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UNIVERSITI TEKNOLOGI PETRONAS

Effect of Filler Composition on the Performance of Asphaltic Concrete Mixture

By

Ayu Permana Sari

A THESIS

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BANDAR SERI ISKANDAR

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JULY, 2008

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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ABSTRACT

Fillers can be used as additive material in bituminous mixtures to minimize distress, such as permanent deformation and fatigue on highway pavements. Fillers with different physical and chemical properties have been found to improve the performance of pavement. However, the exact relationship of specific filler property on the resulting properties of the bituminous mixture has not been clearly defined by previous studies.

This study looks at the effect of the physical and chemical properties of filler on the performance of bituminous paving mixtures by correlating the filler properties to permanent deformation and fatigue characteristic of mixture. Three types of filler namely ordinary Portland cement (OPC), quarry dust and fly ash were combined with two types of bitumen i.e. penetration grade 50-60 and 80-100. Each filler was mixed with each bitumen type at filler to bitumen ratios of 0.75, 1.0 and 1.25 by weight, respectively. Hence, a total of 18 mixtures were prepared.

The properties of the prepared bituminous mixture along with optimum bitumen content (OBC) were determined by using Marshall test. The OBC was then used to prepare the specimens for performance test. The performance test includes permanent deformation test using creep and wheel tracking tests, and beam fatigue test to determine fatigue characteristic.

The test results show that a spherical particle reduces the percentage of voids and OBC of the mixture, thus improving the performance of the bituminous pavement. Irregular particles were found to increase the consistency of filler-bitumen system and the stability and stiffness of bituminous mixture by its interlocking mechanism. The content of silica and alumina in fillers were found to affect the quality of bituminous pavement by increasing the hardness of the mix and hence the pavement becomes more resistant to permanent deformation. However, increased hardness causes the pavement to brittle faster, therefore, fatigue cracking can occur in early pavement life. The combination of bitumen penetration grade 80-100 mixed with cement in the filler-bitumen ratio 1.0 (80/cmt/1.0) shows the superiority in term of fatigue, whilst the combination of bitumen penetration grade 50-60 mixed with fly ash in the filler-bitumen ratio 1.25 (50/fa/1.25) was the most superior in term of permanent deformation.

Key words
Mineral filler, asphaltic concrete, permanent deformation, fatigue

ABSTRAK

Pengisi boleh digunakan sebagai bahan penambah di dalam campuran bitumen bagi mengurangkan kerosakan seperti perubahan bentuk kekal dan lesu pada turapan lebuhraya. Pengisi dengan pelbagai sifat fizikal dan kimia yang berbeza telah didapati berupaya meningkatkan prestasi turapan. Tetapi, hubungkait khusus antara sifat tertentu pengisi dan sifat campuran bitumen yang disebabkan olehnya belum pernah didefinisikan dengan jelas oleh kajian-kajian terdahulu.

Kajian ini melihat kesan sifat-sifat fizikal dan kimia pengisi terhadap prestasi campuran turapan bitumen dengan menghubungkait sifat-sifat pengisi kepada perubahan bentuk kekal dan ciri lesu campuran. Tiga jenis pengisi iaitu simen biasa Portland (OPC), debu kuari dan abu cerobong dicampurkan dengan dua jenis bitumen, gred penusukan 50-60 dan 80-100. Setiap pