice of the binder and mix composition are the main factors which influence the performance of the bituminous mix in the pavement structure.

2.2 Porous Asphalt

Porous asphalt is widely used in areas requiring improved surface drainage and noise reduction in order to enhance comfort and safety for the road user. No fine aggregate fills the voids between the single-sized particles, thus making the mix porous and permeable. Porous asphalt is predominantly composed of narrowly graded crushed coarse aggregate without significant fines, which results in increased surface friction, noise reduction and permeability. Porous asphalt has also been referred to as drainage asphalt, whispering asphalt, popcorn asphalt, open friction course and porous friction course (Darintech, 2011)

Porous asphalt is an innovative road surfacing technology, which allows water to enter into the asphalt mixes beyond its continuous air voids. The designing of air void of porous asphalt shall be more than 20% at form a surface after laying and compacting. Porous asphalt which was used in wearing courses and which always laid on impervious base course, was promising, effective in enhancing traffic safety and also reduced glare (Sasana et al., 2003). Figure 2.1 shows the comparisons between porous asphalt and conventional asphalt which have been used in asphalt pavement.

Figure 2.1 Comparisons between Porous Asphalt and Conventional Asphalt

Source: Barnett, 2008

The first trial was conducted by the British Air Military in 1959 on an airport runway to disperse water rapidly from the surface. On military and civil runways, the full-scale runway test was carried out in 1962 to reduce the risk of aircraft aquaplaning on the wet runway surface. In 1967, the porous asphalt was first laid on the British bituminous road surface on an experimental basis. In 1977, the road trial section was carried out with tests and evaluation as part of the follow up. By 1985, porous asphalt was being widely deployed in Europe with the primary aim of improving traffic safety and driving comfort (Katman, 2006).

2.2.1 Properties of Porous Asphalt

Numerous installations have proven that porous asphalt’s permeability can be high. However, some installations have suffered from clogging by the asphalt binder, meaning that either the binder is too fluid or the bond between the aggregate and the binder is weak. The binder can drain gradually from the pavement surface downward through the pavement’s pores, accumulating into a clogging layer inside the structure and leaving the surface particles unbound (Ferguson, 2005).

Wu et al. (2006) observed porous asphalt from a CT scanning image (Figure 2.2). It was evident that stone-on-stone contact skeleton is mostly in the form of point contact between coarse aggregate. The cohesion strength of asphalt mixture generally depends on the binding strength between these contact points.

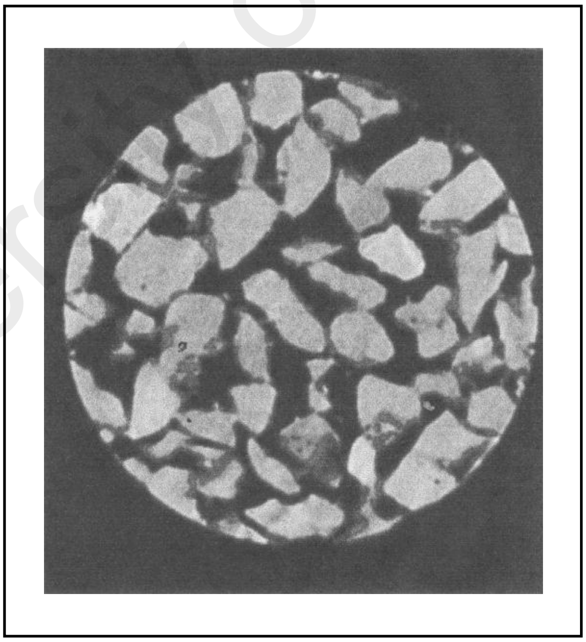


Figure 2.2 CT Scanning Image of Porous Asphalt Mix

Source: Wu et al., 2006

Porous asphalt aggregate should always be clean, hard, and durable because the mix stability typically depends on the aggregate interlock. Strong adhesion is also desirable in order to promote mix stability and to maintain the open structure. Filler is the most important component which is added into the mix and increases resistance to stripping due to the action of water. It also assists in stiffening the binder.

According to the Road Engineering Association of Malaysia [REAM] (2008) the porous asphalt is unsuitable in areas where:

- Along the road shoulder, the free drainage cannot be accommodated.
- There is considerable traction because of braking, sudden acceleration, and turning, for example, at major junctions.
- The pavement structural strength is substandard.
- The radius loops less than 75 metres of tight radius curves.
- 10% of exceeds of the gradient.
- Excessive deposits of debris, oil and fuel may be experienced.
- Length of roads less than 100 metres because of spray carry-over from adjacent surfacing.
- There is high flexibility such as on bridges.
- The statutory undertakers may occur for frequent excavation.
- Because of no beneficial reduction in spray or noise levels achieved at speeds below 40km/h, this is expected to slow moving traffic.
- At opening, the traffic exceeds 4000 commercial vehicles per lane per day.

2.2.2 The Development of Porous Asphalt

Porous asphalt has been installed in the field as much as any other type of porous material. Over the years, various installations have suffered from clogging and decline of infiltration rate due to mediocre construction or the immaturity of the technology.

Today, upgraded technology is being developed to improve porous asphalt's hydrologic, structural durability and reliability. There are several places which can be use of porous asphalt pavement, as below (Mahat, 2009):

1. Town

   Porous asphalt can be extremely tricky in towns, particularly during the rainy season. This is due to the fact that when it rains, the water on the road surface causes the movement of the vehicle to become slow, hence causing traffic congestion. Indeed, through the utilisation of porous asphalt, the water can be discharged quickly.

2. Airport

   Airplanes require a dry landing track otherwise extremely dangerous situations can develop. In reference to this point, the use of porous asphalt can increase the rate at which the tract dries out.

3. Highway (particularly at curve)

   Highways are specially designed for high speed travelling. In light of this, the presence of water on the road surface can cause significant problems particularly in terms of vehicle mobility and driver safety. One the most common parts of the road facing this problem is along the curve. Indeed, by using porous asphalt, water can be drained faster than standard asphalt mixture.

2.2.3 Benefits and Limitations of Porous Asphalt

The Malaysia Public Work Department (PWD) in REAM (2008) has compiled a list of most of the benefits of porous asphalt. The benefits of porous asphalt in asphalt pavement can be identified as:

1. Reduces splash and spray

   Through the reduction of this phenomenon, the presence of water on the surface or water bonding on road surfaces can be avoided. This is due to the fact that porous asphalt effectively improves the visibility and reduces the effect of splash and spray.

2. Reduces hydroplaning effects

   Since the water is allowed to pass through the surface, the probability of hydroplaning is almost nonexistent.

3. Improves road safety

   Its ability to reduce aquaplaning, splash/spray and glare effect has made porous asphalt a favourable choice for road authorities as it reduces road accidents.

4. Reduced glare on wet pavement surface and headlight reflection.

   Porous asphalt can reduce the effects of headlight reflection and glare. Conventional asphalt reflects light because of the smooth surface which resembles a mirror.

5. Reduces rolling tire noise levels.

   The road surface makes an important contribution to highway noise. Porous asphalt has been proven to reduce noise and absorbs the majority of vehicular tire sound energy.

The limitations of porous asphalt include (REAM, 2008):

1. Road surface temperature can be 1-2°C below that of adjacent roads in winter conditions due to availability of the voids. The road surface freezes sooner and thaws later.

2. Air void can quickly be filled with detritus. Pressure washing does not clear the voids and the only alternative is to relay new material and remove the contaminated surface.
3. The unit cost of porous asphalt is far higher than conventional dense wearing coarse.
4. Unsafe situations can occur such as ‘mushrooming’, when rain is followed by freezing conditions. Water in the voids expands when it freezes, rising up above the adjacent road surface.
5. The predicted lifetime for porous asphalt is approximately eight years in comparison to 20 years for the conventional method.

2.2.4 Installation of Porous Asphalt

Cahill et al. (2003) have presented the sequence of porous asphalt installations (Figure 2.3) as follows:

1. The subsurface infiltration bed located beneath the porous pavement must be excavated without heavy equipment compacting the bed bottom, using hand for fine grading.
2. During excavation, the earthen berms (if used) between infiltration beds should be left in place. These berms do not require compaction if proven stable during construction.
3. After fine grading is completed, the non-woven geotextile must be laid immediately.
4. Clean (washed) uniform graded aggregate is placed in the bed as the storage medium.

5. The porous asphalt is laid down in a way identical to that used for conventional asphalt.
6. After installations are finished, the surface resembled conventional asphalt until it rains. Infiltration beds are completely under the parking lots, minimising the disturbance envelope.


1) 2) 3) 4) 5) 6)

Figure 2.3 Sequence of Porous Asphalt Installation

Source: Cahill et al., 2005

Sahul (2010) have mentioned that there are several characteristic designs and considerations with regards to the installation of the porous asphalt pavement:

1. Cross fall - porous asphalt should be laid on an impermeable and relatively even bituminous surface with a minimum cross fall of 2.5%. The reason for this is to ensure that the water can flow smoothly.
2. Thickness - a minimum thickness of 50mm is essential in order to provide adequate drainage within the porous asphalt layer.
3. Cracks – all of the cracks and surface and structural deficiencies must be repaired in order to prevent further structural deficiencies and reflective cracking since porous asphalt is a non structural layer.
4. Compaction – porous asphalt should be compacted using static steel wheel tandem rollers only. Indeed, other rollers such as vibratory rollers are not permitted as they lead to excessive compaction and increase the possibility of aggregates being crushed. As a result, the strength of the pavement is low due to the fact that the aggregates are not longer in best condition. Furthermore, pneumatic tire rollers are not allowed since they knead and are close the surface, resulting in the reduction of pores and thus affecting the draining ability of porous asphalt. In addition, pneumatic rollers also cause stripping of the aggregates.

2.2.5 Porous Asphalt Pavement in Malaysia

Hamzah et al. (2010) mentioned that during wet weather, the porous asphalt pavement in Malaysia had resulted in increased safety for road users and a decrease in the number of accidents. However, its service life is slightly limited due to clogging and poor durability when compared to the conventional dense mix. This is because porous asphalt has the same open nature of the mix itself.

Malaysia started using porous asphalt in 1991 and the first trial on Malaysian roads was carried out along the Cheras-Beranang Road (Hamzah & Samat, 2002). In 2008 for the first time the Malaysia PWD launched specifications and gradation for porous asphalt with two gradations, designated as A and B. Porous asphalt is produced using open graded aggregate mixed with polymer modified binder, which contains air voids of 20 to 25% after compaction (REAM, 2008).

2.2.6 Maintenance and Rehabilitation of Porous Asphalt

The maintenance of porous asphalt is different from that of dense asphalt. Seal coats must not be applied as they would be on dense pavements. Top coating of any kind should be practiced only if a fully porous coating material is available. The pavement must not be sanded in the winter because sand clogs the pores. A porous asphalt pavement which becomes partially clogged by sediment can be rehabilitated by vacuuming and washing; the equipment for which is widely available. In an early experiment, researchers artificially clogged a newly constructed pavement, reducing its infiltration rate from 21 inches per hour to 6 inches per hour; subsequent brushing, vacuuming, and high-pressure washing restored the pavement to full function (Thelen et al., 1978).

All types of cleaning are at their most effective when carried out before clogging is completed. If cleaning is delayed and dirt is allowed to be ground into the surface by rain and traffic, it is harder to vacuum out later. Theoretically, a surface which is completely clogged can be restored by milling off the top one or two inches, where clogging is usually concentrated, and replacing it with an equal thickness of porous asphalt or another porous paving material. When a porous asphalt surface layer reaches the end of its lifetime and requires rehabilitation, it is possible to mill it, heat it, and recycle it in place. Recycled porous asphalt can have the same infiltration rate as new porous asphalt (Huber, 2000).

2.2.7 Characteristics of Porous Pavement on Noise Reduction

Meiarashi et al. (1996) developed a low-noise pavement by considering a porous elastic road surface (PERS). PERS is composed of rubber granulates combined with urethane (using old tires for rubber granulate). They found that the noise characteristics of PERS superior to those of reduction indicated a major noise reduction from double to 10 times the noise reduction offered by DAP.

Baughan et al. (2003) studied the resurfacing of an old brushed concrete section of the M40 west of High Wycombe with porous asphalt. A reduction in noise exposure of between 4.5 to 6 dB (A) was evident at villages 0.5 km from the motorway. This study also indicated the community’s response in that dissatisfaction ratings reduced considerably after the resurfacing. The result showed that resurfacing with porous asphalt substantially reduced both noise exposure and noise nuisance at the survey villages, and that benefits were still apparent four years afterwards.

2.2.8 Fatigue Behaviour of Porous Asphalt

Montepara (1999) presented results regarding the fatigue behaviour of open graded bituminous mixes (OGBM); with thermoplastic SBS polymer was used as the binder. The study showed that OGBM exhibited a fatigue life comparable with the values found for dense bituminous mixes. Other findings indicated that the compaction technique

(Marshall Compactor and gyratory Pine Super Pave-AFGCC compactor) did not significantly influence the fatigue resistance.

2.2.9 The Problem of Drain-Down

According to Ferguson (2005), the hypothesis of gradual asphalt drain-down originated in Georgia during the examination of a porous asphalt residential driveway. The driveway was used only for access to a work shed and for the washing of private cars. It was surrounded by grass and trees which supplied abundant organic debris. The pavement had been built in 1990. Over the years the residents had observed the driveway's relative infiltration rate while washing their cars. During the pavement's first three or four years it had absorbed all rainfall and other water, without runoff. However, this did not last as some visible runoff began to materialise. In 1996, six years after construction, the residents gave an informal demonstration of the driveway's weaknesses. In 2000, the residents reported that the surface was highly clogged and that it produced abundant runoff. The hypothesis was that, after a porous asphalt mixture was installed, the asphalt binder could migrate downward through the pores under the influence only of heat and gravity. On hot summer days, the surface of an asphalt pavement can be notably hot. The heat-softened binder flows, very gradually, down from the surface until it meets a cooler level in the interior, where it slows down or stops, filling the pores. It drags with it any dust or debris from the surface, incorporating it into the clogging matrix.

2.2.10 Density of the Porous Asphalt

Hamzah and Cabrera (1997) noted that the density and bitumen content relationship for porous asphalt was different when compared to the dense mix. In porous asphalt, the density increased proportionally with bitumen content. This was explained by the filling of the pores in porous asphalt with bitumen which then leads to the higher densities. The study found that the mixes made with modified bitumen exhibited a lower average mix density when compared to the mix prepare to used a 100 pen base bitumen (B100). The type of aggregate grading of the two mixes had no significant effect on the mix density. The impact mode of compaction produced denser specimens than those compacted by the Gyratory Testing Machine. The highest bitumen content added does not completely fill all of the void spaces; therefore, none of the aggregates were displaced by the bitumen and mix density increased progressively with further addition of bitumen.

2.2.11 Porosity of the Porous Asphalt

Hamzah & Cabrera (1997) observed that the porosity of the mix reduced as bitumen content increased and also found a linear relationship between porosity and bitumen content. A good statistical correlation was found, regardless of bitumen type, gradation and mode of compaction. It was indicated that mixes prepared with acrylic polymer modified bitumen (ACR) showed the highest porosity at given bitumen contents. It was though that this occurred as a result of the higher bitumen stiffness and lower bitumen penetration which reduced its workability compared to other mix types. In this investigation, the aggregate grading of the PR and BS mixes had equal compacted dry aggregate porosity values. The results of the investigation showed that both mixes exhibited similar porosity irrespective of bitumen content and compaction method. Gyratory specimens exhibited higher porosities than impact specimens. However, both modes of compaction produced specimens of lesser porosities as bitumen content increased.

Hardiman (2004) has stated that porosity and resistance to disintegration have a strong relationship with conventional base bitumen content (Figure 2.4). The porosity can be increased by increasing the proportion of the coarse mineral aggregate and decreasing the amount of fine aggregate fraction.

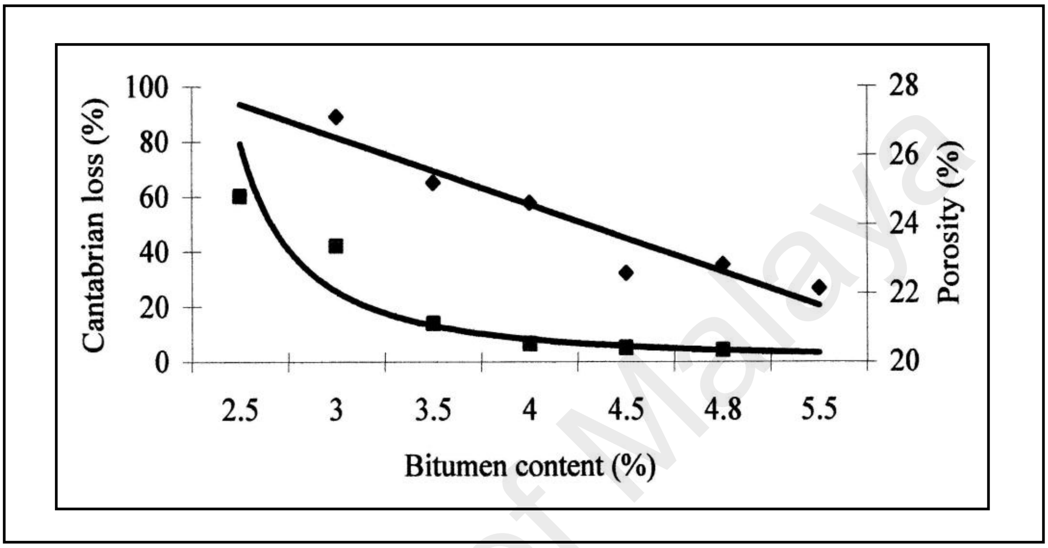


Figure 2.4 Relationships between Cantabrian Loss, Porosity and Binder Content

Source: Hardiman, 2004

2.2.12 Permeability of the Porous Asphalt

Hamzah et al. (2012) published results regarding permeability loss in porous asphalt due to binder creep. The losses of permeability in porous asphalt were due to clogging in service after several years. Permeability measurements were carried out using a falling head water permeameter at regular intervals up to 60 days. The reduction of permeability was measured in terms of reduced coefficient of permeability over time and increased time of flow.

Figure 2.5 shows the actual flows of porous asphalt. The results indicated that specimens conditioned at high temperatures had a more significant impact permeability loss. The reduction of permeability took place more rapidly during the first week but tended to asymptote later on. Moreover, the experiment should have specified a time frame within which porous asphalt permeability measurements must be made.

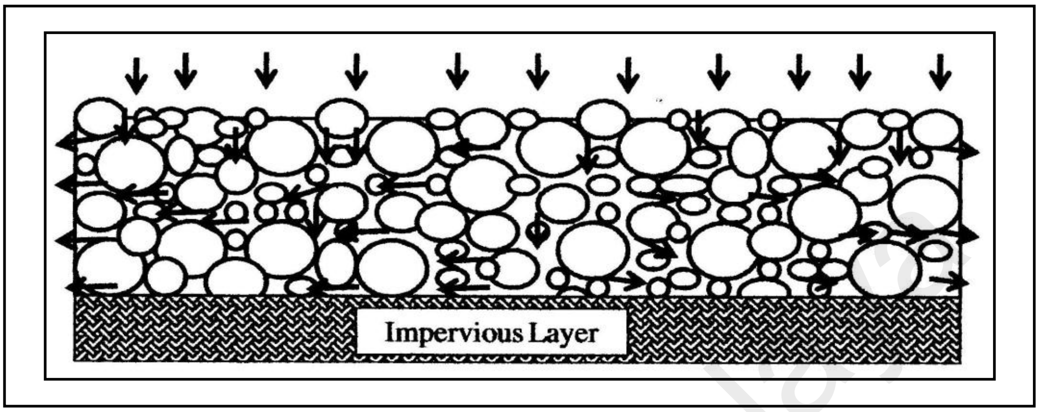


Figure 2.5 Actual Flows in Field Porous Asphalt Pavement

Source: Hamzah et al., 2012

2.2.13 Indirect Tensile Strength of the Porous Asphalt

Hamzah et al. (2010) presented the results of a laboratory investigation regarding the indirect tensile strength (ITS) of two different gradations (Mix A and Mix B) using two bitumen types. The gradation of A contained almost 20% higher aggregate size passing the 5 mm sieve size compared to B. As a result, when gradation was taken as the variable, the ITS value of Mix A was higher when compared to Mix B. This indicated that the higher air voids in Mix B resulted in a reduced contact area between aggregate particles, therefore leading to its lowered ITS.

2.2.14 Ravelling Resistance of Porous Asphalt

Mo et al. (2010) mentioned that the material optimisation – achieved by changing bitumen properties or mortar – resulted in a significant improvement of ravelling resistance. A flexible bituminous binder with ample relaxation behaviour was proven to provide an optimal performance for ravelling resistance. Cohesive failure and adhesive failure were the weak links responsible for raveling and the failure mechanisms within the stone contact. Cohesive failure was the main cause at high temperatures while adhesive failure was predominant at low temperatures. Ageing generally enhanced the high-temperature ravelling performance, but dramatically degraded low-temperature ravelling performance.

2.2.15 Porous Asphalt in Overlays

Porous asphalt overlays on highway pavements have been known to improve driving safety, traffic flow, and the highway environment. The overlays' removal of water from the driving surface essentially eliminates tire spray and hydroplaning, thus reducing glare on wet nights. The water drains onto the highway shoulders or through openings in the sides of grate inlets (Ferguson, 2005). Porous overlays also reduce pavement noise by attenuating the sound energy generated at the interface of pavements and tires. Because of their good traction, they are often called "open graded friction courses" (OGFCs).

Highway overlays have the longest history of all porous asphalt applications. Experience with them began with the "old" porous asphalt mixtures. Although the experience of various agencies with OGFCs has differed widely, today overlays are the most commonly used porous asphalt in the world, and highway personnel are heavily involved in the development of new porous asphalt technologies (Ferguson, 2005).

Kandhal & Mallick (1998) mentioned that approximately 20 U.S. state departments of transportation have a standard specification for certain types of OGFC material which could be referenced in many kinds of porous asphalt applications. Contemporary developments in this field are vital for all types of future porous asphalt applications.

2.2.16 Porous Asphalt in Cold and Hot Climates

Backstrom and Bergstrom (2000) have evaluated the function of porous asphalt in cold climates. The studied involved three experiments, such as the effect of ambient air temperature on the infiltration, simulation of the infiltration during the snowmelt period and the effect of temperature on the drainage process. During wintry conditions, porous asphalt retained some of its infiltrating function. At temperatures of +20ºC, the freezing point was approximately 40% of the infiltration capacity. The condition was similar to the snowmelt period, during which the capacity of infiltration was reduced 90% when the porous asphalt was melting and cycle for 2 days. Because of this, the capacity of infiltration was estimated to be 1-5 mm/min for porous asphalt in snowmelt conditions.

Hamdani (1983) has investigated two failures of open graded surface courses in the desert weather. These failures were an early loss of openness and macro-texture and a lack of mat stability evidenced by surface distortions at locations of changing traffic direction and speed. Loss of openness and macro texture was investigated under conditions simulating heavy and show traffic, summer-noon surface temperature, and a supporting base undergoing fatting-up. Under such conditions, open graded surface courses, regardless of their composition or initial degree of openness, appeared to close voids at approximately equal rate: i.e., 1.7 percentages points for each logarithmic load cycle. This proved that an open surface course should not be regarded as an effective cure to bleeding of pavement surface. The course certainly retard the phenomenon owing to its high initial porosity but, especially on heavily-travelled roads, its macro-texture would soon be wasted by gradual embedment into the bleeding surface underneath.

2.3 Various Types of Fiber

Laboratory tests on binders and mixtures have been developed to increase the performance of pavement. The fibers, constituting perhaps 0.3 to 0.4% of the asphalt by volume, disperse evenly and, despite their tiny size, overlap and form a network (Tom, 2006). Figure 2.6 present the interlock through the binder matrix.

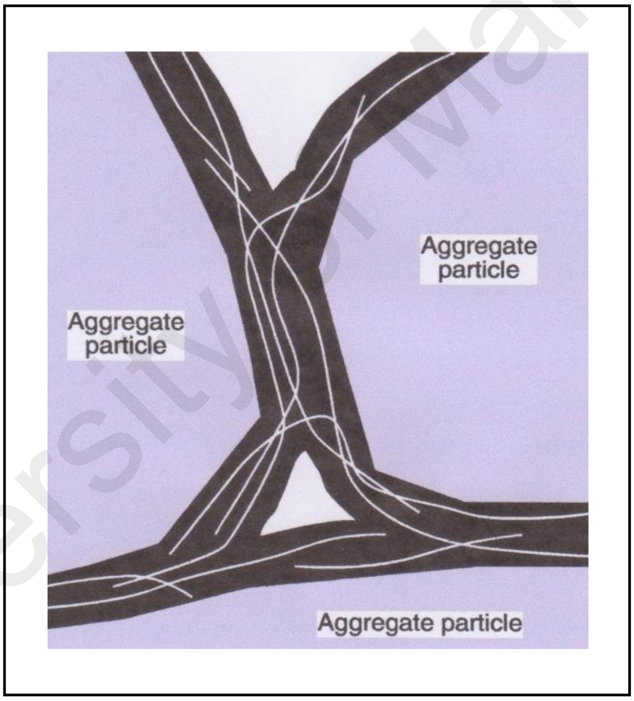


Figure 2.6 Concept of Interlocking Fibers in the Asphalt Coating of Aggregate Particles

Source: Georgia Department of Transportation, no date

A number of past studies have researched different fibers, of which natural fibers or synthetic fibers were used for the reinforced asphalt mixtures (Chen et al., 2009) Some of these were polypropylene fiber, polyester fibers, asbestos (mineral) fiber, glass fiber, cellulose fiber, carbon fiber and nylon fiber.

2.3.1 Polypropylene Fiber

Polypropylene is a synthetic material and commercial polymers for fiber are approximately 90-95% isotatic. Polypropylene imparts properties to the fiber which give it various advantages. The fibers have good durability, high melting point, low cost, do not absorb water and have various geometries and configurations (Zheng & Feldman, 1995).

Huang and White (1996) have used polypropylene fiber in a study of modified asphalt overlays. The results from laboratory investigation showed that the fiber modified mixtures were slightly stiffer and showed improvement in fatigue life. The inherent incompatibility with hot binder due to the low melting point of the fiber was the biggest problem encountered with polypropylene fiber.

2.3.2 Polyester Fibers

Wu et al. (2008) studied the effects of polyester fiber on the rheological characteristic and fatigue properties of asphalt. The results showed that the increase of polyester fiber contents in the mix was followed by an increase in the viscosity of asphalt binder at low temperature. It was observed that the fatigue property of asphalt mixture can be improved by adding fiber.

Maurer and Malasheskie (1989) also investigated the impact of loose fibers on overlay mixtures using polyester. Polyester was chosen over polypropylene due to its higher melting point. It was announced that the construction of the mixture was completed without difficulty or the need for extra equipment. A number of types of fiber reinforced interlays and a control section were used to compare with the polyester fiber modified mixture. Test sections were rated for ease of construction, resistance to reflection cracking and cost.

2.3.3 Asbestos (Mineral) Fiber

Asbestos is a mineral substance used as a textile fiber with separable, long, and thin fibers. At first, non-synthetic fibers were tested in pavements; therefore, asbestos fibers and cotton fibers were used, but these were degradable and were not suitable as long term reinforcements (Bushing & Antrim, 1968). Separated asbestos fibers are flexible enough and strong enough to be woven and spun. Asbestos fibers are heat resistant and useful for many industrial purposes.

Huet et al. (1990) conducted a study which compared changes in void contents and hydraulic properties of plain and modified asphalt mixture placed on the Nantes fatigue test track in France. Asbestos (mineral) fiber and polymer modifier (styrene-butadiene styrene, SBS) were used to modify the base mixture. The result showed that after the same loading was induced, there was no reduction in void content. Its drainage properties were practically identical and rutting was minimal. However, after 1,100,000 load cycles the polymer modifier (SBS) mixture showed a similar decrease in hydraulic properties and void content.

2.3.4 Glass Fiber

Glass fiber is relatively inexpensive to produce and can be composed of various materials in various quantities. Therefore, this fiber is the most widely used material for reinforcement. The glass fiber is made by melting together finely ground raw materials such as silica (SiO_2) with the addition of oxides of calcium, boron, sodium, iron, and aluminum. It has 100% elastic recovery and will not burn but will become soft at approximately 815ºC. The advantage of glass fiber is continuous filament with high elastic modulus, high durability, and high tensile strength (Mahrez & Karim, 2010).

Najd et al. (2005) used glass fiber reinforced asphalt concrete (FRAC) in asphalt mixture. The fracture toughness or critical stress intensity factor was higher than that for plain asphalt concrete which indicated stronger resistance to crack propagation. It was also found that Glass fiber-reinforced can improve the deformability and the stability of the asphalt concrete with no increasing bitumen content of asphalt mixture. This will be extremely beneficial to evade rutting and bleeding in high temperature degrees during the hot season.

2.3.5 Cellulose Fiber

Cellulose fibers have been used as a reinforcement material in polyester composites and manufactured from dissolving pulp. Another approach is to employ networks of cellulose fiber containing 10-20% of polyethylene matrix which can be thermally bonded by melting the polyethylene at 150°C (About.com, 2012).

Decoene (1990) investigated the affect of cellulose fibers on bleeding, abrasion, reduction, drainage and void content in porous asphalt. The addition of cellulose fiber increased the need for asphalt content of the mix but on the other hand, decreased bleeding of the binder. The test sections were applied on Belgian roads and monitored for drainage over the six-month period. Without fibers, the drainage time was doubled. Meanwhile the section containing fibers found that the same quality over six months.

2.3.6 Carbon Fiber

Chung (1994) evaluated the effect of carbon fibers on binders. Carbon fiber is produced at over 1000ºC. Therefore with regards to carbon fiber, the melting is not a significant issue due to high mixing temperatures. The tensile strength of carbon fibers should increase the tensile strength and related properties of AC mixtures as well as resistance to thermal cracking. Carbon fiber modified mixtures resulted in a stiffening effect and increased the fatigue life of pavements. It was indicated that carbon fibers should be the best performing fiber type available and the most compatible for asphalt binder modification.

Adding carbon fiber to the asphalt mixture will improve deformation and fatigue in flexible pavement (Jahromi & Khodaii, 2008). Carbon fibers have the ability to resist structural distress in pavements in the wake of growing traffic loads, and can improve fatigue by increasing resistance to cracks or permanent deformation.

2.3.7 Nylon Fiber

Nylon fiber is known as the most common type of synthetic fiber and is manufactured with more emphasis on durability and its ability to absorb water. Nylon fiber is also known as polyamides and popular facing yarn of carpets. It is used for the actual recycled carpet fibers in asphalt pavement (Lee et al., 2005)

Lee et al. (2005) investigated the effect of nylon fibers on the fatigue cracking resistance of asphalt concrete using fracture energy. The study consisted of two stages: the single fiber pull-out test and the indirect tension strength test. For pull-out tests of 15-denier single nylon fibers, the critical fiber embedded length was determined to be 9.2 mm. Meanwhile for indirect tension strength tests, specimens of asphalt mixture were mixed with nylon fibers of two lengths, i.e. 6 and 12 mm. They were designed and tested based on the results of the pull-out tests (critical embedded length) and three volume fractions of 0.25%, 0.5% and 1%. The specimens fabricated with fibers of 1% volume and length of 12 mm showed an 85% higher fracture energy than non-reinforced specimens which improved fatigue cracking resistance.

2.4 Oil Palm Fiber

The typical of oil palm tree is showed in Figure 2.7a. Oil palm fiber is a non-hazardous biodegradable material extracted from palm oil vascular bundles in the empty fruit bunch fiber. The fruits and nuts are stripped from fruits bunches leaving behind the empty fruits bunches as waste after the oil extra process (Figure 2.7b). This has created an important issue due to the vast amount of empty oil palm fruit bunches.


a) b)

Figure 2.7 a) Oil Palm Tree and b) Oil Palm Fiber for Export

Source: a) Oil palm fibers Malaysia, 2012 and b) Africa-Trace.ci, 2012

Manufacturers have been using oil palm fiber to make various fiber composites such as infrastructures, furniture, and mattresses. After the extraction of oil palm fruits, the producing of oil palm fiber is considered as waste. To produce the useable fiber, the oil palm empty fruit bunches goes through a process which involves shredding, separating, refining and drying the empty fruit bunches.

In tropical regions such as West Africa and Southeast Asia, oil palm is one of the most economical perennial oil crops for its valuable oil-producing fruits (Khozirah & Khoo 1991). The manufacturing process does not involve any chemical reaction or exposure and it is clean and non-carcinogenic

According to Wan Rosli et al. (2004), the explosive expansion of oil-palm plantation in Malaysia, Indonesia and Thailand has generated enormous amounts of vegetable waste, tremendous environmental concerns and problems pertaining to replanting operations. During recent years, Malaysia alone has produced an annual quantity of 30 million tones of oil-palm biomass, including trunks, fronds, and empty fruit bunches. Husin et al. (1986) noted that in Malaysia large amounts of oil palm biomass are generated by the palm oil industry, for example around 5000 million tones of felled trunks in 2000.

2.4.1 Physico-Mechanical Properties and Chemical Composition of Oil Palm Fiber

Tables 2.1 and 2.2 summarise the physico-mechanical properties and chemical composition of oil palm fiber as reported by various scholars (Shinoj et al., 2011). The range values indicated that the differences warrant comparisons with other researchers.

Table 2.1: Physico-Mechanical Properties of Oil Palm Fiber

Property	Range
Cell-wall thickness (µm)	3.38
Density (g/cm^3)	0.7-1.55
Diameter (µm)	150-500
Elongation at break (%)	4-18
Fiber coarseness (mg/m)	1.37
Fines (<0.2mm) (%)	27.6
Length-weighted fiber length (mm)	0.99
Microfibrillar angle (º)	46
Rigidity index, (T/D)3 ×10-4	55.43
Tensile strain (%)	13.71
Tensile strength (Mpa)	50-400
Young's modulus (GPa)	0.57-9

Source: Shinoj et al., 2011

Table 2.2: Chemical Composition of Oil Palm Fiber

Constituents	Range
Alcohol–benzene solubility (%)	2.7-12
Alfa-cellulose (%)	41.9-60.6
Alkali soluble (%)	14.5-31.17
Arabinose (%)	2.5
Ash Content (%)	1.3-6.04
Cellulose (%)	42.5-65
Extractives in hot water (100 ºC) (%)	2.8-14.79
Galactose (%)	1.0
Glucose (%)	66.4
Hemicellulose (%)	17.1-33.5
Holocellulose (%)	68.3-86.3
Lignin (%)	13.2-25.31

‘Table 2.2, Continued’

Constituents	Range
Mannose (%)	1.3
Pentosan (%)	17.8-20.3
Solubles in cold water (30 ºC) (%)	8-11.46
Xylose (%)	33.1

Source: Shinoj et al., 2011

2.4.2 The Element of Oil Palm Fiber

Ismail (2009) has presented the elements of oil palm fiber (Table 2.3). The principal elements of an OPF are determined by EDX analysis. The results also show that the main components in Palm Oil Fiber are oxygen, silica, copper, calcium, sodium, potassium, manganese and iron.

Table 2.3: Element of Oil Palm Fiber

Constituents	Range
Copper (g/g)	0.8
Calcium (g/g)	2.8
Iron (g/g)	10
Manganese (g/g)	7.4
Oxygen (%)	84.50
Potassium (%)	11.32
Silica (% atomic)	0.64-1.8
Sodium (g/g)	11

Source: Ismail, 2009

2.4.3 Surface Treatments on Oil Palm Fiber

The effects of the treatment on surface properties of oil palm fiber have been reported by various studies due to its advantages and ability to improve compatibility of the fiber with the matrix, loading etc. Shinoj et al. (2011) reported the effects of the treatment on surface properties of OPF as displayed in Table 2.4.

Table 2.4: The Effects of the Treatment on Surface Properties of OPF

Treatment	Effect on OPF
Acetylation	Makes the fiber hydrophobic and removes waxy layer from the surface.
Alkali Treatment	Makes the surface pores wider and fiber becomes thinner due to artificial impurities and dissolution of natural.
Benzoylation	Impacts a rough surface to the fibers ad make pores prominent.
Latex coating	Partially masks the pores on the fiber surface.
Mercerization	Amorphous waxy cuticle leaches out.
Oil extraction	Impact bright colour to fiber. Removal of oil layer exposes surface pits and makes surface coarse.
Permanganate treatment	Changes the colour and makes fiber soft. Porous structure is observed after treatment.
Silane treatment	Imparts a coating on fiber surface.
Titanate treatment	Smoothens fiber surface.
TDI treatment	Makes fiber surface irregular as particles adhere to surface.
γ irradiation	Partially eliminates the porous structure of the fiber and causes microlevel disintegration.

Source: Shinoj et al., 2011

2.5 The Use of Oil Palm Fiber

There are several investigations regarding asphalt mixture which have used oil palm fiber as an additive to improve performance of asphalt mixture.

2.5.1 Incorporation in Bitumen Pavement

Muniandy et al. (2009) studied the use of oil palm fiber in rubberized stone mastic asphalt. It showed that using fiber in asphalt pavement helped to improve the service properties of stone mastic asphalt mixes (SMA). This was due to the loss of asphalt as when the binder is heated up it tended to soften and drain down slowly. The literature research has made various attempts to compare special fiber (Viatop66) which is usually used in SMA pavement and which was imported from Germany, with oil palm fiber from local material (Muniandy et al., 2009)

2.5.2 Fatigue Performance in Mix Asphalt

Muniandy and Bujang (2006) have mentioned that the tensile or fatigue cracking along wheel paths of the vehicle are predominant on Malaysian roads when compared with other forms of distress. This is also due to the fact that the traditionally used 80/100 penetration binder is poor in shear strength and is further made worse due to the hot wet nature of the Malaysian climate. The use of cellulose oil palm fiber was found to improve fatigue performance of SMA. The fatigue life increased to a maximum at fiber content of approximately 0.6%, likewise the tensile strength and stiffness also showed a similar trend in performance.

2.5.3 Marshall Stability and Indirect Tensile

Muniandy et al. (2002) investigated the Marshall Stability and indirect tensile strength in SMA mixes. The PG 64–22 was used and cellulose oil-palm fibers were prepared with a range of 0.2–1.0% by total weight of the mix. A percentage of 0.6% by total weight of the mix appeared to provide the optimum performance. The available results showed that the fibers have a good potential to be used in SMA mixes.

2.6 Microscopic Examination of Oil Palm Fiber

Sreekala et al. (2002) studied the water sorption in oil palm fiber reinforced phenol formaldehyde composite. The cross-sectional structure of the oil palm fiber is evident from the scanning electron micrographs of the fracture surface of the embedded fibers in PF matrix (Figure 2.8).

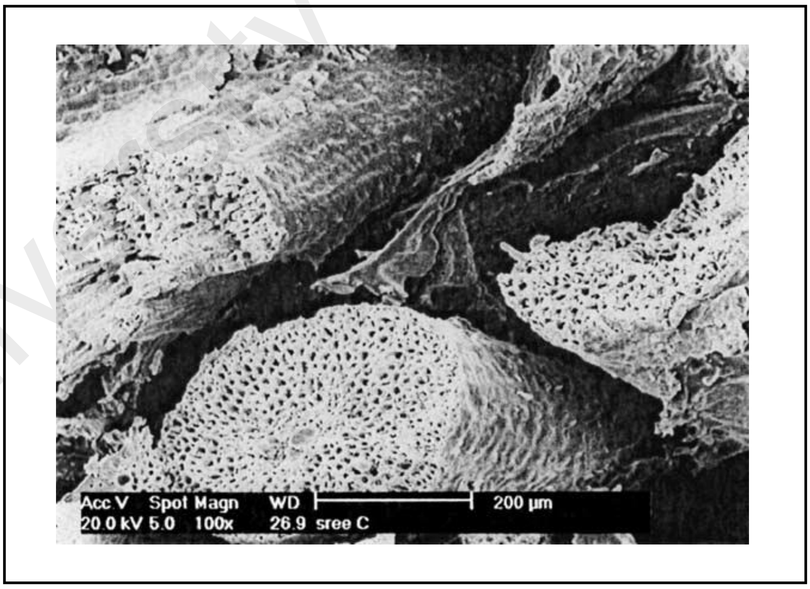


Figure 2.8 SEM of Tensile Fractured OPF Embedded in Phenol Formaldehyde Matrix

Source: Sreekala et al., 2002

Yusoff et al. (2010) presented results regarding the mechanical properties of short random oil palm fiber reinforced epoxy composites. Figure 2.9 shows that there was a small gap between fiber and matrix which indicated a poor adhesion. This was probably caused by incomplete wet ability or bonding between matrix resin and fiber during the fabrication of composites.

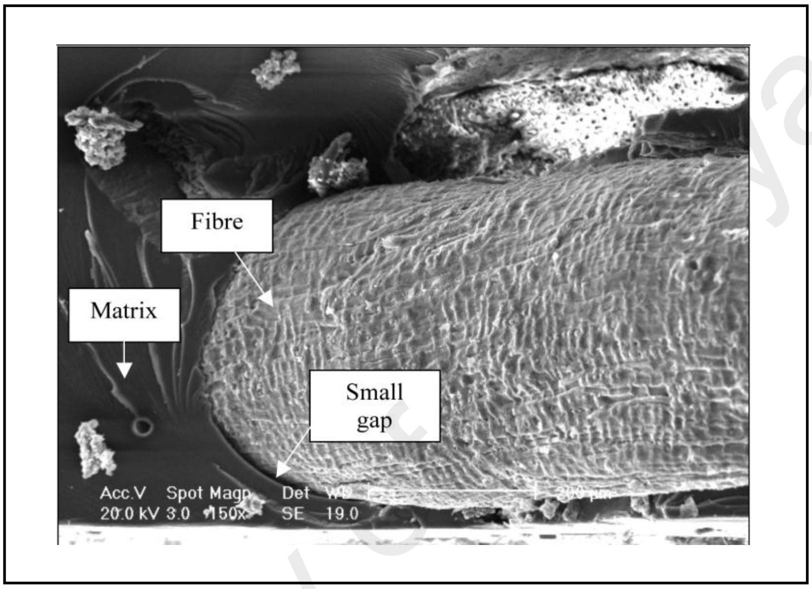


Figure 2.9 SEM Showing a Small Gap between OPF and Matrix

Source: Yusoff et al., 2010

CHAPTER 3

METHODOLOGY

3.1 General

This chapter describes the materials and methods used for the research. The laboratory experiments conducted in this study focused on the effect of oil palm fiber on the properties of porous asphalt. The preparation and testing of specimens were carried out in accordance with the prescribed standards, such as the Malaysia Public Work Department (PWD) specification, American Society of Testing and Materials (ASTM) and British Standard (BS).

3.2 Materials

Materials are an important component and play a key role to producing asphalt mixture. In the experiment, asphalt mixture is a composite material which must be considered in the selection gradation, binder and filler. Figure 3.1 shows the materials which are used to produce porous asphalt.

3.2.1 Aggregates

The types of aggregate were a mixture of coarse aggregate, fine aggregate and mineral filler which was obtained from the Malaysia Standard Specification (REAM, 2008). The coarse aggregate was crushed granite stone with size ranging between 10 mm to 20 mm. The aggregate type (porous asphalt) used was obtained from Kajang Rock.

3.2.2 Bitumen

The conventional bitumen penetration-grade 80/100 was used in this study since it is the most common type of bitumen available in Malaysia and is generally used for most laboratory experiments and road construction. It has an average consistency of 90 penetrations at 25°C from the penetration test.

a)

b)

c)

Figure 3.1 a) Aggregates, b) Bitumen, and c) Hydrated Lime.

3.2.3 Mineral Filler

According to Malaysia PWD, mineral filler shall be incorporated as part of the combined aggregate gradation. It shall be of finely divided mineral matter of hydrated lime (calcium hydroxide). The bitumen and the hydrated lime shall be sufficiently dry to flow freely and essentially free from agglomerations during the mixing. The weight of mineral filler to be added shall be not less than 2% by weight of combined aggregates. However, if hydrated lime is used, the weight shall be limited to not more than 2%. Table 3.1 shows the specification of hydrated lime which has been used in this study.

Table 3.1: Specification of Hydrated Lime

Parameter	Specification
ALI Ca $(OH)_2$	Min 90%
SiO_2	Max 1%
AI_2O_3	Max 1%
CaCO3	Max 3%
CaO	Min 69%
MgO	Max 4%
Moisture	Max 1%
Fe_2O_3	Max 0.1%
Passing 200#	Min 90%

3.2.4 Additives

Throughout this study, OPF was used as a stabilising additive in the preparation of specimen mixes. Oil palm fiber was supplied by Malaysian Palm Oil Board (MPOB) and was fresh and raw without treatment or chemical reaction. Five different additive contents were used to assess the effect of fiber content on the performance of the mixes. The amounts of oil palm fiber were 1%, 2%, 3%, 4% and 5% by weight of the binder content. The oil palm fiber has to be washed to remove other materials before being sieved through a 425 µm sieve (Figure 3.2).

Figure 3.2 Oil Palm Fiber

3.3 Aggregate Gradation

Gradation-B for porous asphalt was chosen for this study. According to Malaysia PWD, the aggregate gradation is a combination of coarse and fine aggregates, together with at least 2% mineral filler and conform to the appropriate envelope, as illustrated in Table 3.2 and Figure 3.3.

Table 3.2: Aggregates Gradation for Porous Asphalt (Grading B)

Sieve Size (mm)	Lower Limit	Upper Limit	Mid Point	Design	Retain (%)	Wt (g)
20	-	100	100	100	-	-
14	85	100	92.5	92.5	7.5	82.5
10	55	75	65	65	27.5	302.5
5	10	25	17.5	17.5	47.5	522.5
2.36	5	10	7.5	7.5	10	110
0.075	2	4	3	3	4.5	49.5
PAN	0	0	0	0	3	33
					100	**1100**

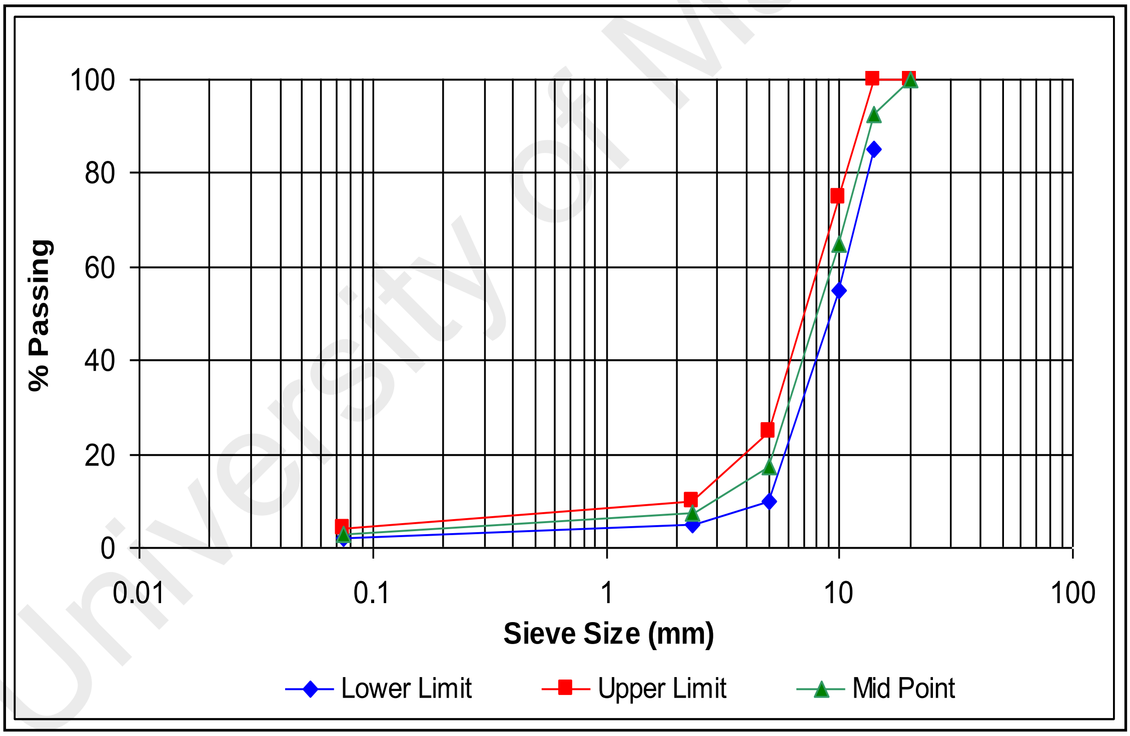


Figure 3.3 Aggregates Gradation for Porous Asphalt (Grading B)

3.4 Preparation of Oil Palm Fiber

After sieved, the oil palm fiber was dried in the oven before mixing to make sure that it had no influence on the result. The tray was placed in the oven at a temperature of 80°C for an hour until a constant percentage value of water loss was obtained. Following this, the OPF was stored in the desiccators in order to keep the temperature constant (Figure 3.4).

Figure 3.4 Oil Palm Fiber Stored in the Desiccators

3.5 Microscopic Examination

The oil palm fiber was observed using the scanning electron microscope (SEM). Figure 3.5 shows the scanning electron microscope machines, meanwhile Figure 3.6 shows the sputter coater equipment.

Figure 3.5 Scanning Electron Microscope Machines

Figure 3.6 Sputter Coater Equipment

3.6 Mix Proportioning

In this study, the weight of bituminous binder was designed and prepared with five contents of 4%, 4.5%, 5%, 5.5% and 6% by weight of aggregate while incorporating

OPF at five contents of 1%, 2%, 3%, 4% and 5% by weight of bitumen. The weights of binder and OPF in this study are given in Table 3.3.

Table 3.3: The Weight of Binder and Oil Palm Fiber

Binder Contents	Weight of Binder (g)	Oil Palm Fiber Contents	Weight of Oil Palm Fiber (g)
4%	45.8	1%	0.46
		2%	0.92
		3%	1.38
		4%	1.83
		5%	2.29
4.5%	51.8	1%	0.52
		2%	1.04
		3%	1.55
		4%	2.07
		5%	2.59
5%	57.9	1%	0.58
		2%	1.16
		3%	1.72
		4%	2.32
		5%	2.89
5.5%	64.0	1%	0.64
		2%	1.28
		3%	1.92
		4%	2.56
		5%	3.20
6%	70.2	1%	0.70
		2%	1.40
		3%	2.11
		4%	2.81
		5%	3.51

3.7 Physical Properties Test of Aggregate

3.7.1 Flakiness Index

The flakiness index of an aggregate test shall be taken in accordance with BS 812: Section 105.1-89. Figure 3.7 shows the equipment of flakiness index test. Aggregate particles are classified as flaky when they have a thickness (smallest dimension) of less than 0.6 of their nominal size, this size being taken as the mean of the limiting sieve apertures used for determining the size fraction in which the particle occurs. Aggregate flakiness index is evidenced by separating the flaky particles and expressing their mass as a percentage of the mass of the specimen tested. The test shall comply with the minimum mass, for sieve analysis with die allowed for a 6.30 mm BS test sieve or retained on a 63.0 mm BS test sieve.

From the sums of the masses of the fractions in the trays (M1), calculate the individual percentage retained on each of the different sieves. Dispose of any fraction of which the mass is 5% or less of mass M1.

The flakiness index value was calculated using the following formulae.

Flakiness = (M3 / M2) x 100

where, M3 = Combine and weigh all the particles passing the gauges or special sieves.

M2 = Record the mass remaining

Figure 3.7 Flakiness Index Equipment

3.7.2 Elongation Index

The measurement of the elongation index was carried out in accordance with BS 812: Section 105.2-90. An Equipment of elongation index value is shown in Figure 3.8. This test is based on the classification of aggregate particles as elongated when they have a length (greater dimension) of more mote than 1.8 of their nominal size, this size being taken as the mean of the limiting sieve apertures used for determining the size-fraction in which the particle occurs. Aggregate elongation Index is evidenced by separating the elongated particles and expressing their mass as a percentage of the mass of the specimen tested. The test is not applicable to material passing a 6.30 mm BS test sieve or retained on a 50.0 mm BS test sieve.

From the sum of masses of the fractions in the trays (M1), calculate the individual percentages retained on each of the different sieves. Dispose of any fraction whose mass is 5% or less of mass M1.

The elongation index value was calculated using the following formulae.

Elongation Index = (M3 / M2) x 100

where, M3 = Combine and weigh all the elongated particles

M2 = Record the mass remaining

Figure 3.8 Elongation Index Value Equipment

3.7.3 Aggregate Impact value

Standard impact value tests on the specimens were conducted according to BS 812: Part 112-90. A test specimen was compacted in a standardised manner, into an open steel cup as shown in Figure 3.9. The specimen was then subjected to a number of standard impacts from a dropping weight. This action broke the aggregate to a degree which was dependent on the resistance of an aggregate to a sudden shock or impact. This degree was assessed by means of a sieving test on the impacted specimen and was taken as the aggregate impact value (AIV).

The impact value was calculated using the following formulae.

Aggregate Impact Value = (M2 / M1) x 100

where, M2 = the mass of the test specimen (in g);

M1 = the mass of the material passing the 2.36 mm test sieve (in g).

Figure 3.9 Aggregate Impact Value Equipment

3.7.4 Los Angeles Abrasion Value

The Loss Angeles (L.A) abrasion test apparatus was used to characterise toughness and abrasion resistance. The test was performed following a method adapted from ASTM C 131-81. The machine rotates (Figure 3.10) at a speed of 30 to 33 rpm for 500 revolutions. The material was then extracted and divided into material passing the 1.70 mm (No. 12) sieve and material retained on the 1.70 mm (No. 12) sieve. The retained material (larger particles) was then weighed and compared to the original specimen mass. The difference in mass was reported as a percentage of the original mass.

The Los Angeles abrasion value was calculated using the following formulae.

$$\textbf{Los Angeles Abrasion Value, } = 3\,(\mathbf{M1} - \mathbf{M2}) / \boldsymbol{d}$$

where, M1 = the mass of specimen before abrasion (in g);

M2= the mass of specimen after abrasion (in g)

d = the particle density of the aggregate (on saturated surface dried Mg/m3)

Figure 3.10 Los Angeles Abrasion Machine

3.7.5 Soundness

This test method made it possible to estimate the soundness of aggregate for use in asphalt pavement. Figure 3.11 shows some apparatus used for soundness test. The specimens of aggregate were dried and immersed in a saturated solution of magnesium sulfate or sodium sulfate (ASTM C 88-90) followed by oven drying to completely dehydrate the salt precipitated in permeable pore spaces. The saturated solution which penetrates the particles of stone and the crystals of sulfate which form when the specimen is dried tend to cause splitting or cracking of aggregate particle. The extent of degradation (splitting and cracking) is based on the soundness of the aggregate.

Figure 3.11 Soundness Basket

3.7.6 Aggregate Crushing Value

According to BS 812: Part 110-90, the test of aggregate crushing value is used to determine the resistance of an aggregate to crushing under a gradually applied compressive load. A test specimen was compacted in a standardised manner into a steel cylinder fitted with a freely moving plunger (Figure 3.12). The specimen was then subjected to a standard loading regime applied through the plunger. This achievement crushed the aggregate to a degree which was dependent on the crushing resistance of the material. This degree was assessed by a sieving test on the crushed specimen and was taken as a mass of the aggregate crushing value (ACV).

The aggregate crushing value was calculated using the following formulae.

Aggregate crushing value = (M2 / M1) x 100

where, M2 = the mass of the test specimen (in g);

M1 = the mass of the material passing the 2.36 mm test sieve (in g).

Figure 3.12 Aggregate Crushing Value Equipment

3.8 Physical Properties Test of Bitumen

3.8.1 Penetration

Figure 3.13 shows the penetration apparatus. These test methods were conducted according to ASTM D5-97. The procedure described in the method was closely followed throughout the test in order to achieve consistent results. The temperature was 25°C, load was 100gm and the time was 5 seconds respectively.

The penetration needle holder and guide were examined to establish the absence of water and other extraneous matter. The specimen container was completely covered with water at 25 ± 0.5°C temperature. The needle was slowly lowered until its tip made contact with the surface of the Specimen. The pointer of the penetrometer was set to zero. The needle holder was released at the specified period of time (5 seconds) and the reading was recorded. These procedures were repeated at three points on the surface of the specimen, not less than 10mm from the side of the container and not less than 10mm apart.

Penetration value was calculated using the following formulae.

$$\textbf{Penetration value} = (R1 + R2 + R3)/3$$

where, R1, R2, R3 = the penetration reading at different locations.

Figure 3.13 Penetration Test Equipment

3.8.2 Softening Point

The objective of softening point value is to determine the temperature at which a phase change occurs in the porous asphalt. The softening point value of bitumen 80/100 was determined in accordance with ASTM D36- 86 (Reapproved 1993) or BS 2000: Part 58:1988 by using the ring and ball method. According to BS2000: Part 58: 1998, the softening point is defined as the temperature at which a substance attains a particular degree of softness under the specified conditions of the test.

The bitumen was poured into the ring and cooled at room temperature for about 30 minutes. The specimens were levelled and placed on the ring holder. Following this, the Specimens were kept in the water bath at a level of not less than 102mm and not more than 108mm from the bottom of the bath. A steel ball of specified mass was placed onto a disk of bitumen contained within a metal ring of specified dimensions. The assembled apparatus was placed in a bath of liquid and the temperature of the liquid was raised at a specified rate as shown in Figure 3.14.

The softening point value was calculated using the following formulae.

Softening Point Value = (R1 + R2)/2

where; R1, R2 = Temperature reading upon the ball touches the bottom plate.

Figure 3.14 Softening Point Equipment

3.8.3 Flash and Fire Point

The flash point and fire point was used to determine fire point, which is a temperature above the flash point. The test was performed following a method adapted from ASTM D 92 - 05. The Cleveland open cup apparatus (semi automatic) was used (Figure 3.15) and the method is applicable to all petroleum products with flash points above 79ºC

(175ºF) and below 400ºC (752ºF) with the exception of fuel oils. The specimen will carry out the combustion for a minimum of 5 seconds.

Figure 3.15 Cleveland Open Cup Apparatus (Semi Automatic)

3.8.4 Ductility

Figure 3.16 shows the ductility machine. This ductility of bituminous material is determined by the distance to which it will elongate before breaking when two ends of briquet specimen of material are pulled apart at a specified speed and at a certain temperature. The temperature of test was 25 ± 0.5ºC with a speed of 5 cm/min ± 5.0% (ASTM D 113-07) and was maintained continuously.

Figure 3.16 Ductility Machine

The mould is assembled on a brass plate. Thoroughly coat the surface of the plate and the interior sides' surface of the mould with a thin layer of a mixture f talc to prevent the material under investigation from sticking. The plate upon which the mould is placed shall be level and perfectly flat. The material is carefully heated until it has become sufficiently fluid to pour. The mould containing the material is cooled to room temperature for a period of 30 to 40 min following which the specimens are placed in the water bath at a specified test temperature of 25ºC for 30 minutes. The excess bitumen is cut off with a hot straight edged putty knife to make the moulds just level full. Detach the side pieces and attach the ring at each end of the clips. The two clips are pulling apart at a uniform speed as specified until the briquet ruptures. Measure the distance in centimetres in which the clips have been pulled to produce rupture.

3.8.5 Viscosity

The Brookfield Thermosel apparatus (Figure 3.17) was used to determine the viscosity of binder at elevated temperatures. The test was performed according to the ASTM D4402-87 (Reap proved 2000).

Figure 3.17 Brookfield Thermosel Apparatus

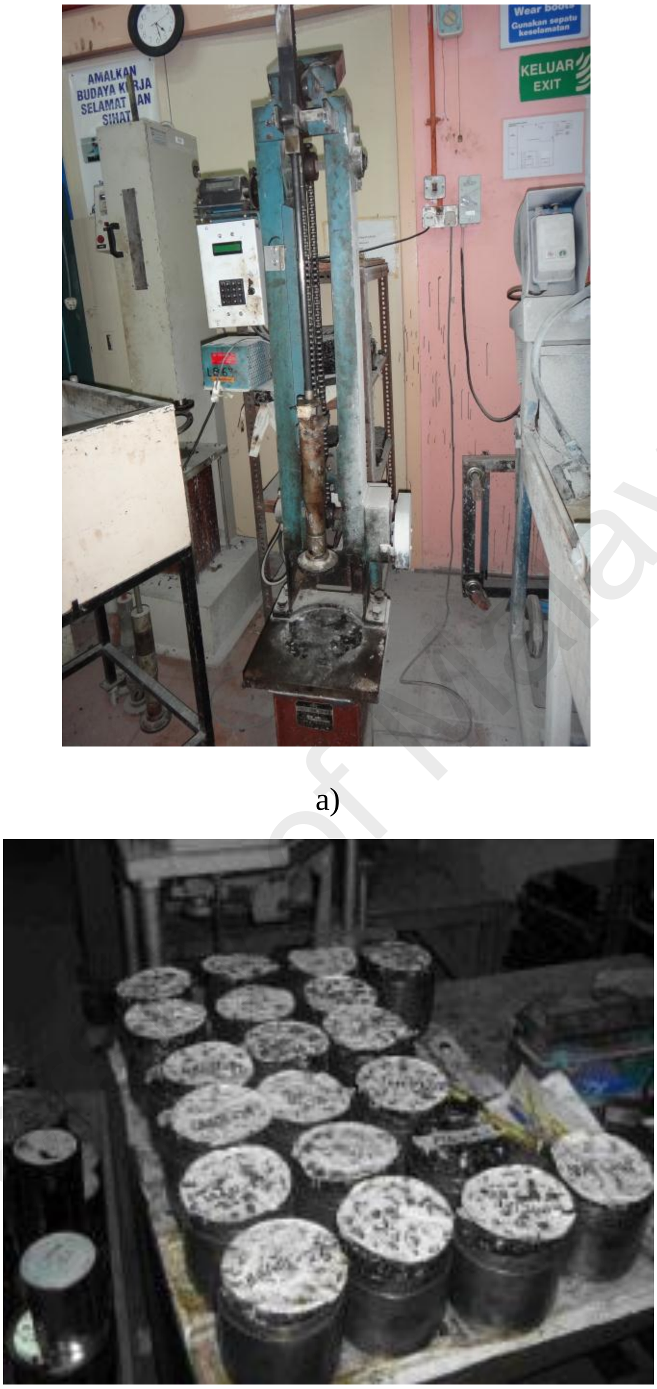
Calibrate the controller as directed by the on-screen instructions. The specimen in the oven was heated. Approximately 10± 0.5g of specimen was placed into the holder. Before transferring to Brookfield Thermosel, the specimen was cooled in ambient temperature 90°C using the extracting tool. The specimen holder was then placed into the thermo container, before the viscometer was lowered and the thermo-container was aligned. The spindle (No.27) was inserted into the liquid in the chamber and was coupled with the viscometer. The specimen was rotated at a lower speed and the required speed was 20 rpm. If the specimen was too hard, attempts would be made to get the speed required by increasing the temperature to the next 10°C (i.e. 100°C). Taking the reading for viscosity, shear stress after the torque reading stabilises.

3.9 Preparation of the Mix Specimens

The preparation of the mix specimens are shown in Figure 3.18 and 3.19. Bitumen 80/100 penetration-grade was poured into a container and heated in the oven at a temperature of 100°C until becoming liquid. After its weight was recorded, molten bitumen was poured into the small container.

Figure 3.18 Mix the Specimen Coated with Bitumen

Specimens were prepared using a dry process, during which bitumen 80/100 penetration-grade was mixed with the heated aggregate before adding OPF to the mix. The compactness of porous asphalt mixes was determined in accordance with ASTM D 1559 based on the laboratory test by using the Marshall method.


a)

b)

Figure 3.19 a) Marshall Compactor, and b) Specimens been Cooled for 24 hours

The specimens shall then be used for further analysis for the test. With high air voids, high binder contents were essential to ensure the mix integrity, increase resistance to oxidation, ravelling and improve durability. The quantity of the binder was carefully balanced such that it was not deemed too excessive to cause a binder drain-down during production, transport and laying or deemed too little to adversely affect durability. Because of the limited comp active effort applied in the field on porous asphalt mixes, the number of blows per face shall be 50. The specimen was removed from the Marshall Mould using a hydraulic jack after cooling at room temperature for one night. The specimen was then stored at room temperature for further testing.

3.10 Laboratory Investigation on Porous Asphalt

3.10.1 Voids in the Mix

The tests for density and air void analysis were implemented according to the ASTM D2726-90. Figure 3.20 shows the specimen weight in air and weight in water. The average height and diameter were measured to the nearest 0.1 mm with venire calliper. The specimens were wrapped tightly with the plastic to prevent water from penetrating and filling the voids inside the specimens.

Each specimen was weighed to the nearest 0.1 gm and designated this mass as A. The specimen was then soaked in water and the mass of the specimen in the water was recorded as C. The specimen was surface dried by blotting quickly with a damp towel and then weighed in air; this mass was designated as B (Katman, 2006).

The bulk specific of gravity of each specimen was calculated using the below formulae.

$$\textbf{Bulk sp gr} = A/(B-C)$$

where; A = mass of the dry specimen in air, g

(B-C) = mass of the volume of water for the volume of the specimen at 25°C

B = mass of the saturated surface-dry specimen in air, g

C = mass of the specimen in water, g

a)

b)

Figure 3.20 a) Specimen Weighted in Air and b) Specimen Weighted in Water

3.10.2 Cantabro

The Cantabro test was performed in order to analyse the resistance of the compacted porous mixture to abrasion loss. This is an abrasion and impact test carried out in the Los Angeles machine. This test measures the resistance of asphalt mixes to particles losses and determines the minimum binder content which is necessary to provide the correspondence minimum cohesion.

3.10.2.1 Cantabro Test on Air Cured Specimens

The aim of this test was to evaluate the cohesion or ravelling resistance of the bituminous mixtures. The specimens were maintained at a temperature of 25°C and the weight of the Marshall specimen was recorded before being placed into a Los Angeles drum (ASTM C131-96) without the steel balls. 300 rotations were completed with a speed of 30 to 33 rpm before the weight loss was calculated. Figure 3.21 shows the specimen before and after cantabro test on air cured specimens.

Calculation of weight loss at each hundred rotations:

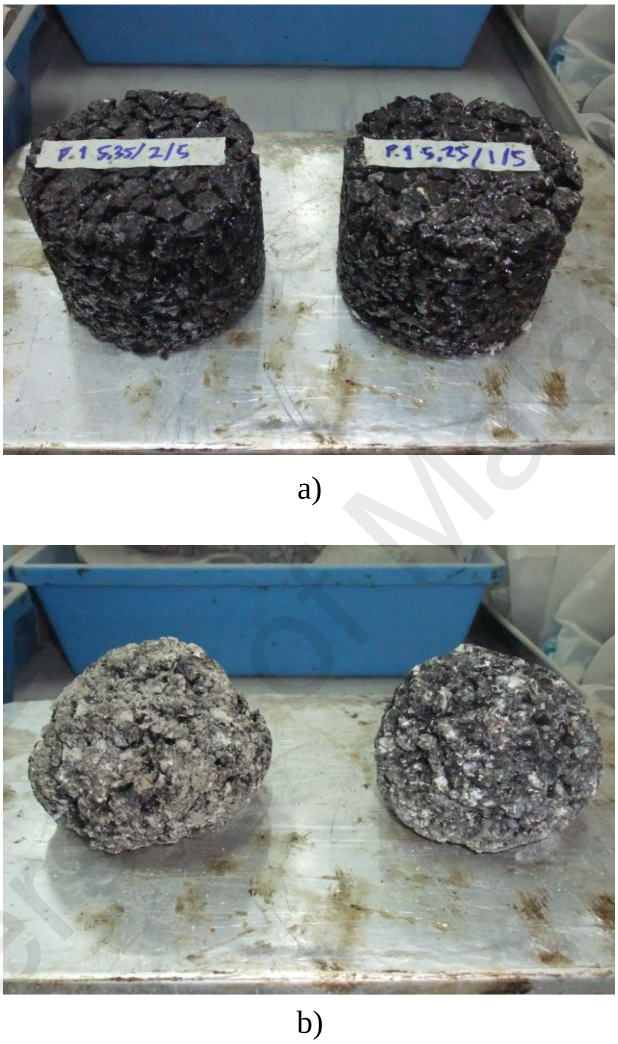
$$\textbf{Weight Loss} = [\,(Mi - Mr\,)\,/\,Mi\,] * 100$$

where; Mi = Initial mass of Specimen

Mr = Mass of Specimen after each hundred rotation

3.10.2.2 Cantabro Test on Water Cured Specimens

The Cantabro test on water cured specimens was used to measure the resistance of mixes to stripping. In this test, the initial weight of the Marshall specimen was recorded following which specimens were placed into a water bath for four days at 49±1°C. The specimens were taken out of the bath on the fifth day and left for 18 hours. The Los Angeles testing was adopted similar to the Cantabro test on air cured specimens.



a)

b)

Figure 3.21 a) Specimens before Cantabro and b) Specimens after Cantabro

3.10.3 Binder Drain-Down

Figure 3.22 shows the binder drain-down specimens. The binder drain-down test was carried out in order to determine the binder content which an asphalt mixture could hold without excessive binder drainage. This test was also conducted to prevent excessive binder drainage occurring during manufacture, transport and laying (Daines, 1992). This test was conducted by closely following the Malaysia PWD guidelines. Place the whole specimen in the wire basket. The retained binder (percentage) for each mix should be calculated after the specimen has been in oven for 3 hours.

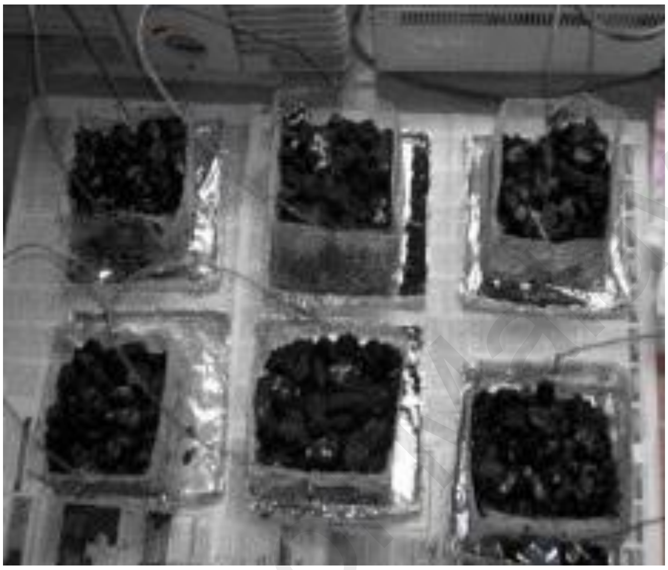


Figure 3.22 Binder Drain-Down Specimens

3.10.4 Determination of Optimum Binder Content

The optimum binder content (OBC) in porous design was selected based on test results of binder drown, air void and abrasion loss. The optimum binder content was determined from the limit requirement according to Malaysian PWD for porous asphalt. The binder drain-down test should not exceed 0.3%. Air void test results should be in the range of 18 to 25% and the average of the Cantabro test should not be more than 15%.

3.10.5 Falling Head Permeability

In this test, the specimens were used permeability equipment (Figure 3.23) and tested to measure the rate of flow of water through prepared specimens. The specimens were tested for permeability before extraction to take advantage of tight bonds between the specimens and the mould. The specimens were therefore allowed to cool in the mould after compaction.

Figure 3.23 Permeability Equipment

Calculation for coefficient of permeability, k:

$$\mathbf{k = 2.3\, aL \log10 (h_1/h_2) / At}$$

where; a = Area of stand pipe (cm2)

A = Cross sectional area of the Specimen (cm2)

L = Length of the Specimen (cm)

h_1 = Initial head (cm)

h_2 = Final head (cm)

t = Time interval (s)

3.10.6 Indirect Tensile Modulus

Indirect tensile modulus test parameters are tabulated in Table 3.4. According to the American Society Testing and Materials (ASTM) D4123-82, the Indirect Modulus test was carried out using the Universal Material Testing Apparatus (Figure 3.24) in order to apply compressive loads with acts parallel and along the vertical diametrical plane by two curves loading strips at 25ºC. Following this, the information was sent to a computer program for data attainment.

Table 3.4: Indirect Tensile Modulus Test Parameters

Parameter	Value
Temperature	25ºC
Preconditioning pulse	5 pulse
Load duration	100 ms
Load cycle time	3 seconds
Required strain	10
Poisson ratio	Assumed value (0.4)
Load magnitude	1270 Newton
Specimens dimension	Varied

The resilient modulus values can be used to determine the relative quality of material as well as to generate input for pavement evaluation analysis and pavement design. The results obtained from the resilient modulus test can be used to study effects of temperature, loading rate, rest period, etc (ASTM D4123-82 (Reapproved 1995)).

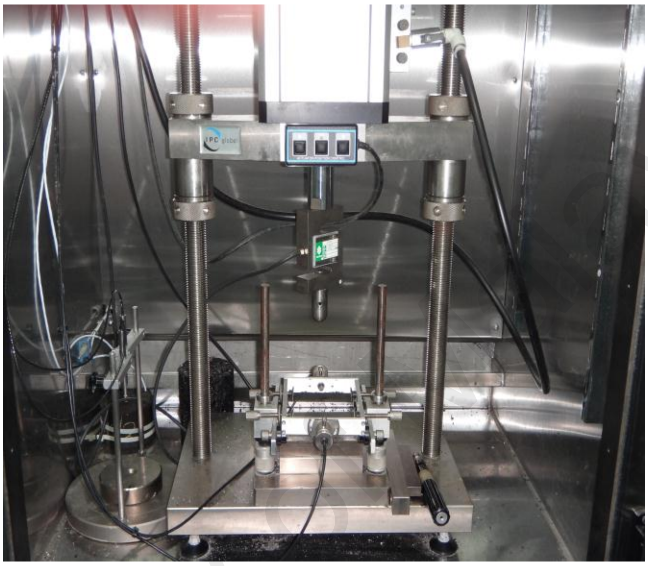


Figure 3.24 Indirect Tensile Stiffness Modulus Test

3.11 Statistical Analysis

Analysis of variance (ANOVA) was used as the statistical tool to evaluate the effect of OPF content on performance characteristics of porous asphalt. Two-factor ANOVA without replication and single-factor ANOVA were adopted to evaluate the results of laboratory tests with a confidence level of 95% ($\alpha = 0.05$).

The test was examined under two opposing conjectures (hypothesis) H_0 and H_A (Table 3.5). The means that a null hypothesis (H_0) is equal whereas alternate hypothesis (H_A) is different. Furthermore, in order to determine the effect of OPF, F-result from the experiments was compared to F-critical. The result was significant given α if F-result was more than F-critical, contrariwise the results were insignificant if F-result was less than F-critical.

Table 3.5 Hypothesis for ANOVA Results

If	Then
F-results>F-critical	Significant and reject the null hypothesis
P-value<0.05	Significant and reject the null hypothesis
F-results<F-critical	Insignificant and accept the null hypothesis
P-value>0.05	Insignificant and accept the null hypothesis

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

This chapter presents the result analysis and discussion of the investigation into the effect of OPF on some physical properties of porous asphalt. The results were evaluated base on a regression analysis and analysis of variance (ANOVA) in order to establish the relationship performance of oil palm fiber-modified in porous asphalt.

4.2 Physical Properties of Aggregates

The results of the physical properties of aggregates tested are given in Table 4.1. Physical properties of aggregates test was carried out in accordance with the American Society of Testing (ASTM) and British Standard (BS) as the reference standard. The test was an important parameter to ensure the quality of aggregates and should be strong enough under laboratory testing even for application on pavement traffic load.

Table 4.1: Physical Properties of Crushed Granite Aggregate

Properties	**Requirement (REAM, 2008)**	**Test Value (%)**
Flakiness index	Not more than 25%	4
Elongation index	Not more than 30%	16
Impact value	Not more than 25%	20
Los Angeles abrasion value	Not more than 25%	21
Soundness	Not more than 18%	4.1
Aggregate crushing value	Not more than 25%	20

From Table 4.1, it is evident that the aggregate has met the requirement to ensure a reliable value for further testing. More detailed results of physical aggregate value tests are provided in Appendix A.

4.3 Interfacial Examination of Oil Palm Fiber

A scanning electron microscope (SEM) was used to detect and analyse the typical properties of oil palm fiber. Figure 4.1 and Figure 4.2 show the SEM micrograph of OPF (fresh raw). The SEM micrograph shows the surface view at magnification 500X (Figure 4.1) and interior view at magnification 1.00KX (Figure 4.2). It seems that the fresh raw of oil palm is unfairly uniform and rough. These conditions may lead to a larger specific surface area and better asphalt absorption.

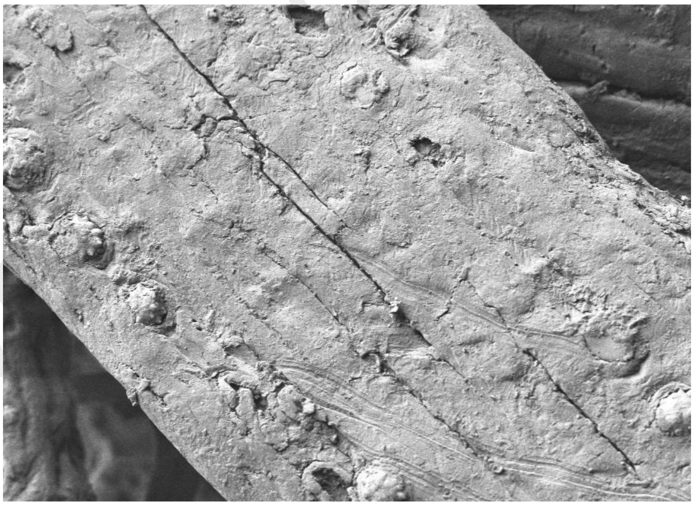


Figure 4.1 Surface View of Oil Palm Fiber at Magnification 500X

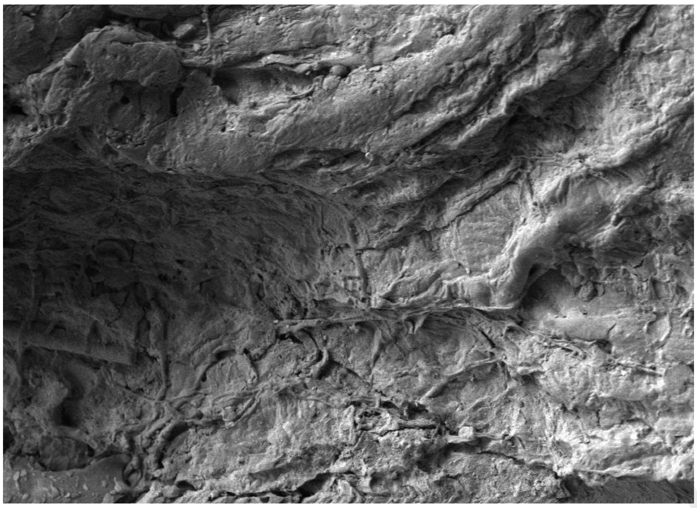


Figure 4.2 Interior View of Oil palm Fiber at Magnification 1.00KX

4.4 Physical Properties of Bitumen

4.4.1 Penetration Test

The results obtained from the penetration test are shown in Table 4.2. The penetration value is determined in accordance with ASTM D5-97.

Table 4.2: Penetration Test Results

Number of specimens	Penetration Value (tent of mm)
Penetration 1	87.0
Penetration 2	84.0
Penetration 3	86.0
Average	**85.6**

These results only focused on bitumen 80/100 without fiber. The addition of OPF was not allowed to measure the penetration value when the depth of the needle into the binder. This is due to the fact that the oil palm fiber was more homogeneous and stiffer in the mix. Average penetration value for 80/100 bitumen without fiber was 85.6 as shown in Table 4.2. This value was acceptable where the penetration value was in the range of 80 to100 mm.

4.4.2 Softening Point Test

Figure 4.3 presents the result of softening point test for bitumen 80/100 with different fiber contents. The test was carried out in accordance with ASTM D36 - 86 (Reapproved 1993) or BS 2000: Part 58:1988.The values of softening point are given in Appendix A.

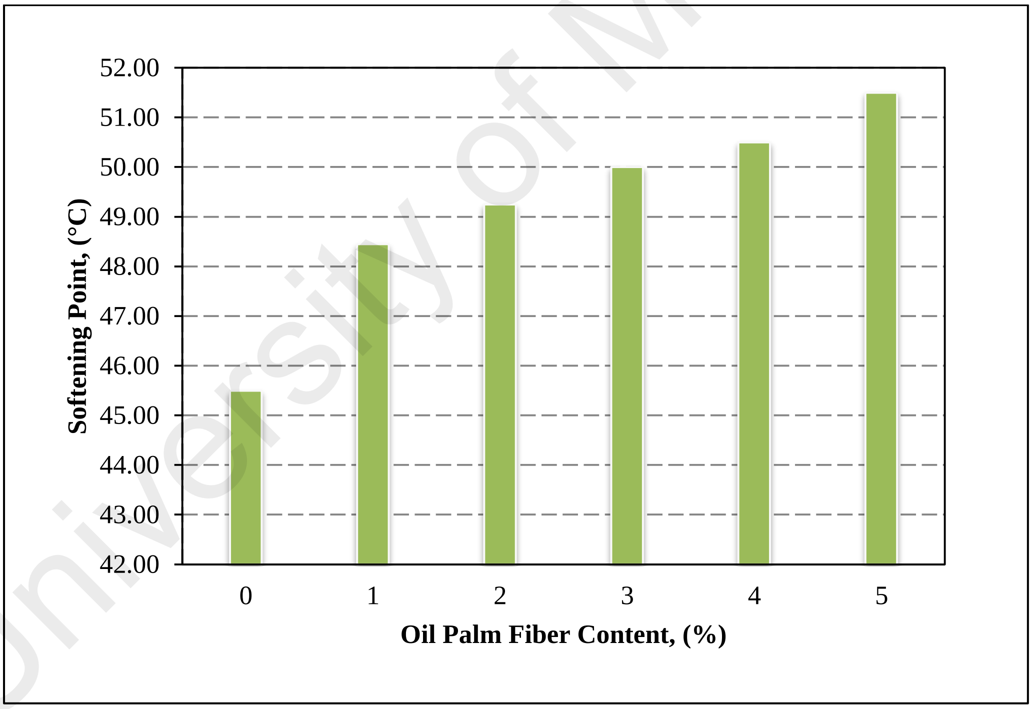


Figure 4.3 Softening Point Test Results

The specimens with higher OPF content had the largest value of softening point. As contents of OPF increased, the value of softening point also increased. In contrast, the softening point decreased as the OPF content decreased. This also showed that the

80/100 penetration bitumen properties meant the softening values which should be between 40 to 50ºC are specimens made with 0%, 1%, 2%, 3% fiber contents. Meanwhile, specimens at 4% and 5%, the value of softening point higher from 50ºC. The test results indicated that the higher temperature and the addition of OPF would enhance the ability of control specimens (no fiber) to resist flow.

Single factor ANOVA was used as the statistical tool for softening point test. F-value for OPF different content was 62.011 which was higher than F-critical of 2.772 and its P-value was 1.03 x 10^{-10} which was smaller than 0.05. This showed that the addition of OPF has a significant impact on softening point. The results of analysis of variance are given in Appendix B.

4.4.3 Flash and Fire Point Test

Flash and fire point test was carried out in accordance with ASTM D92 – 05. This test was determined using three specimens of bitumen 80/100. The average result is shown in Table 4.3.

Table 4.3: Flash and Fire Point Test Results

Number of specimens	**Flash and Fire Point Value (ºC)**
Flash and Fire Point 1	282
Flash and Fire Point 2	290
Flash and Fire Point 2	285
Average	**285.6**

From the results obtained it is evident that the average of flash and fire point value is 285.6ºC. This is in accordance with flash and fire point ranging between 79ºC (175ºF) to 400ºC (752ºF).

4.4.4 Ductility Test

The ductility test was carried out in accordance with ASTM D113 - 07. The value was obtained using tree specimens of bitumen 80/100 without adding fiber. The average result obtained is tabulated in Table 4.4. Ductility value at temperature of 25ºC was 102.3. This value was in accordance with bitumen 80/100 properties which limited the ductility value to a minimum of 100 cm.

Table 4.4: Ductility Test Results

Number of specimens	**Ductility Value (cm)**
Ductility 1	104
Ductility 2	101
Ductility 3	102
Average	**102.3**

4.4.5 Viscosity Test

The test was determined in accordance with ASTM D4402 - 87 using a Brookfield's Test parameter to evaluate asphalt flow-ability of the mix and temperatures with different contents of OPF. The detailed values of viscosity test are given in Appendix A.

4.4.5.1 Effect of Different OPF Content on Viscosity

The effects of the different OPF contents on viscosity are summarised in Figure 4.4. The results indicated that the increase in viscosity was a result of adding the OPF contents from 0% to 5%. Results also found that the viscosity value at 0% OPF content was the lowest, with values of 4093.27, 986.50, 438.10, 418.13, and 128.29 mPa.s for temperatures of 90ºC, 110ºC, 130ºC, 135ºC and 150ºC respectively. Meanwhile, 5%

OPF content had the higher value of viscosity, with values of 12010.14, 3948.02, 1675.65, 1016.50, and 813.87 mPa.s for temperatures of 90°C, 110°C, 130°C, 135°C and 150°C respectively. The addition of OPF must be maintained during the blending process so as to be more viscous in the stability of the asphalt mixture, which may be influenced by characteristics of OPF, asphalt binder and temperature.

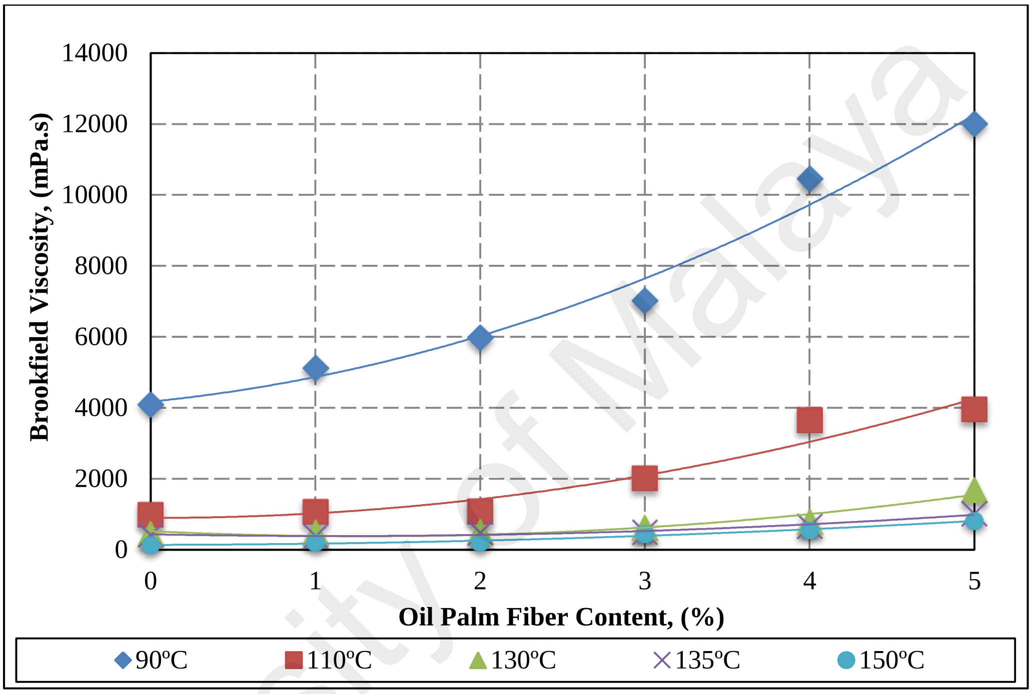


Figure 4.4 Viscosity Value with the Different OPF Contents

4.4.5.2 Effect of Different Temperature on Viscosity

Figure 4.5 shows the viscosity in the mixes with different temperature**.** The test was obtained for temperatures ranging between 90 to 150°C. The contributions of OPF content in bitumen increased the viscosity of the binder. It is clear that the ability of resist flow would decrease at higher temperatures. When the fiber content increased to 5%, the local networks gradually began to interact to initiate a continuous network throughout asphalt (Wu et al., 2008). This also showed a similar trend between the control specimen and specimen with fiber. As such, temperature influenced the viscosity when OPF was added.

A two-factor ANOVA without replication was carried out for viscosity test results. It showed a significant effect from different contents of OPF. F-value of 34.287 (F=34.287>F-critical=2.866) and P-value smaller than 0.05. The results of analysis of variance are given in Appendix B.

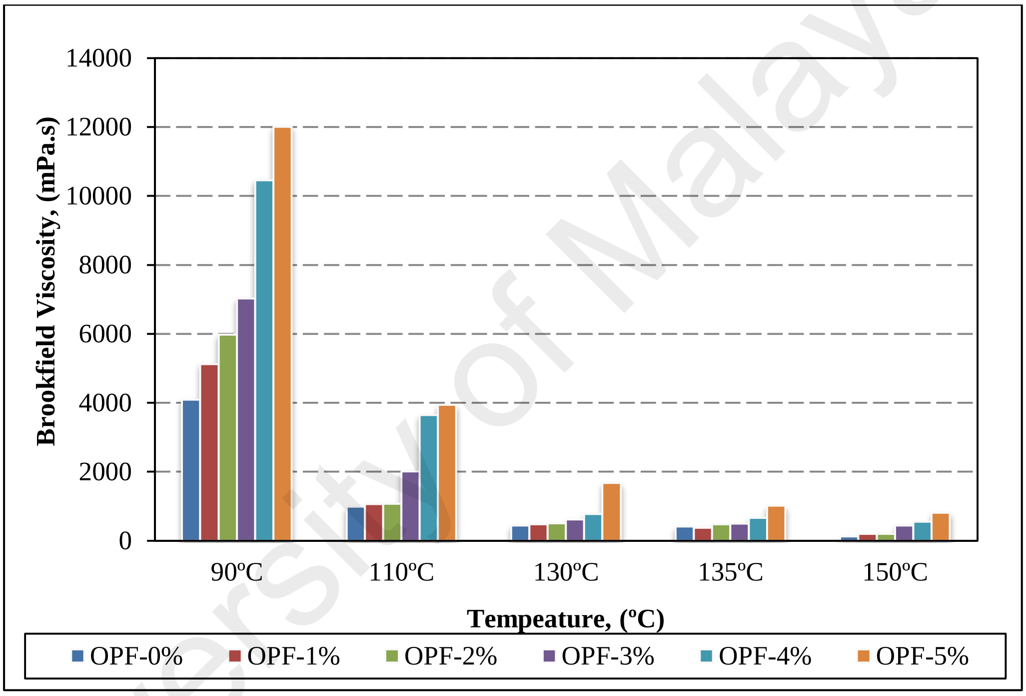


Figure 4.5 Viscosity Value with the Different Temperature

4.4.5.3 Viscosity and Softening Point Relationship

Figure 4.6 shows the relationship between viscosity values at 135ºC and softening point for each OPF content. As seen in Figure 4.6, regression line (R^2 = 0.963) between viscosity and softening point was achieved. The results indicated that as the viscosity value increased, softening point value also increased. The higher the OPF content in bitumen blend values the higher the viscosity and also the softening point value.

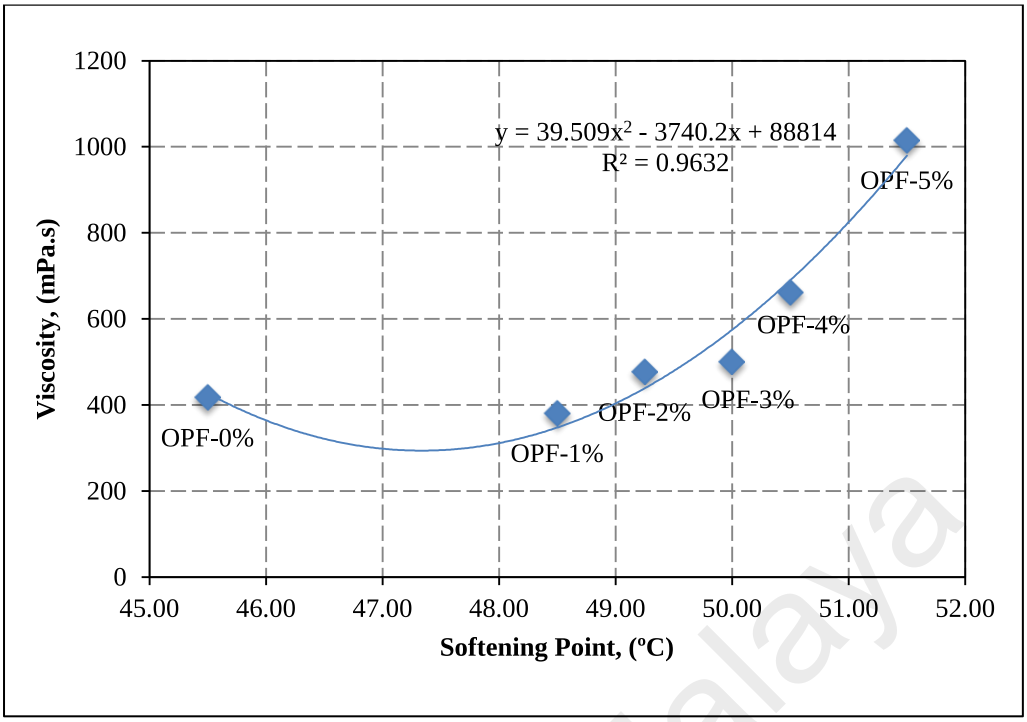


Figure 4.6 Viscosity and Softening Point Relationship

4.5. Mixture of Porous Asphalt

4.5.1 Air Void Test

The air voids denote the pockets of air between the bitumen-coated aggregate particles in a compacted bituminous paving mixture. The air void test value was determined in accordance with ASTM D2726 - 90. In this section, the performance of porous asphalt was tested with different content of OPF and binder. The values of air voids are given in Appendix A.

4.5.1.1 Effect of Different OPF Content on Air Voids

Figure 4.7 shows the air voids in the mixes with different fiber contents. The results indicate that the mean air voids in all of the mixes were more than 22%.

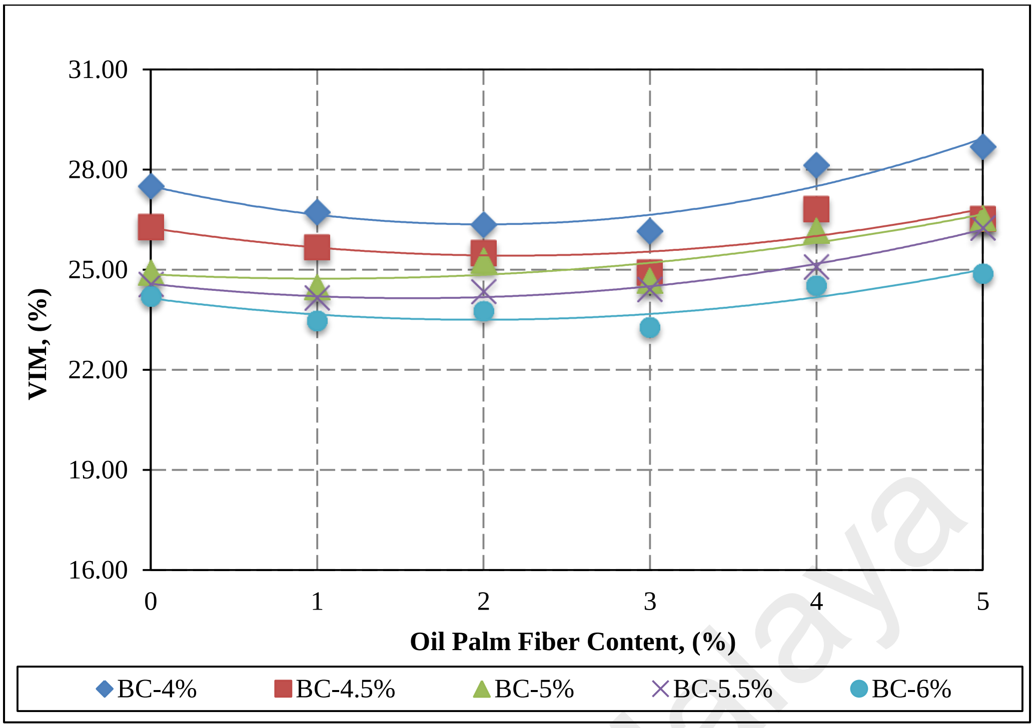


Figure 4.7 Air Voids in the Mix Value with the Different OPF Contents

The results showed that the increase of OPF contents in the mix was followed by a decrease of the air void until 3% OPF at which point it began to increase. It was also observed that the specimens made with 5% fiber content, with values of 28.70%, 26.53%, 26.55%, 26.27%, and 24.89% for binder 4%, 4.5%, 5%, 5.5%, and 6% respectively had higher air voids than the specimens containing 3% fiber content and control specimens (no fibers). This may be due to the larger surface area as higher OPF must be covered by the binder, thus leading to an increase in higher air voids.

4.5.1.2 Effect of Different Binder Content on Air Voids

The effect of different binder contents on air voids is summarised in Figure 4.8. In this figure, the air void contents are generally decreased as the binder content increases (Wu et al., 2006).

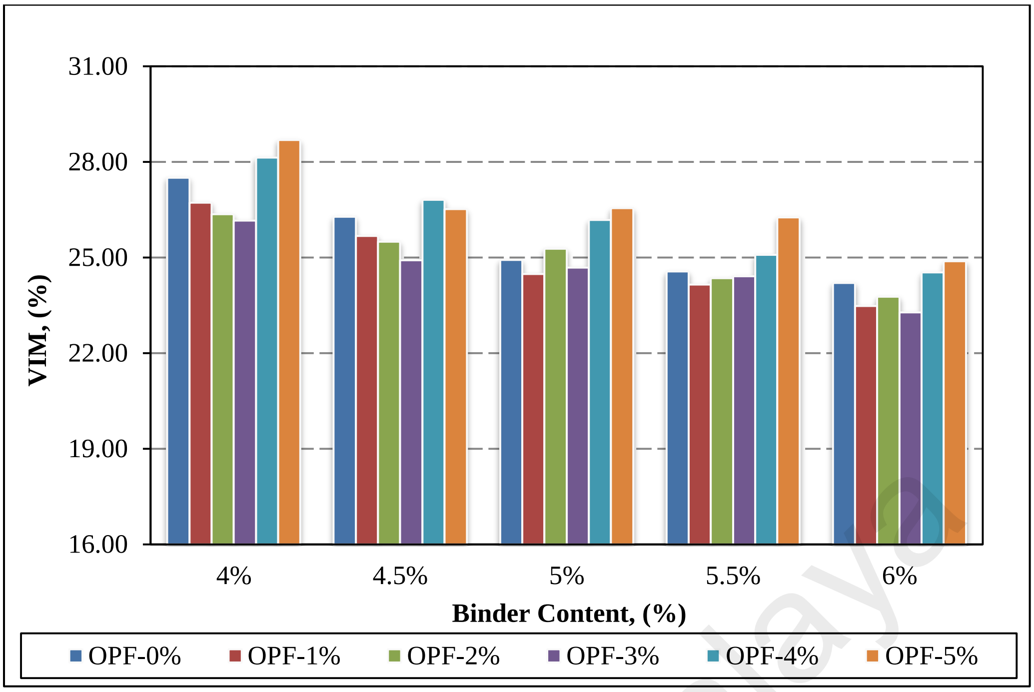


Figure 4.8 Air Voids in the Mix Value with the Different Binder Content

The air voids decrease when OPF content increases from 1% to 3%. However, at high OPF content (4% to 5%), the air voids increase. For any OPF content, any reduction of binder content will lead to an increase in the air voids. Thereby, there is a limit on how much fiber can be added to the asphalt mixes to prevent excessive voids, which may result in oxidative hardening and consequently reduce pavement durability. With regards to pavement design, porous asphalt is a non-structural layer which is related to mixture performance and durability. A number of factors contribute to this, mainly because of the high air void content in the final mix (Masondo, 2001).

For further verification, a two-factor ANOVA without replication was used to statistically analyse the air void test results. As such, the addition of OPF significantly affected air void value which had an F-value of 81.853 (F=81.853>F-critical=2.866) and P-value smaller than 0.05. The results of analysis of variance are given in Appendix B.

4.5.2 Air Abrasion Loss

The abrasion loss was determined by following the standard test method ASTM C131 - 96. The abrasion loss test is an important test for porous asphalt to estimate the resistance to particle loss by impact and abrasion. The maximum permissible abrasion loss should be no more than 18%. The values of air abrasion losses are given in Appendix A.

4.5.2.1 Air Abrasion Loss at 300 Revolutions of Different OPF Content on Air Cured Specimens

The air abrasion loss at 300 revolutions of the different OPF contents on air cured specimens are summarised in Figure 4.9. For any OPF content, the abrasion loss decreased as the binder content increased. This was due to the greater adhesion between the binder and aggregates because of the increased availability of binder to coat both the aggregates and fibers. The fluctuation in abrasion loss across the range of OPF content was found to be more pronounced as the binder content decreased. As the binder content increased, this fluctuation in abrasion loss across the range of OPF content diminished (Figure 4.9). As such, there was a critical link between the amount of OPF used in porous asphalt and the binder content in order to ensure that the durability of the porous asphalt pavement was not compromised.

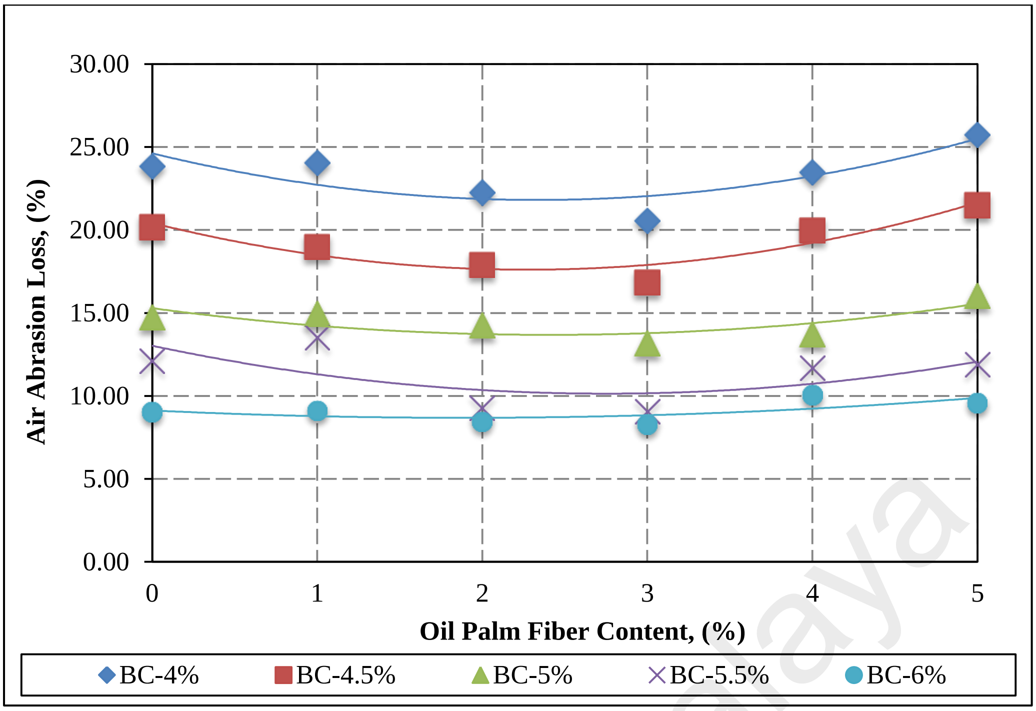


Figure 4.9 Abrasion Loss at 300 Revolutions Value with the Different OPF Contents (Air Cured Specimens)

4.5.2.2 Air Abrasion Loss at 300 Revolutions of Different Binder Content on Air Cured specimens

The effects of different binder content on air cured specimens is summarised in Figure 4.10. The results show that the abrasion loss decreased with an increase in binder content. The specimen prepared with 4% binder content had the lower resistance to abrasion in porous asphalt. Moreover, specimens made with 5%, 5.5% and 6% binder content showed the best resistance to abrasion in porous asphalt. This clearly shows that the increasing amount of binder is sufficient to coat aggregates and fibers. With a high amount of binder content, the mixes can provide better performance on durability because of greater binder film thickness (Chiu, 2008). The use OPF in porous asphalt requires a little more binder in order to prevent abrasion loss.

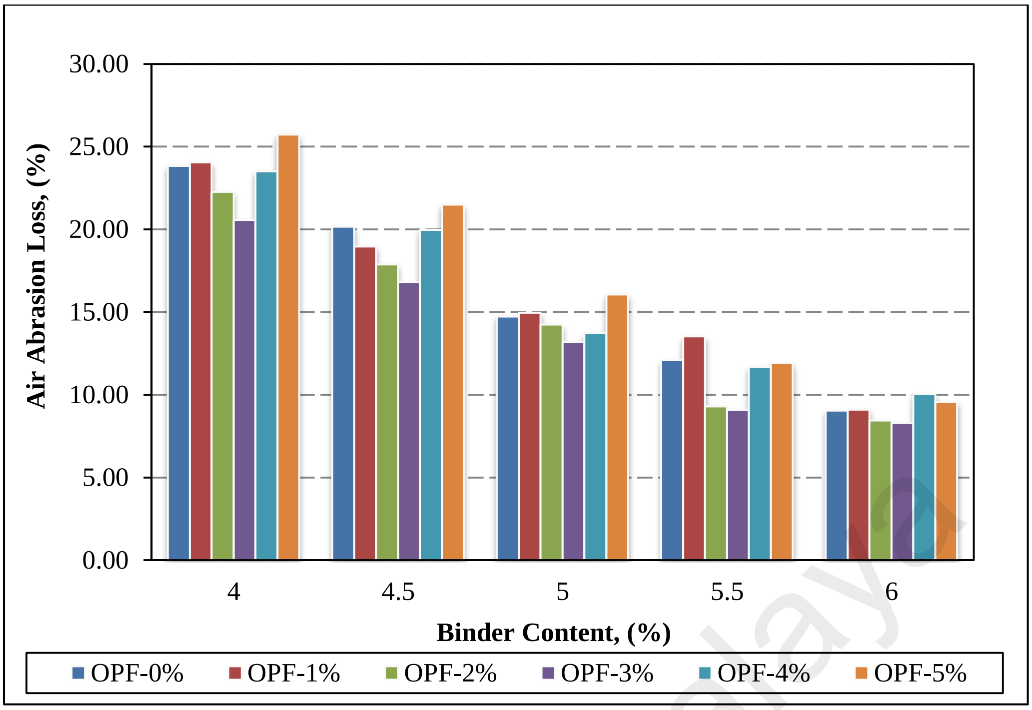


Figure 4.10 Abrasion Loss at 300 Revolutions Value with the Different Binder Contents (Air Cured Specimens)

From the analysis, it was found that the different OPF contents influenced the performance of porous asphalt. The F value for different OPF contents was 290.833 which is higher than F-critical of 2.866. Its P-value was 2.06 x 10^{-17} which is smaller than 0.05. A summary and analysis of variance results is provided in Appendix B.

4.5.2.3 Air Abrasion Loss at Every Hundred Revolutions of Different OPF Content on Air Cured Specimens

The effects of the different OPF contents on air cured specimens at every hundred revolutions are summarised in Figure 4.11. The air abrasion loss generally increased followed by an increase in the number of revolutions (Figure 4.11). The available results show that the air abrasion loss of specimens with some OPF content had inconsistent trend values, especially at 100 revolutions to 200 revolutions. However, the specimens made with 2% and 3% OPF content showed the lowest air abrasion value.

The results also found that all of the mixes with 0 to 5% OPF content had better performance at 5, 5.5 and 6% binder content which was in accordance with maximum air abrasion loss. In addition, it seemed that there was a limit to added OPF in the porous asphalt to ensure no large gaps in the mix.

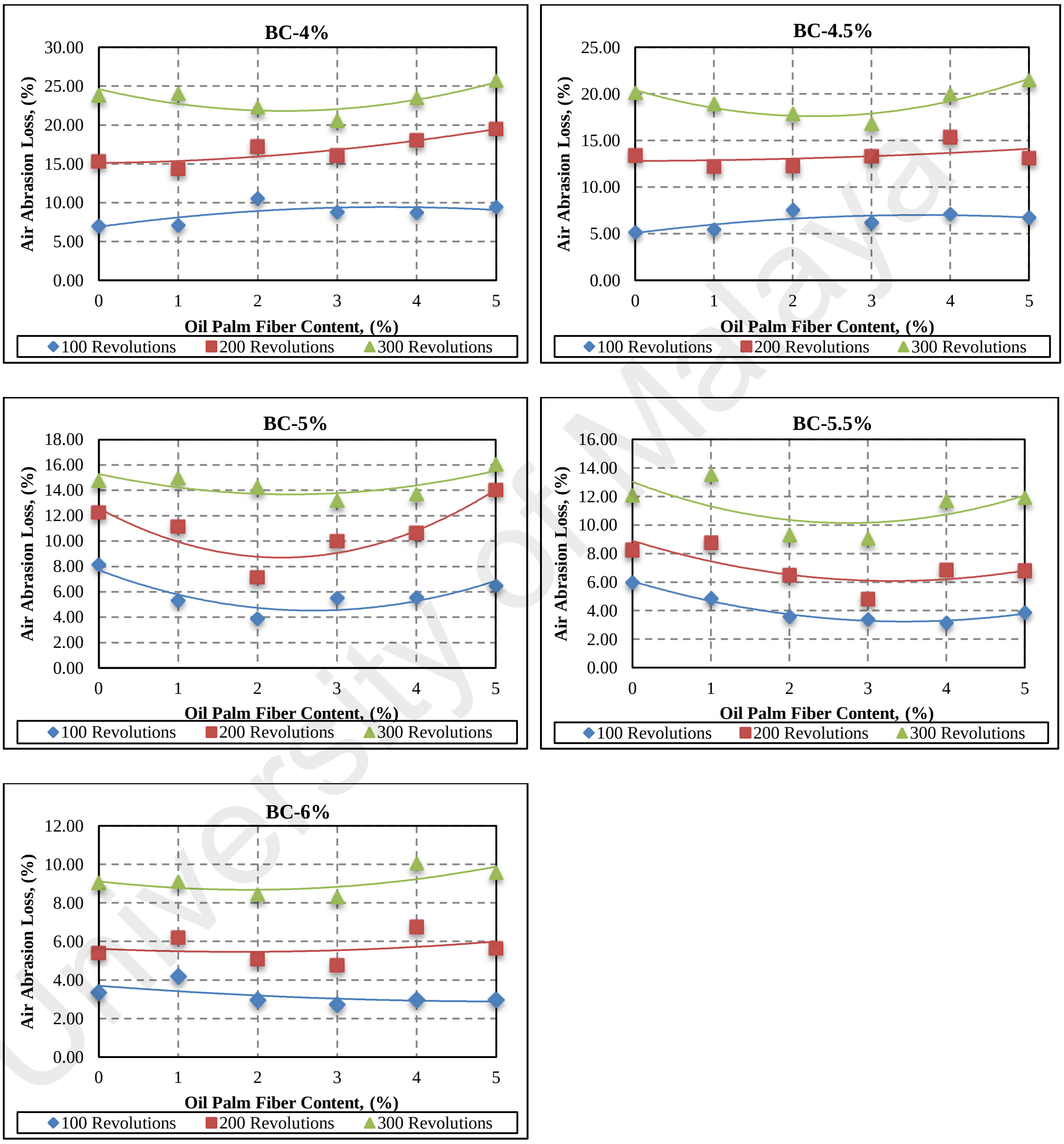


Figure 4.11 Abrasion Loss at Every Hundred Revolutions Value with the Different OPF Contents (Air Cured Specimens).

4.5.2.4 Air Abrasion Loss at Every Hundred Revolutions of Different Binder Content on Air Cured Specimens

The effects of the different binder contents on air cured specimens at every hundred revolutions are shown in Figure 4.12. The revolutions of air abrasion loss test varied from 100 to 300.

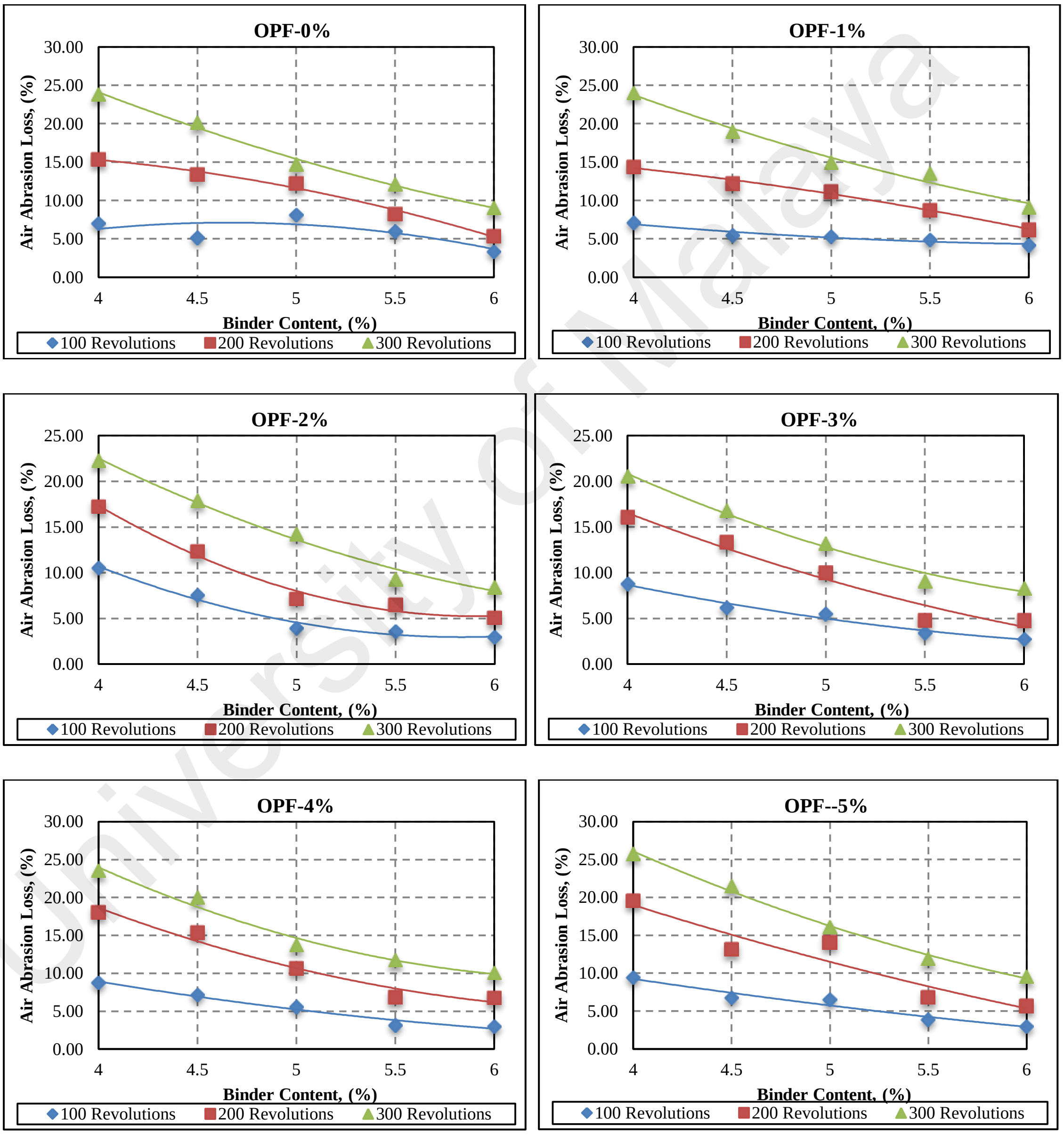


Figure 4.12 Abrasion Loss at Every Hundred Revolutions with the Different Binder Contents (Air Cured Specimens)

From the results, it is clearly evident that the increasing amount of binder decreased the loss of abrasion value at each specimen and revolution. In addition, the value of air abrasion loss was slightly decreased when specimens were obtained by 6% binder content. In contrast, specimens made with 4% binder content had higher air abrasion loss values. This was the case for all specimens with different OPF content.

Figure 4.11, Figure 4.12, and Table 4.5 present the numbers of revolutions of the specimens which exceed the maximum limits of air abrasion loss. As previously mentioned, the maximum permissible of abrasion loss should be no more than 18%.

Table 4.5: Number of Revolutions of the Specimens which Exceed the Maximum Limits of Air Abrasion Loss

OPF Contents	**Binder Contents**				
	4%	**4.5%**	**5%**	**5.5%**	**6%**
0%	300	300	-	-	-
1%	300	300	-	-	-
2%	300	-	-	-	-
3%	300	-	-	-	-
4%	200	300	-	-	-
5%	200	300	-	-	-

It was observed that the value of abrasion loss decreased as the binder content was increased (Table 4.5). At 4.5% binder content, the specimens made with 2% and 3% OPF content started to satisfy the recommended limit value for each revolution and binder content of 4.5%, 5%, 5.5%, and 6%. It seemed that the air abrasion loss decreased when the amount of binder was adequate to coat aggregates and oil palm fiber.

4.5.3 Water Abrasion Loss

The standard tests on water cured specimens were conducted according to ASTM C131-96. The Cantabro test on water cured specimens was used to measure the resistance of mixes to stripping and water damage. The maximum permissible water abrasion loss should be no more than 40% (Skvarka, 1996). The values of water abrasion losses are tabulated in Appendix A.

4.5.3.1 Water Abrasion Loss at 300 Revolutions of Different OPF Content on Water Cured Specimens

The performances of the Cantabro test at 300 revolutions on water cured specimens are shown in Figure 4.13. As a result, the abrasion value showed behaviour identical to the Cantabro test on air cured specimens whilst the abrasion loss decreased as the binder content increased (Figure 4.13).

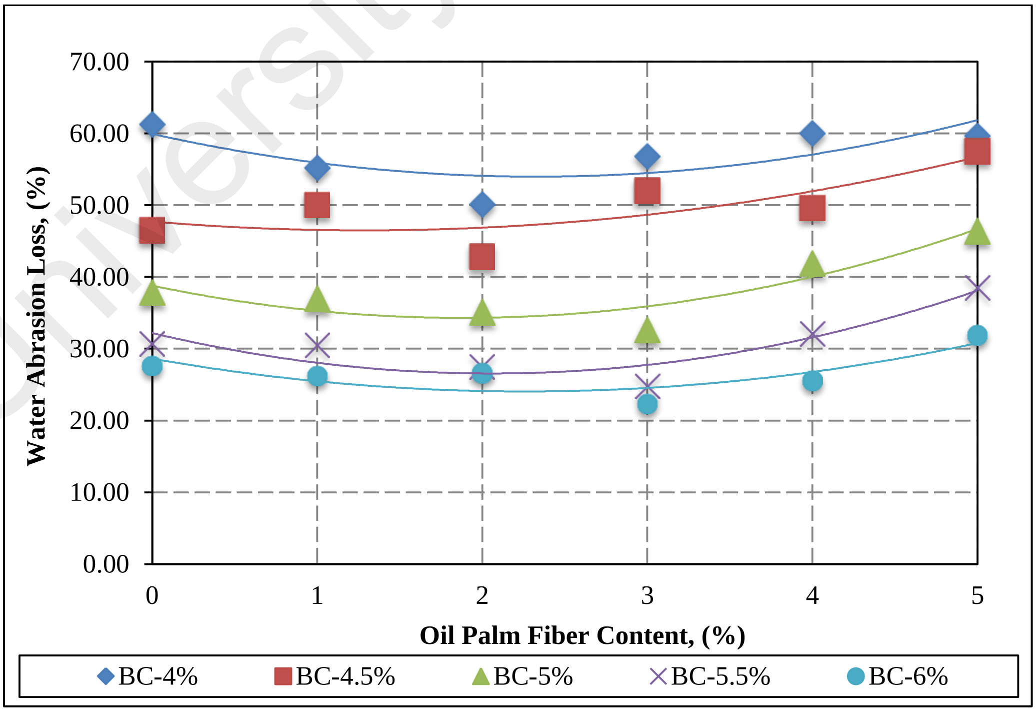


Figure 4.13 Abrasion Loss at 300 Revolutions Value with the Different OPF Contents (Water Cured Specimens)

The specimen made with 3% OPF content exhibited better resistance to water abrasion loss for all mixes with values of 56.86%, 52.01%, 32.70%, 24.82%, and 22.31% for binder content 4%, 4.5%, 5%, 5.5%, and 6% respectively. This applied to all contents with the exception of specimens made with 4% and 4.5% binder content. This was because of OPF in the mix act to fill the air voids of specimens. The miniscule amount of OPF content created a better aggregate interlocking in the mix and thus increased the resistance. However, with an increase in the amount of OPF (4% and 5%) the loss abrasion value was increased.

4.5.3.2 Water Abrasion Loss at 300 Revolutions of Different Binder Content on Water Cured specimens

Figure 4.14 illustrates the water abrasion loss with different binder contents. As a result, the abrasion loss decreased as the binder content increased.

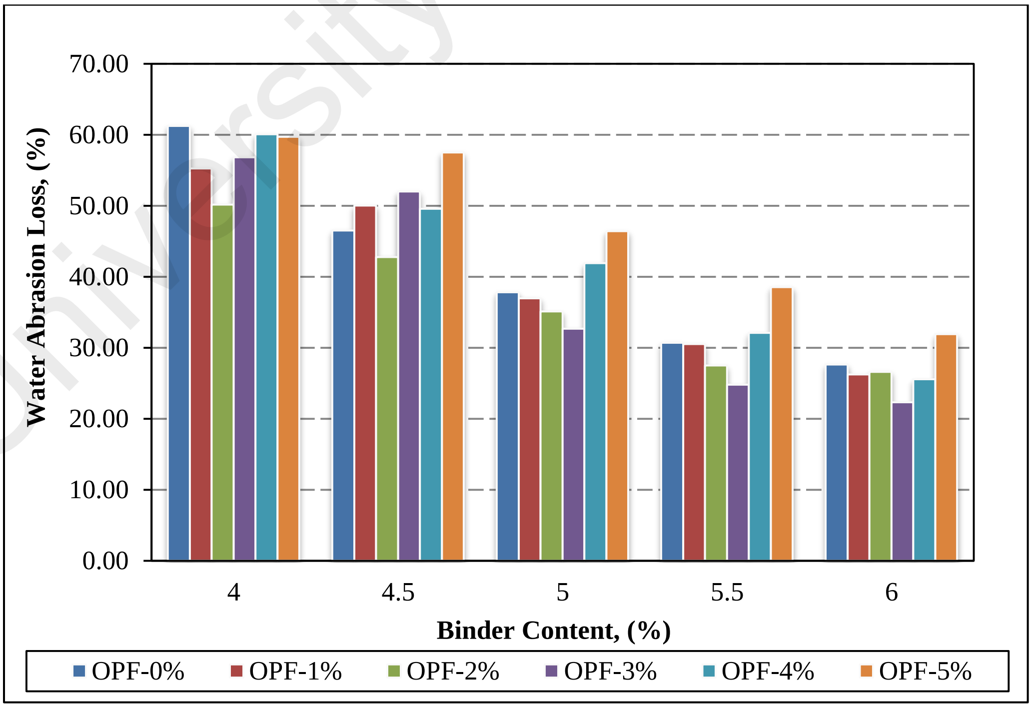


Figure 4.14 Abrasion Loss at 300 Revolutions Value with the Different Binder Contents (Water Cured Specimens).

The results also revealed that in general, only specimens prepared with 5%, 5.5% and 6% binder content satisfy the recommended limit value. The content weight loss for water cured specimens was greater than that of air cured specimens. This may be due to water influence, the abrasion resistance and also the binder-aggregate bonding in the porous asphalt. This also indicated that water is a serious factor in affecting the stripping process (Katman et al., 2005).

A two-factor ANOVA test without replication was carried out for Cantabro test results on water cured specimens. It showed a significant effect from different OPF content. F-value was 125.997 (F=125.997>F-critical=2.866) and P-value was smaller than 0.05. The results of analysis of variance are given in Appendix B.

4.5.3.3 Water Abrasion Loss at Every Hundred Revolutions of Different OPF Content on Water Cured Specimens

The effects of the different OPF contents on water cured specimens are summarised in Figure 4.15. The available results displayed the same trend as the revolution results of air abrasion loss with different OPF content. However, the abrasion loos value on water cured specimens was higher than the air cured specimens. The general trend from Figure 4.15 shows that the addition of OPF decreased loss abrasion values when compared to specimens with no fiber (OPF-0%), but the mix with more fiber content gave the abrasion loss of specimen’s increases back.

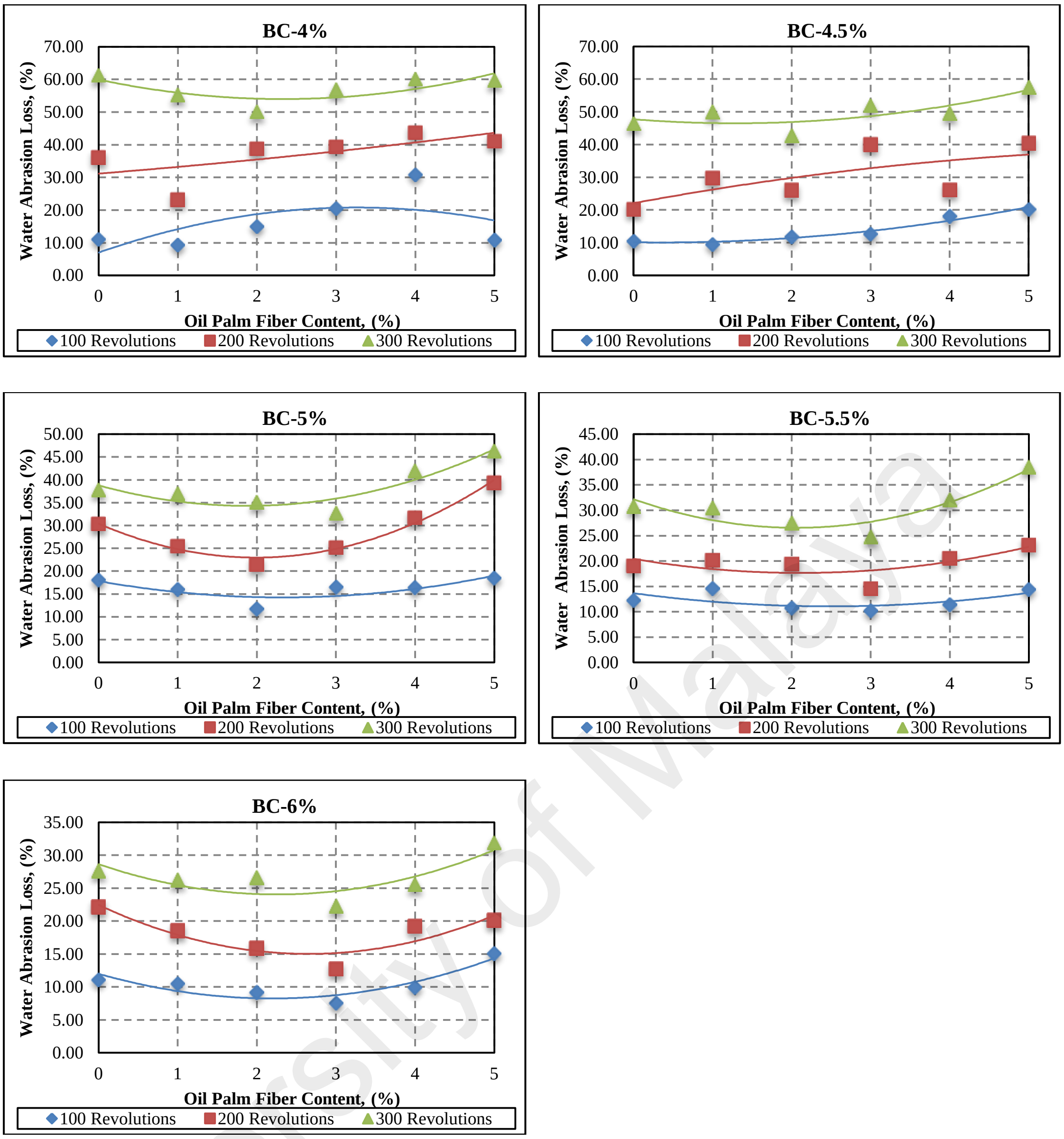


Figure 4.15 Abrasion Loss at Every Hundred Revolutions Value with the Different OPF Contents (Water Cured Specimens).

4.5.3.4 Water Abrasion Loss at Every Hundred Revolutions of Different Binder Content on Water Cured Specimens

The results obtained for water abrasion loss for porous asphalt with the different binder content and different revolutions (Figure 4.16).

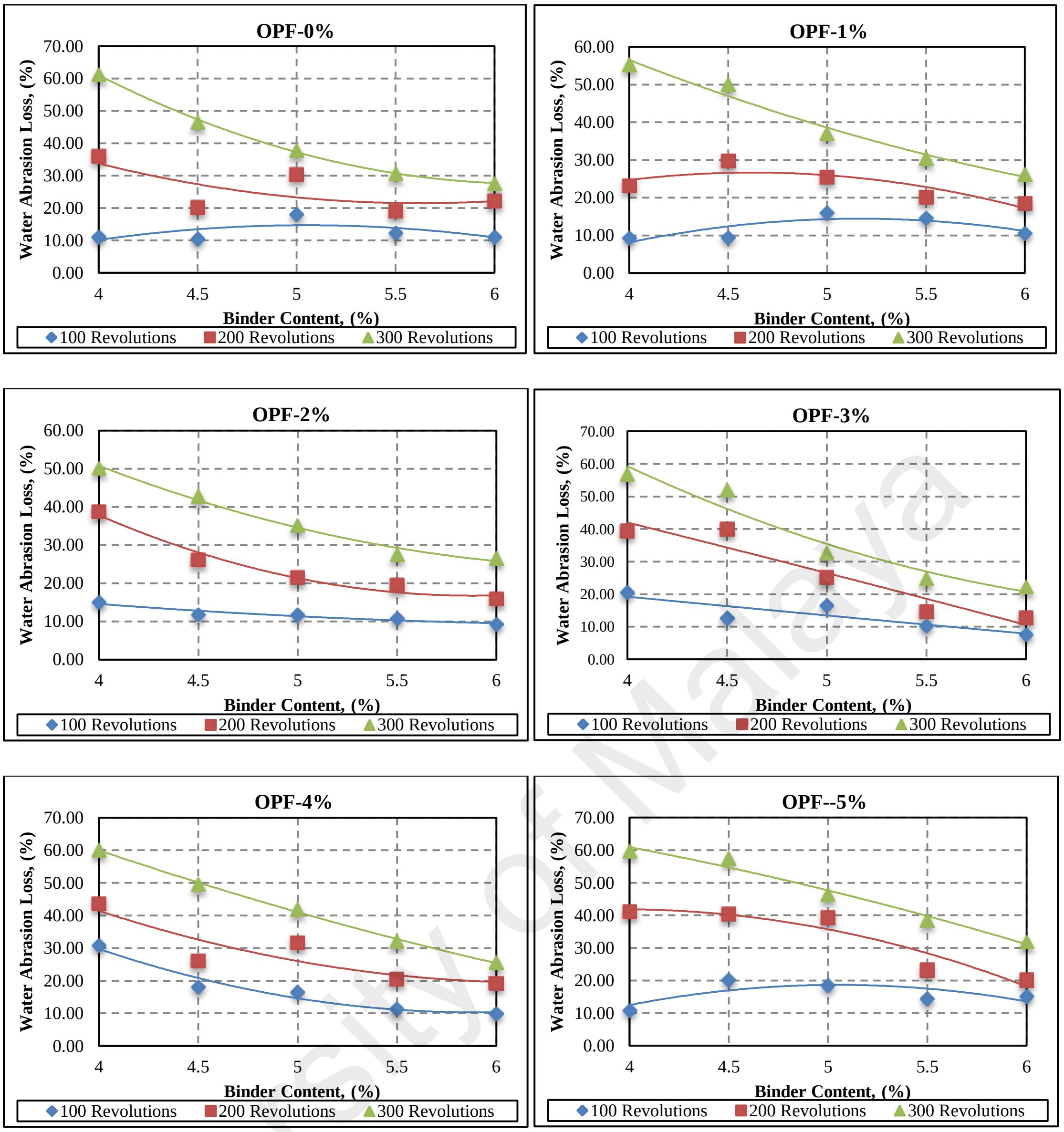


Figure 4.16 Abrasion Loss at Every Hundred Revolutions Value with the Different Binder Contents (Water Cured Specimens)

The numbers of revolutions in the mix are clearly followed by the higher abrasion loss. The water abrasion loss test results can be enhanced depending on binder content and fiber content. Figure 4.16 also shows the plot of water abrasion versus binder content. It is apparent that all the specimens resulted in decreasing of abrasion loss. The decrease was due to the improvement of amount bitumen in the resulting mix. In this study, it was noted that mixes made with 5% binder content began to exhibit the optimum binder at all revolutions except for the specimens with 4% and 4.5% OPF content.

The maximum permissible abrasion loss is considered as 40%. From Figure 4.15 and Figure 4.16, the numbers of revolutions of the specimens which exceed the maximum limits of water abrasion loss are tabulated in Table 4.6.

Table 4.6: Number of Revolutions of the Specimens which Exceed the Maximum Limits of Water Abrasion Loss

OPF Contents	**Binder Contents**				
	4%	**4.5%**	**5%**	**5.5%**	**6%**
0%	300	300	-	-	-
1%	300	300	-	-	-
2%	300	300	-	-	-
3%	300	300	-	-	-
4%	300	300	300	-	-
5%	300	300	300	-	-

From the results obtained in Table 4.6, it can be seen that the resistance to abrasion is lowest at 4% and 5% binder content. This indicated that the low binder content gave the lowest cohesion between the aggregates. In contrast, the higher resistance to abrasion in the porous asphalts was found in specimens with 5%, 5.5% and 6% binder content. Base on different OPF contents, it can be concluded that the water abrasion loss increased as the OPF content achieved a higher content of OPF (4% and 5%).

4.5.4 Comparative Results on Performance Porous Asphalt between Cantabro Test on Air Cured Specimens and Cantabro Test Water Cured specimens

The results of the Cantabro test on air cured specimens and the Cantabro test on water cured specimens are summarised in Figures 4.17 and 4.18.

4.5.4.1 Effect of Different OPF Content on Abrasion Loss

Figure 4.17 shows the striking difference on abrasion loss value. It was obvious that the high amount of binder improved resistance in the mix. The contents of weight loss in both air cured specimens and water cured specimens were decreased as the amount of binder decreased.

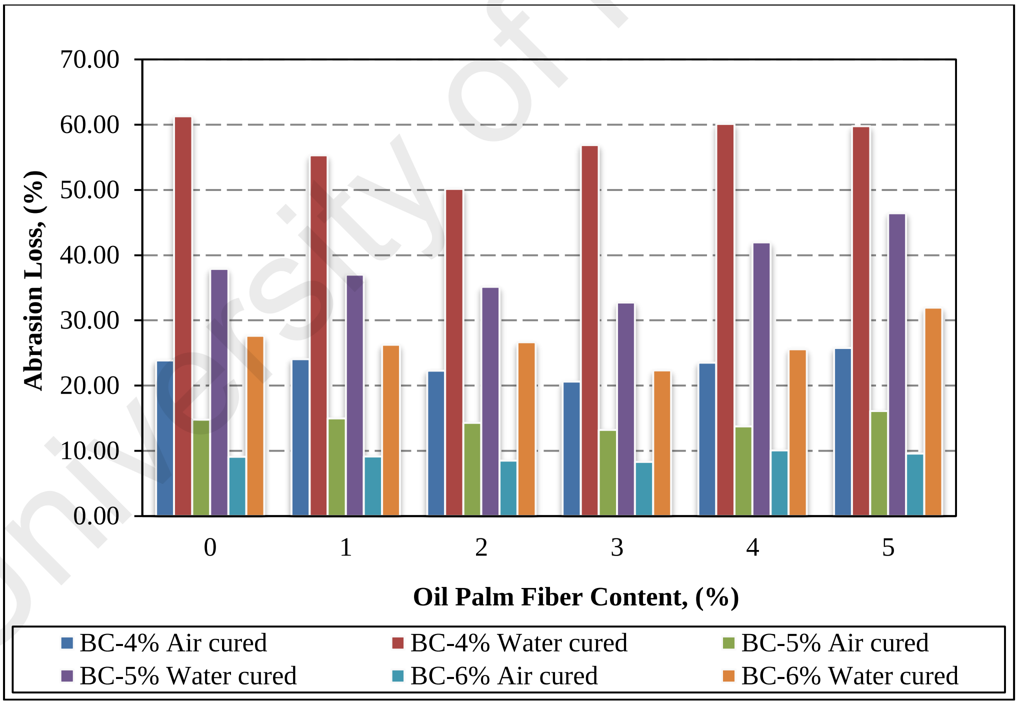


Figure 4.17 Effect of Different OPF Contents between Air Cured and Water Cured on Abrasion Loss.

4.5.4.2 Effect of Different Binder Content on Abrasion Loss

The effect of different binder content between air cured and water cured on abrasion loss are shown in Figure 4.18. The content of weight loss water cured specimens was greater than Cantabro on air cured specimens. As previously mentioned, this indicated that the water influenced the abrasion resistance. In fact, water would affect the aggregate bonding and increase the air void content in the porous asphalt.

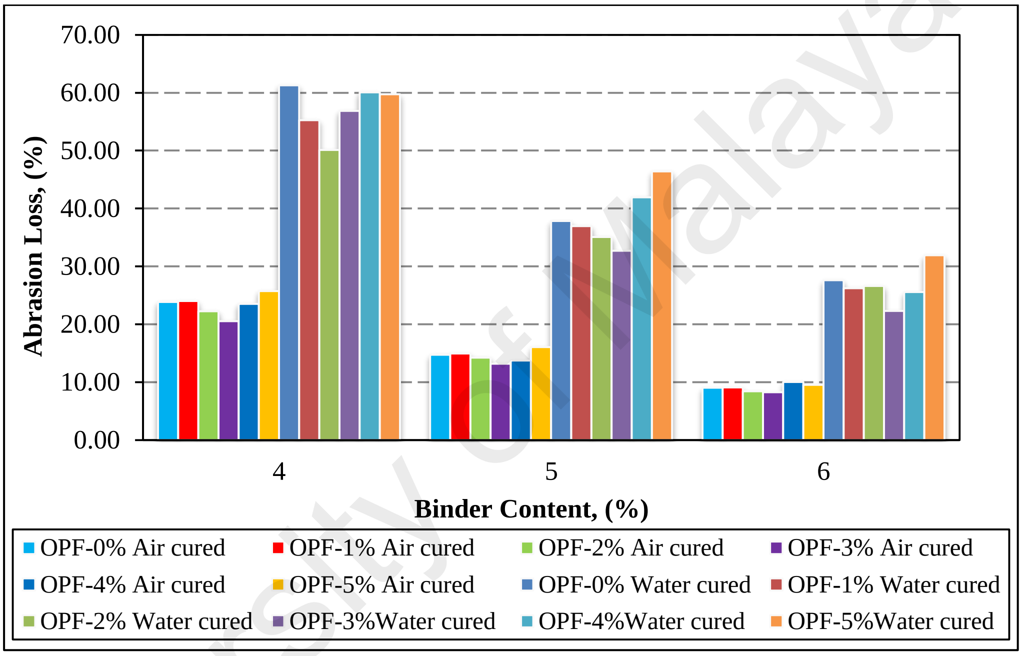


Figure 4.18 Effect of Different Binder Content between Air Cured and Water Cured on Abrasion Loss.

4.5.4.3 Abrasion Loss (Air Cured and Water Cured) and Air Voids Relationship

Results of abrasion loss test (air cured and water cured) in the air voids value at 0% and 3% OPF contents are illustrated in Figure 4.19. The results clearly show that the abrasion loss value for both conditions (air cured specimens and water cured specimens) increased as the value of air void increased (Figure 4.19). The results also show that abrasion loss and air void decreased when 3% of OPF was added. Besides this, the value of loss abrasion and air void for air cured specimens was lower than the water cured specimens. It seemed that the contact points among the aggregate and wetted aggregate surface were reduced because of increases in air void, hence succumbing to the ravelling process (Katman et al., 2005).

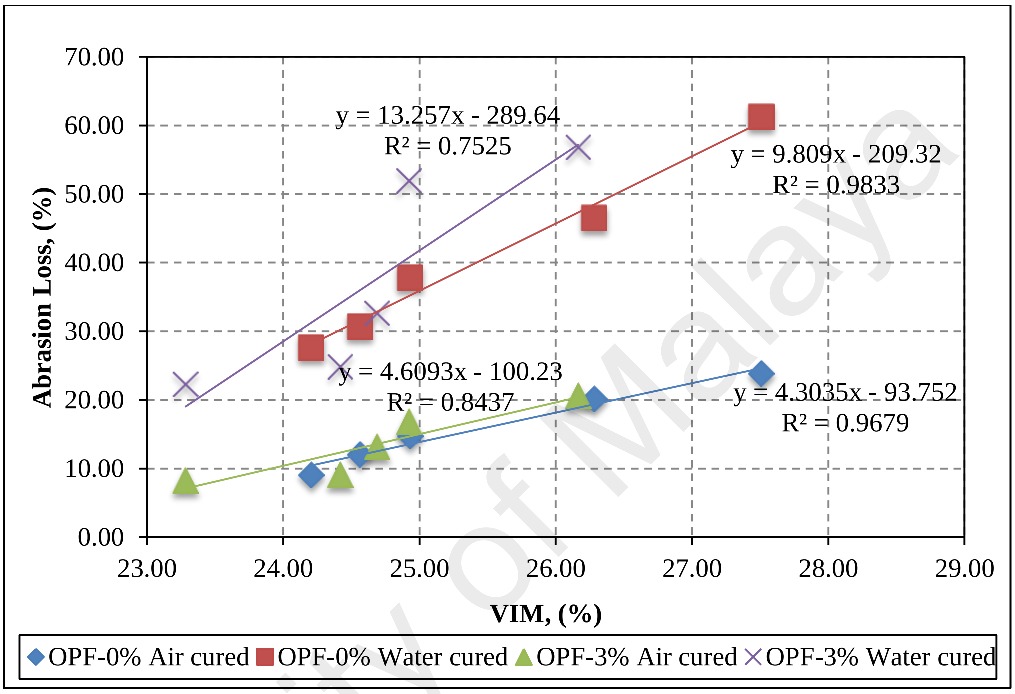


Figure 4.19 Abrasion Loss and Air Voids Relationship

4.5.5 Binder Drain-Down Test

The binder drainage test is commonly used to determine the number of acceptable binder levels in asphalt mixture. In this section, the performance of the control specimens (no fiber) and the oil palm fiber are evaluated. The maximum allowable binder drain down is 0.3% by weight of the total mix (REAM, 2008). The binder drain-down values are tabulated in Appendix A.

4.5.5.1 Effect of Different OPF Content on the Binder Drain-Down

The effects of different contents on the binder drain down are summarised in Figure 4.20.

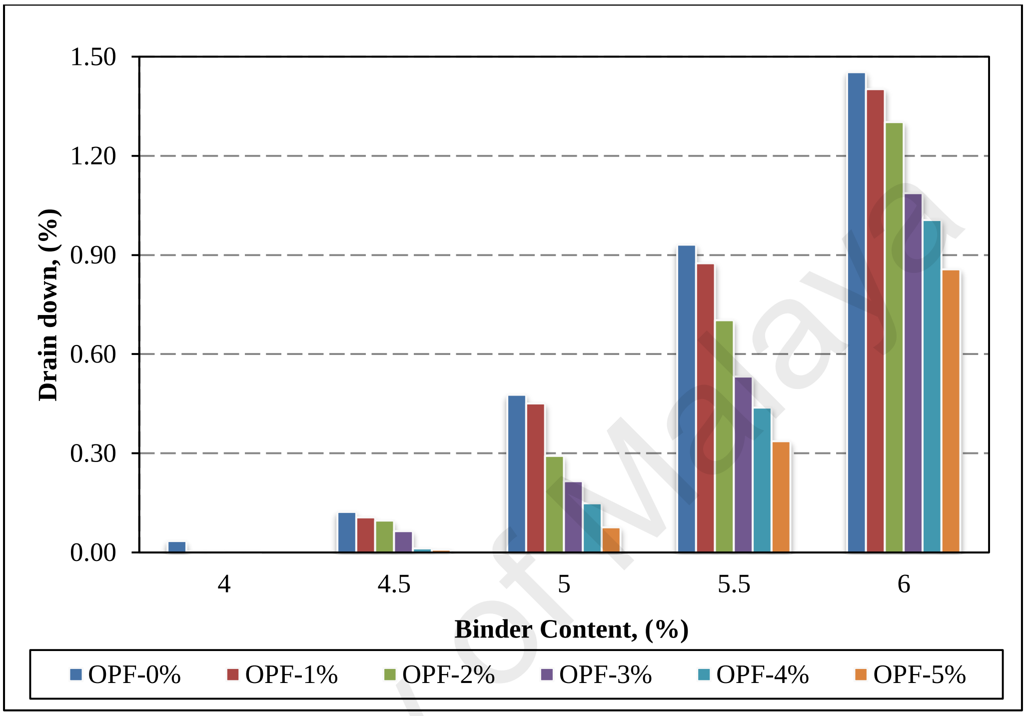


Figure 4.20 Binder Drain-Down Value with the Different Binder Contents

As Figure 4.20 shows, the binder drain-down decreased after adding fiber to the mix. It was found that the drain-down of the mix with 2% to 5% OPF content performed better at 4%, 4.5% and 5% binder content. At 4% binder content, the results showed no drainage in all mixes. Adding fiber means that more asphalt must be wrapped onto the surface due to its relatively higher specific surface area and absorption of lighter components of asphalts (Sertass & Samanos, 1996). However, it was found that the binder drainage value of control specimens (no fiber) and 1% fiber content had little effect on the mix. This result indicated that unit weight of 1% fiber had no significant effect on the surface area and the absorption.

4.5.5.2 Effect of Different Binder Content on the Binder Drain-Down

The results for different binder contents on the binder drain-down are shown in Figure 4.21. The results showed that the mixes containing 5% fiber always exhibited the lowest amount of drain down, with values of 0.00%, 0.01%, 0.08%, 0.34%, and 0.86% for binder content 4%, 4.5%, 5%, 5.5% and 6% respectively. As a result, the binder drain-down value of 0% and 1% fiber content were higher than the specimens of 2%, 3%, 4%, and 5% fiber contents.

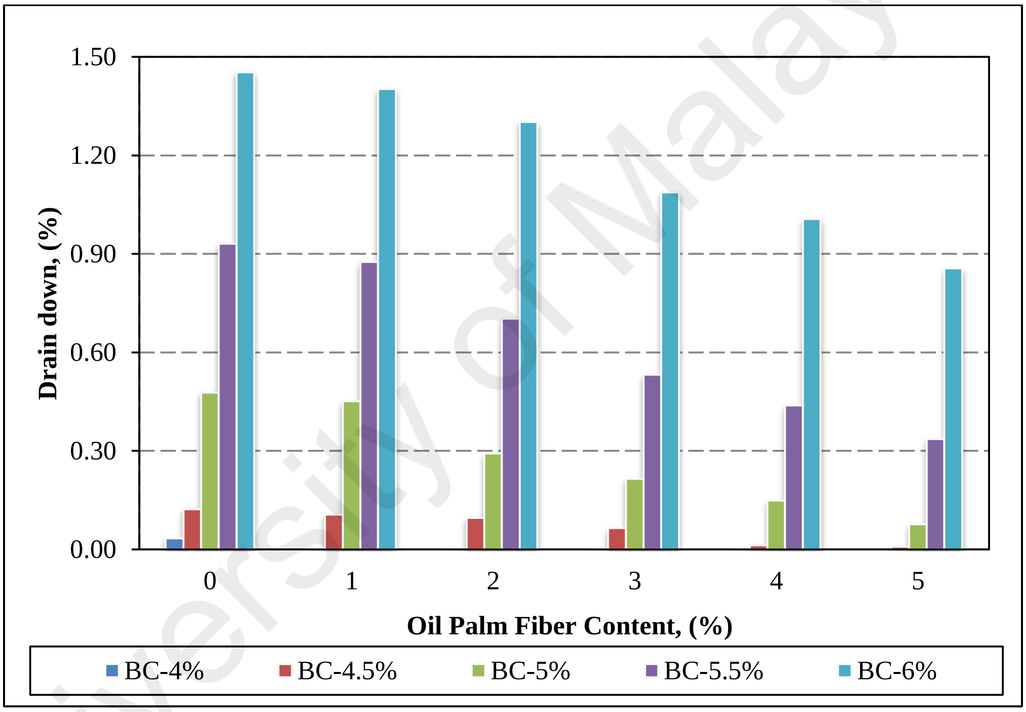


Figure 4.21 Binder Drain-Down Value with the Different OPF Contents

A two-factor ANOVA without replication was carried out in order to determine whether there was a significant effect from the addition of OPF on porous asphalt. For the binder drain down test, the analysis gave an F-value of 121.163 (F=121.163>F-critical=2.866) and P-value smaller than 0.05. The results of analysis of variance are given in Appendix B.

4.5.6 Determination of Optimum Binder Content

As previously mentioned, the optimum binder content (OBC) in porous asphalt design was selected and determined based on the results of air void, abrasion loss, and binder drain down. The results of the OBC are summarised in Table 4.7.

Table 4.7: Optimum Binder Content Results

Tests	**Requirement (REAM)**	**The Binder Contents which Met the Requirement, (%)**					
		OPF Contents					
		0%	**1%**	**2%**	**3%**	**4%**	**5%**
Binder Drain-Down	Max 0.3	4 and 4.5	4 and 4.5	4, 4.5, and 5	4, 4.5, and 5	4, 4.5, and 5	4, 4.5, and 5
Air Void	18% – 25%	4, 4.5, and 5	4, 4.5, and 5	4 and 4.5	4, 4.5, and 5	4	4
Cantabro	0% - 15%	5, 5.5, and 6	5, 5.5, and 6	5, 5.5, and 6	5, 5.5, and 6	5, 5.5, and 6	5.5, and 6
Binder Content Studied (%)		5	5	5	5	5	5

The available results show that the optimum binder content for each of the tests parameters is varied. The amount of OPF used significantly affected the value of optimum binder content in porous asphalt. However, the optimum binder results have met the requirement to ensure a reliable value for permeability testing. In this study, the optimum binder content was determined and selected as 5% for the oil palm fiber contents of 0%, 1%, 2%, 3%, 4% and 5%.

4.5.7 Falling Head Permeability

The test was determined using a falling head permeameter to measure the rate of flow of water through the specimens. The measurement of permeability or drainage capacity will more accurately quantify the performance of porous asphalt when compared to the air voids content (Guwe et al., 2000). The values of permeability coefficient are given in Appendix A.

4.5.7.1 Effect of Different OPF Content on Permeability

The available results show the permeability coefficient in the mixes with different fiber contents (Figure 4.22).

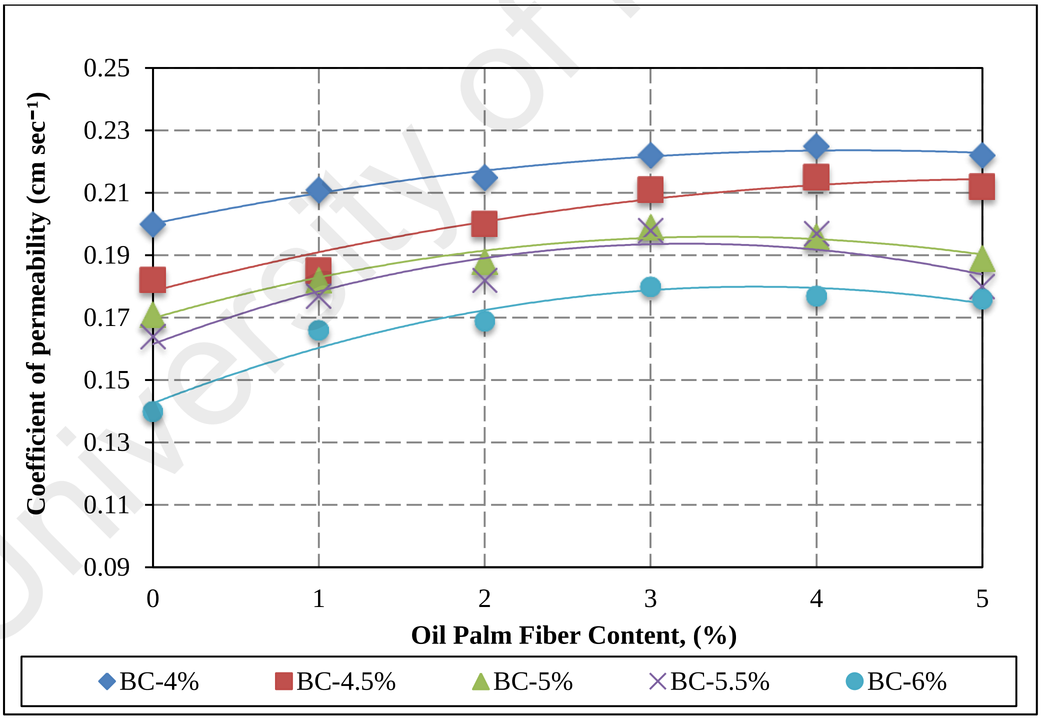


Figure 4.22 Permeability Value with the Different OPF Contents

The results indicated that for any particular OPF content the coefficient of permeability will decrease as the binder content increases. The increase of OPF amount followed the highest permeability coefficient until 3% (0.222, 0.211, 0.199, 0.198, 0.180 cm sec^{-1} for binder content 4%, 4.5%, 5%, 5.5%, and 6% respectively) and 4% (0.225, 0.215, 0.196, 0.197, 0.177 cm sec^{-1} for binder content 4%, 4.5%, 5%, 5.5%, and 6% respectively) OPF contents. The mix with 0% (no fiber) and 1% OPF showed the lowest permeability coefficient. It seemed that OPF may increase the air voids in the mix for certain amounts.

4.5.7.2 Effect of Different Binder Content on Permeability

Figure 4.23 illustrates the results of permeability on porous asphalt for different binder contents.

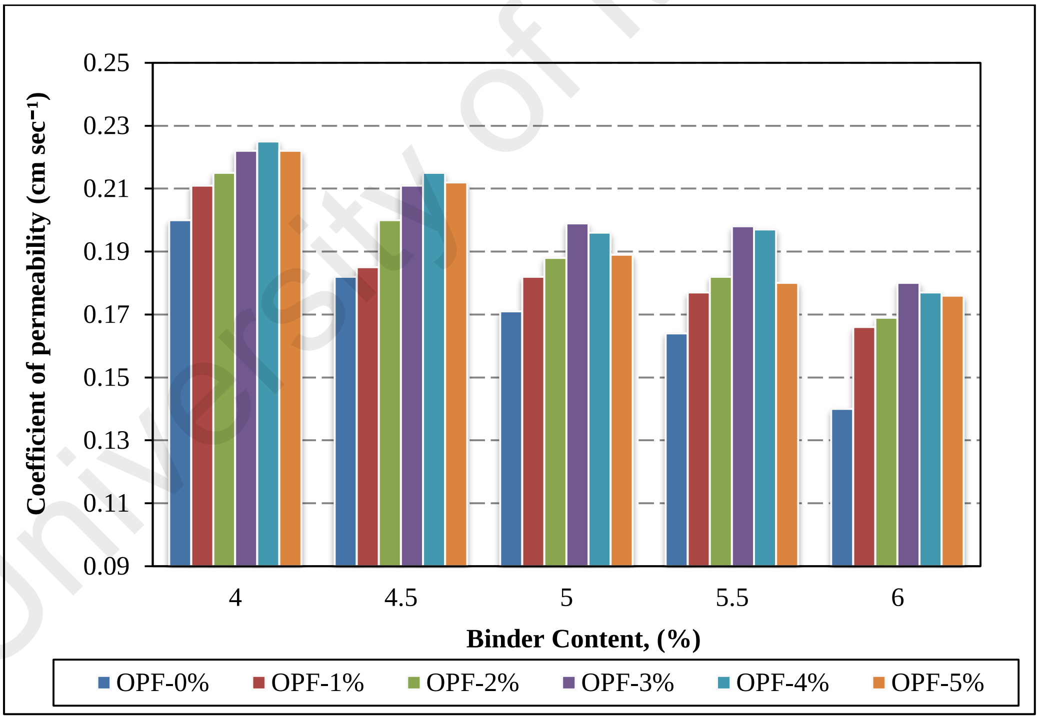


Figure 4.23 Permeability Value with the Different Binder Contents

The results clearly show that the coefficient of permeability decreased as the binder content increased. As a result specimens with no fiber (0%-OPF) at 4%, 4.5%, 5%, 5.5% and 6% recorded a coefficient of permeability of 0.200, 0.182, 0.171, 0.164, 0.140 cm sec^{-1}, respectively. Besides this, results also showed that the permeability coefficient at 6% binder content was the lowest, with values of 0.140, 0.166, 0.169, 0.180, 0.177 and 0.176 cm sec^{-1} for OPF content 0%, 1%, 2%, 3%, 4% and 5% respectively. It can be inferred that the higher amount of binder content was clogging the air voids, hence slowing the flow of water through the specimens.

A two-factor analysis of variance (ANOVA) without replication was used as the statistical tool for permeability test. F-value for OPF different contents was 97.00 which is higher than F-critical of 2.866 whilst its P-value was 0.0005 which is smaller than 0.05. As such, the addition of OPF significantly affected the properties and characteristic of the porous asphalt mixes. A summary of analysis of variance results are given in Appendix B.

4.5.7.3 Permeability and Air Voids Relationship

Figure 4.24 shows the effect of permeability coefficient in the air voids value at 0% (no fiber), 3%, and 5% OPF contents. The results show that addition of OPF contents to the porous mixes significantly affected the value of permeability and air voids. As seen in Figure 4.24, the permeability coefficient was influenced by the value of air voids in the mixes which showed that the value of permeability coefficient increased as the air voids increased.

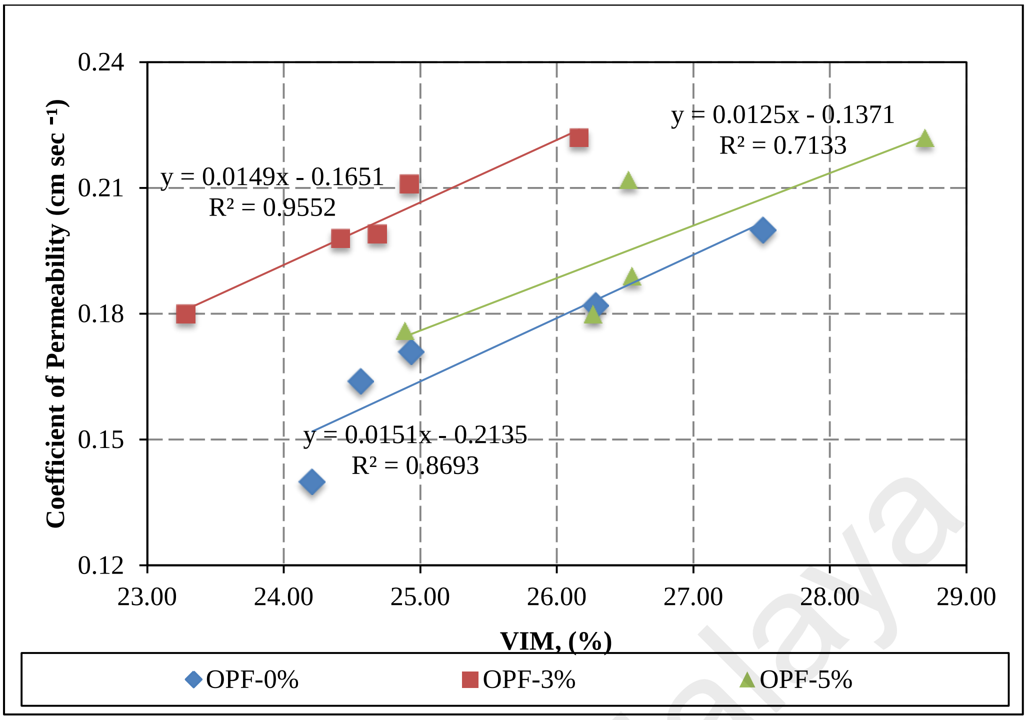


Figure 4.24 Permeability Coefficients and Air Voids Relationship

4.5.7.4 Permeability at Optimum Binder Content

The results of permeability test at optimum binder contents are illustrated in Figure 4.25. The results indicate that at the optimum binder content (5%) there was a maximum value for the coefficient of permeability as the OPF content increased from 0% to 5%. It appeared that with 3% OPF, the coefficient of permeability will be at maximum. In fact, the performance and regression analysis of the laboratory tests such as air void, Cantabro and binder drainage showed that 3% of fiber content was the best fiber content in porous asphalt. Based on limit requirements and performance, the appropriated contents of OPF-modified in this study are presented in Table 4.8.

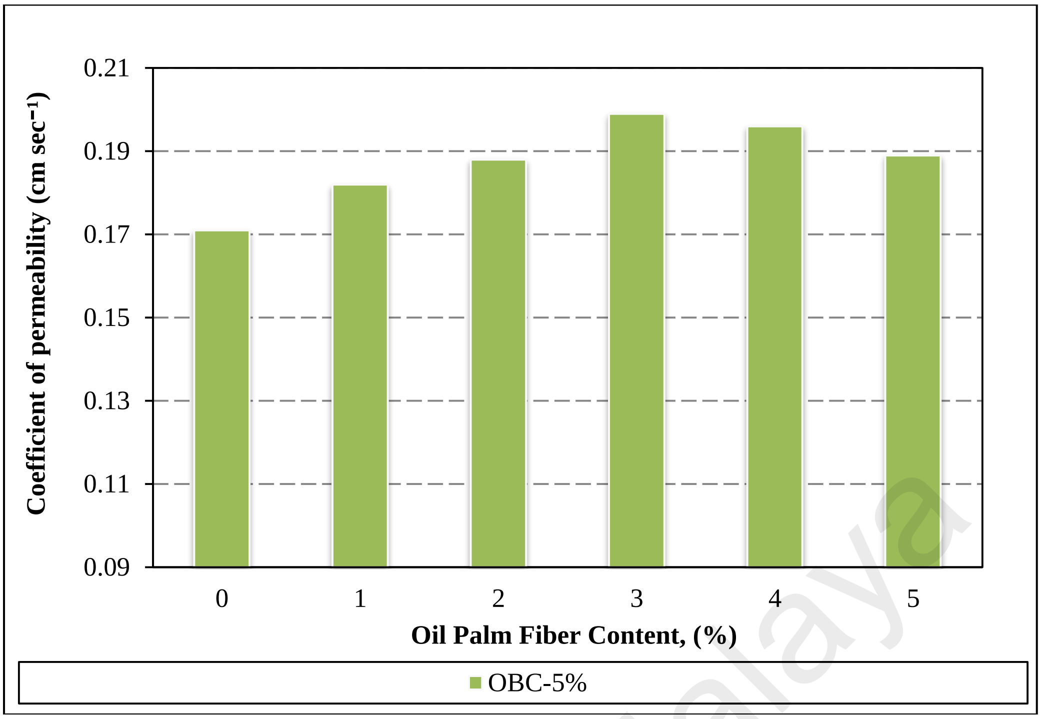


Figure 4.25 Permeability Value with the Different OPF Content at Optimum Binder Content

Table 4.8: Optimum OPF Content Results for each Test.

Binder Contents	**Tests**				
	Air Voids	**Air Abrasion**	**Water Abrasion**	**Binder Drain-Down**	**Permeability**
4%	-	-	-	OPF-0%	OPF-4%
4.5%	OPF-3%	-	-	OPF-0%	OPF-4%
5%	OPF-1%	OPF-3%	OPF-3%	OPF-2%	OPF-3%
5.5%	OPF-1%	OPF-3%	OPF-3%	-	OPF-3%
6%	OPF-3%	OPF-3%	OPF-3%	-	OPF-3%

4.5.8 Resilient Modulus Test

Resilient modulus is a special parameter with which to measure the performance of asphalt pavement by analysing response of the pavement to traffic loading. The test procedure was referred to in ASTM D4123 - 82. The indirect tensile test with repeated loading at 25°C was used to determine the stiffness modulus of porous asphalt. The values of resilient modulus are given in Appendix A.

4.5.8.1 Effect of Different OPF Content on Resilient Modulus

The results for different contents of OPF on the resilient modulus are shown in Figure 4.26. For all particular binder contents, there appeared to be a maximum resilient modulus value as the OPF content increased from 0 to 5%. As expected, for any value of OPF content the resilient modulus value decreased as the binder content increased. This implied that the higher amount of binder at any particular OPF content would result in a more pronounced viscous component of the binder when compared to the elastic component, hence reducing the resilient modulus value.

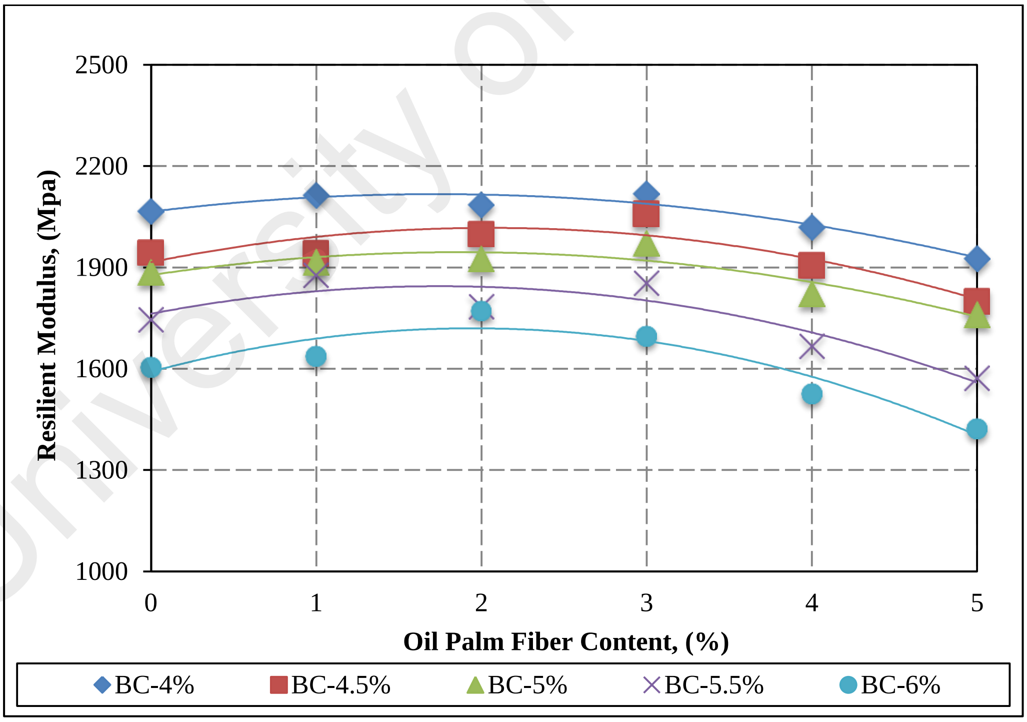


Figure 4.26 Resilient Modulus Value with the Different OPF Contents

4.5.8.2 Effect of Different Binder Content on Resilient Modulus

Figure 4.27 illustrates the effect of different binder content on resilient modulus. From the available results, it seemed that the resilient modulus was high at 4% binder content and decreased at 6% binder content. This may have been due to increments in binder content. High amounts of OPF content were found to achieve the lowest resilient modulus. However, it was found that the resilient modulus of the mix with certain OPF contents had an inconsistent value. This indicated that the damage accumulation of the specimen is not a linear process (Gubler et al. 2005).

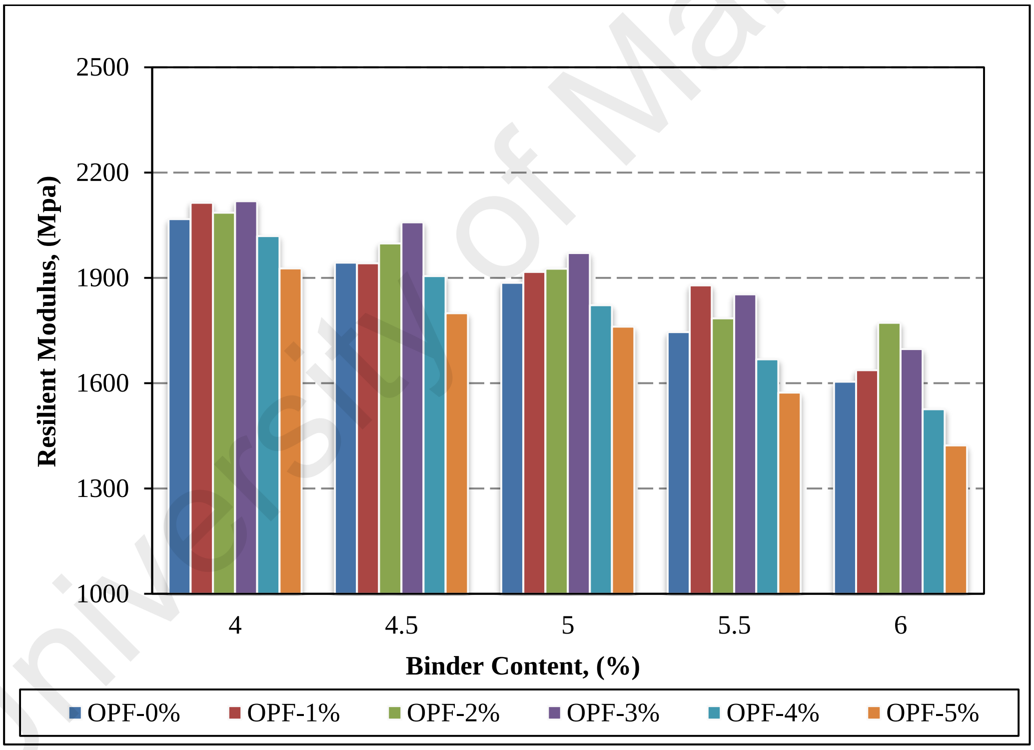


Figure 4.27 Resilient Modulus Value with the Different Binder Contents

A two-factor ANOVA without replication was carried out in order to determine the significance of effects brought about by adding OPF to the porous asphalt. For the resilient modulus, the analysis gave an F-value of 122.93 (F=122.93>F-critical=2.866) and a P-value smaller than 0.05. The results of analysis of variance are given in Appendix B.

4.5.8.3 Resilient Modulus and Air Voids Relationship

Figure 4.28 shows the effect of resilient modulus in the air voids value at 4%, 5%, and 6% binder contents.

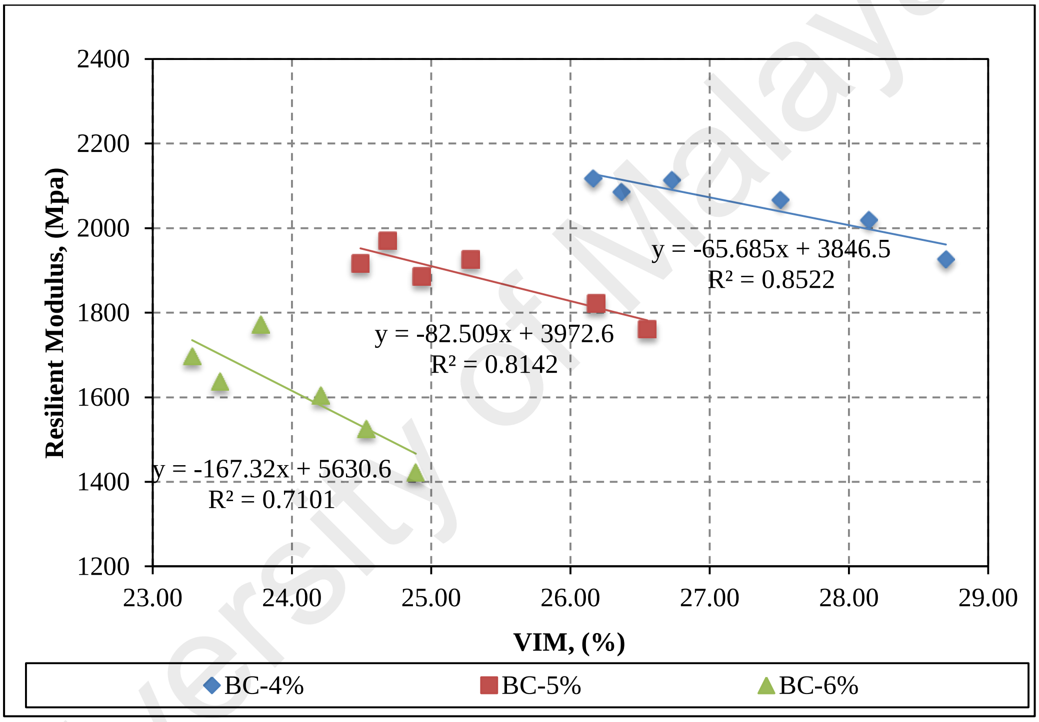


Figure 4.28 Resilient Modulus and Air Voids Relationship

The available results show that the values of resilient modulus decreased as air void content increased (Gubler et al., 2005). This indicated that the air void influenced the value of resilient modulus in porous asphalt. It could also be seen that 4% binder content gave the higher resilient modulus for any OPF content in this study.

4.5.8.4 Resilient Modulus at Optimum Binder Content

The results of the resilient modulus at optimum binder contents are summarised in Figure 4.29. As shown in Figure 4.29, the results of the resilient modulus at the optimum binder content indicated that the mixes are generally higher than the specimen without fiber (0% OPF content) except for specimens made with 4% and 5% OPF content, with values of 1886Mpa, 1917Mpa, 1926Mpa, 1971Mpa, 1822Mpa, and 1761Mpa for fiber content 0%, 1%, 2%, 3%, 4% and 5% respectively. Therefore it can also be seen that the oil palm fiber began to be affected and reduced the performance of specimens when the fiber content was higher.

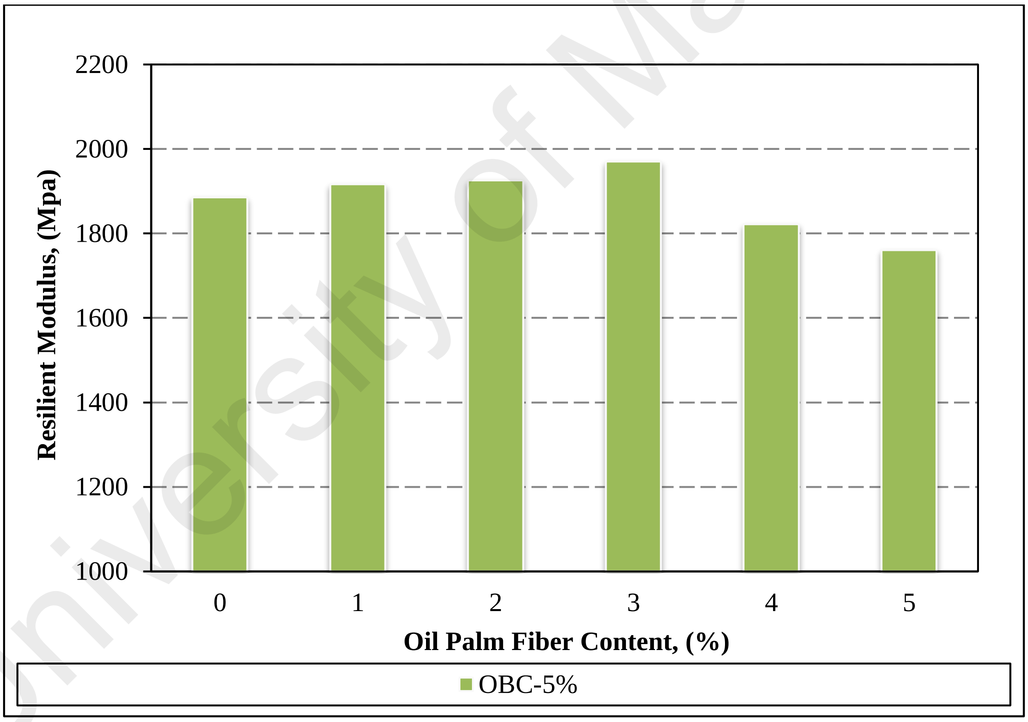


Figure 4.29 Resilient Modulus Value with the Different OPF content at Optimum Binder Content

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This section summarises conclusions which have been drawn from the previous chapter and analysis. The findings of an experimental laboratory on the performance of porous asphalt with respect to oil palm fiber are reported. A number of observations and conclusions can be drawn.

1. The result showed the significant effects on the incorporation of oil palm fiber-modified in bitumen mixes. The softening point value increased with higher OPF content, indicating that oil palm fiber-modified enhances the ability of fresh bitumen (no fiber) to resist flow. The effects of the OPF contents on viscosity also showed that the use of OPF in bitumen increased the viscosity of binder. Moreover, the ability of OPF content to resist flow would decrease at higher temperatures. The stability of the more viscous asphalt mixture was influenced by the characteristics of OPF, asphalt binder and temperature.

2. The amount of OPF used was found to significantly affect the air voids present in the porous asphalt, thus necessitating the need to determine the optimum OPF content for specific applications. An increase in binder content for a particular OPF content would result in a slight decrease in air voids. Nevertheless, the resulting air voids still had adequate porosity to allow the porous asphalt to function satisfactorily. This may have been due to the larger surface area which was present due to higher OPF which must be covered by the binder. This led to an increase in higher air voids. In addition, there was a limit on how much fiber could be added to

the asphalt mixes to prevent excessive voids which may have resulted in oxidative hardening and the consequent reduction of pavement durability.

3. The abrasion loss for any particular amount of OPF used in porous asphalt was highly sensitive to the variation in binder content. This calls for greater care in determining the optimum OPF to be used in porous asphalt so as not to significantly affect its durability. As the amount of OPF to be used increased, more binder was needed to avoid excessive abrasion loss. Since the amount of binder content increase, the mixes can exhibit larger binder film thickness which provides a good performance on durability. Therefore, this is not compromised to ensure that durability of the porous asphalt pavement as there is a critical link between the amount of OPF used in porous asphalt and the binder content.

4. Binder drain down was significantly reduced by the presence of OPF. Thus, the presence of OPF would increase binder film thickness, hence enhancing pavement durability. It may take more binder content to cover the surface when adding oil palm fiber.

5. The optimum binder content for porous asphalt can be determined using the binder drain down test, air voids test and abrasion loss test. The optimum binder content for porous asphalt mixes without fiber was lower than porous asphalt mixes using fiber. In this study an optimum asphalt content of 5% was recommended.

6. The use of OPF affected certain properties of the porous asphalt mix. For any particular binder content, the permeability of the porous mix improved as the amount of OPF increased. However, as the amount of binder to be used increased, the permeability of the porous asphalt decreased because the binder began to clog the air voids, thus slowing the flow of water through the specimens.

7. The amount of OPF used in porous asphalt also had a significant effect on its resilient modulus. The resilient modulus value decreased as the binder content increased for any value of OPF content. This implied that a higher amount of binder at any particular OPF content would result in a more pronounced viscous component of the binder when compared to the elastic component, hence reducing the resilient modulus value. However, the results showed that inconsistent value of some relationships between OPF contents and binder contents indicated that the damage accumulation of specimens was not a linear process.

8. Based on the relationship between viscosity values and softening point, the viscosity value increased as softening point value increased. For any particular OPF content, the value of viscosity and softening point increased with the increase of OPF content.

9. The air void influenced performance of porous asphalt in the relationship between abrasion loss, permeability and resilient modulus value. The abrasion loss was increased as the values air void increased. For permeability test, the increase of air void was slightly above the permeability coefficient. Meanwhile, the air void influenced the value of resilient modulus which increased air void value to give the lowest resilient modulus. This occurred with all OPF content.

10. From the results of regression analysis and analysis of variance (ANOVA), it was evident that the addition of oil palm fiber-modified significantly affected the properties and characteristics of the porous asphalt mixes.

11. On the whole, OPF content of 3% by weight of 80/100 penetration-grade bitumen may be recommended for use in porous asphalt as an optimum fiber content.

5.2 Recommendations

There are several suggestions for further improvements to investigate the influence of oil palm fiber in asphalt mixes, including:

1. Selecting different sizes and proportions of oil palm fiber to determine the optimum contribution in asphalt mixture.

2. The preparation of a different mixing method and different aggregate gradation. This is due to be completed and compares the other possibility of this study.

3. Investigating the effect of different temperatures, oil palm fiber contents and binder contents on the abrasion loss of porous asphalt.

4. There is a need to strike a balance between the two opposing requirements if OPF is to be used as an additive in porous asphalt. Nevertheless, this initial study will hopefully open the door to a more in-depth study on this subject.

REFERENCES

About.com. (2012). *Cellulose fiber; natural*. Retrieved from http://composite.about.com/library/glossary/c/bldef-c988.htm

Africa-Trace.ci. (2012). *Malaysia natural oil palm fibres for export.* Retrieved from http://www.africa-trade.ci/asia/eng/malaysia-natural-oil-palm-fibres.htm

Ahmadinia, E., Zargar, M., Karim, M.R., Abdelaziz, M. & Shafigh, P. (2011). Using waste plastic bottles as additive for stone mastic asphalt. *Materials and Design, 32*, 4844-4849.

ASTM C88-90. (1990). Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM C131-96. (1997). Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the los angeles machine. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D5-97. (1997). Standard test method for penetration of bituminous materials. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D36-86 (Reapproved 1993). (1990). Standard test method for softening point of bitumen (ring-and ball apparatus). Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D92-05. (2005). Standard test method for flash and fire points by cleaved open cup tester. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D113-07. (2005). Standard test method for ductility of bituminous materials. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D1559. (1992). Standard test method for resistance of plastic flow of bituminous mixtures using marshall apparatus. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D2726-90. (1992). Standard test method for bulk specific gravity and density of compacted bituminous mixture using saturated surface-dry specimens. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D4123-82 (Reapproved 1995). (1995). Standard test method for indirect tension test for resilient modulus of bituminous mixtures. Pennsylvania, USA: American Society Testing and Materials (ASTM).

ASTM D4402-87 (Reapproved 2000). (2000). Standard test method for viscosity determinations of unfilled asphalts using the brookfield thermosel apparatus. Pennsylvania, USA: American Society Testing and Materials (ASTM).

Backstrom, M., & Bergstrom, A. (2000). Draining fuction of porous asphalt during snowmelt and temporary freezing. *Canadian Journal of Civil Engineering, 27*(3), 594-598.

Barnett, E. (2008). *Porous streets: the evidence*. Retrieved from http://www.worldchanging.com/archives/007821.html

Baughan, C. J., Chinn, L., Harris, G., Stait, R., & Phillips, S. (2003). Resurfacing a motorway with porous asphalt; Effects on rural noise exposure and community response. *Transportation Research Laboratory Report, TRL536*.

BS 812: Part 110. (1990). Method for determination of aggregate crushing value (ACV). London: British Standard Institutions (BSI).

BS 812: Part 112. (1990). Method for determination of aggregate impact value (AIV). London: British Standard Institutions (BSI).

BS 812: Section 105.1. (1989). Flakiness index. London: British Standard Institutions (BSI).

BS 812: Section 105.2. (1990). Elongation index of coarse aggregate. London: British Standard Institutions (BSI).

BS 2000: Part 58. (1988). Methods of test for petroleum and its products, softening point of bitumen (ring and ball). London: British Standard Institutions (BSI).

Bushing, H. W. & Antrim, J. D. (1968). *Fiber reinforcement of bituminous mixtures*. Paper presented at the Association of Asphalt Paving Technologist, 37, 629-660.

Cahill, T. H., Michele, A. P. E., & Marm, C. (2003). Porous asphalt: the right choice for porous pavements. 26-40. Retrieved from http://www.cleanwatermn.org/documents/ms4%20toolkit%20files/good%20housekeeping/porous%20pavement/asphalt-right%20choice%20for%20porous%20pavements.pdf

Chen, H., Xu, Q., Chen, S., & Zhang, Z. (2009). Evaluation and design of fiber-reinforced asphalt mixtures. *Materials and Design, 30*(7), 2595-2603.

Chiu, C.-T. (2008). Use of ground tire rubber in asphalt pavements: Field trial and evaluation in Taiwan. *Resources, Conservation and Recycling, 52*(3), 522-532.

Chung, D. (1994). *Carbon fiber composites*. Newton, USA: Butterworth-Heinemann.

Daines, M. E. (1992). Trials of porous asphalt and rolled asphalt on the A38 at Burton bypass (pp. 28): TRRL Research Report.

Darintech. (2011). *Ecophalt Technology*. Retrieved from http://www.darintech.com/eng/ek1_5.php?PHPSESSID=1b9e97144a13f32a1925d3a0892df036

Decoene, Y. (1990). Contribution of cellulose fibers to the performance of porous asphalts. *Journal of the Transportation Research Board*(1265), 82-86.

Ferguson, B. K. (2005). *Integrative studies in water management and land development*. Florida, USA: CRC Press.

Georgia Department of Transportation. (no date). *Georgia's Modified Open-Graded Friction Course*. Office of Materials and Research. Retrieved from http://www.dot.state.ga.us

Gubler, R., Partl, M. N., Canestrari, & Grilli, A. (2005). Influence of water and temperature on mechanical properties of selected asphalt pavements. *Materials and Structures, 38*, 523-532.

Guwe, Y. K., Chuai, C. T., Fwa, T. F., & A., T. S. (2000). *Developing permeability meaning procedure for drainage mix on expressway*. Paper presented at the Proceeding of SPT2000, 4th PES-CTR Symposium of Pavement Technology, Singapore.

Hamdani, S. K. (1983). *Open-graded surface course in hot climates.* Paper presented at the Association of Asphalt Paving Technologists Proceedings, 254-269.

Hamzah, M. O., & Cabrera, J. G. (1997). *Properties of porous asphalt.* Paper presented at the Proceeding 2nd European Symposium, Performance and durability of Bituminous Materials, Leeds.

Hamzah, M. O., Hasan M. R. N, Che Wan C.N, & Abdullah N.H. (2010). A comparative study on performance of Malaysian porous asphalt mixes incorporating conventional and modified binder. *Journal of Applied Sciences, 10*, 2403-2410.

Hamzah, M. O., Hasan, M. R. M., & Ven, M. v. d. (2012). Permeability loss in porous asphalt due to binder creep. *Construction and Building Materials, 30*, 10-15.

Hamzah, M. O., Samat, M. M., & Hion-Joon, K. (2002). *Application of the binder drainage test for a porous mixture*. Paper presented at the Malaysia Universities Transport Research Forum (MUTRF) Conference 2002, Malaysia.

Hardiman. (2004). *Peran gradasi dan bahan pengikat dalam perbaikan campuran aspal porus.* Paper presented at the Proceeding of Forum Studi Transportasi antar Perguruan Tinggi (FSTPT) 2004, Parahyangan University, Bandung, Indonesia.

Huang, H., & White, T. D. (1996). Dynamic properties of fiber-modified overlay mixture. *Journal of the Transportation Research Board*, 98-104.

Huber, G. (2000). Performance survey on open-graded friction course mixes. Indianapolis, Indiana: National Cooperative Highway Research Program.

Huet, M., de Boissoudy, A., Gramsammer, J.-C., Bauduin, A., & Samanos, J. (1990). Experiments with porous asphalt on the nantes fatigue test track. *Journal of the Transportation Research Board*, 54-58.

Husin, M., Hassan, A. H. H., Mohammed, A. T., & Malaysia, I. P. M. K. S. (1986). *Availability and potential utilisation of oil palm trunks and fronds up to the year 2000*: Institiut Penyelidikan Minyak Kelapa Sawit Malaysia, Kementerian Perusahaan Utama, Malaysia.

Ismail, M. A. E. (2009). *Study on the properties of palm oil fiber.* Project Report. Faculty of Civil Engineering, Skudai, Johor.

Jahromi, S., & Khodaii, A. (2008). Carbon fiber reinforced asphalt concrete. *The Arabian Journal for Science and Engineering, 33*, 355-364.

Katman, H. Y. (2006). *Effects of rubberized bitumen on properties of porous mixes.* University Malaya, Kuala Lumpur.

Katman, H. Y., Karim M.R., Mahrez, A., & Ibrahim M. R. (2005). *Effect of mixing type on performance of rubberized porous asphalt.* Paper presented at the Proceeding of the Eastern Asia Society for Transportation Studies, Bangkok, Thailand.

Khandal, P. S., & Mallick, R. B. (1998). *Open-graded friction courses; State of the practise*. Washington, DC: Transportation Research Board.

Khozirah, S., & Khoo, K. C. (1991). *Oil palm stem utilization: Review of research*. Kuala Lumpur: Forest Research Institute Malaysia (FRIM).

Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y., R. & Borden, R. H. (2005). Fatigue cracking resistance of fiber-reinforced asphalt concrete. *Textile Research Journal, 75*(2), 123-128.

Mahat, M. N. I. (2009). *Pernilaian dan perbandingan kebolehtelapan dan kesan perpalohan di antara campuran turapan berliang dan campuran conventional (ACW20).* Universiti Teknologi Malaysia, Johor Bahru.

Mahrez, A, & Karim, M.R. (2010). Fatigue characteristics of stone mastic asphalt mix reinforced with fiber glass. *International Journal of the Physical Sciences, 5*(12), 1840-1847.

Masondo, P. T. (2001). *Further development of twin lay porous asphalt surfaces.* Master’s thesis, Peninsula Technikon, South Africa.

Maurer, D. A., & Malasheskie, G. J. (1989). Field performance of fabrics and fibers to retard reflective cracking. *Geotextiles and Geomembranes, 8*(3), 239-267.

Meiarashi, S., Ishida, M., Fujiwara, T., Hasebe, M., & Nakatsuji, T. (1996). Noise reduction characteristics of porous elastic road surfaces. *Applied Acoustics, 47*(3), 239-250.

Mo, L. T., Huurman, M., Woldekidan, M. F., Wu, S. P., & Molenaar, A. A. A. (2010). Investigation into material optimization and development for improved ravelling resistant porous asphalt concrete. *Materials & Design, 31*(7), 3194-3206.

Montepara, A. (1999). *Mechanical performance and fatigue life of open grade bituminous mixes.* Paper presented at the Proceeding 3rd European Symposium on Perfomance and Durability of Bituminous Materials and Hydraulic Stabilised Composites, Leeds.

Mudiandy, R., & Bujang, K., H. (2006). Laboratory diameteral fatigue performance of stone mastic asphalt with cellulose oil palm fiber. *American Journal Sciences 3*(9), 2005-2010.

Mudiandy, R., Ishak, S., & Umar, R. S. (2009). A study on the use oil palm fiber in rubberized stone mastic asphalt, *REAAA Journal, 7*(1), 19-24.

Muniandy, R., Selim, A., & Omar, H. (2002). Laboratory evaluation of Malaysian cellulose oil palm fiber for use in stone mastic asphalt mixes. *International Journal of Pavement Engineering, 1*(3), 19-21.

Najd A, Chuan-chaol, Z., & Jin-ying, G. (2005). Experiments of fracture behavior of glass fiber reinforced asphalt concrete. *Journal of Chang'an University (Natural Science Edition), 25*(3), 28-32.

Oil palm fibers Malaysia. (2012). *Oil palm tree.* Retrieved from http://www.oilpalmfibers.com

Road Engineering Association of Malaysia. (2008). Specification for porous asphalt. Malaysia: Malaysia Public Works Department (PWD).

Sahul, H. M. A. (2010). *Performance of porous asphalt using steel slag as aggregates replacement.* University Teknologi Malaysia, Johor Bahru.

Sasana, P., Ismanto, B. S., & Diana, I. W. (2003). *The influence of using local materials on quality of porous asphalt in Indonesia.* Paper presented at the Proceedings of the Eastern Asia Society for Transportation Studies, 4, 323-328.

Sertass, J. P., & Samanos, J. (1996). Fiber-modified asphalt concrete characteristics, applications and behavior. *Journal of the Association of Asphalt Paving Technologists, 65*, 193-230.

Shinoj, S., Visvanathan, R., Panigrahi, S., & Kochubabu, M. (2011). Oil palm fiber (OPF) and its composites: A review. *Industrial Crops and Products, 33*(1), 7-22.

Standards and Industrial Research Institute of Malaysia (SIRIM). (2009). Standards for oil palm fibre. Retrieved from http://www.aseansec.org/7011.htm

Skvarka, I. G. R. (1996). *A rational for the design of open graded friction course asphalt*: Royal Melbourne Institute of Technology.

Sreekala, M. S., Kumaran, M. G., & Thomas, S. (2002). Water sorption in oil palm fiber reinforced phenol formaldehyde composites. *Composites Part A: Applied Science and Manufacturing, 33*(6), 763-777.

Thelen, Edmund, & Howe, L., F. (1978). *Porous pavement*. Philadelphia: Franklin Institute Press.

Tom, K. (2006). A new era for permeable pavements. *Better Roads*, *73*, 28-32.

Wan Rosli, W. D., Law, K. N., Zainuddin, Z., & Asro, R. (2004). Effect of pulping variables on the characteristics of oil-palm frond-fiber. *Bioresource Technology, 93*(3), 233-240.

Wu, S., Ye, Q., & Li, N. (2008). Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. *Construction and Building Materials*, *22*(10), 2111-2115.

Wu, S.-p., Liu, G., Mo, L.-t., Chen, Z., & Ye, Q.-s. (2006). Effect of fiber types on relevant properties of porous asphalt. *Transactions of Nonferrous Metals Society of China*, *16*, *Supplement*, *2*, 791-795.

Yusoff, M. Z. M., Salit, M. S., Ismail, N., & Wirawan, R. (2010). Mechanical properties of short random oil palm fibre reinforced epoxy composites. *Sains Malaysiana*, *39*(1), 87-92.

Zheng, Z., & Feldman, D. (1995). Synthetic fibre-reinforced concrete. *Progress in Polymer Science*, *20*(2), 185-210.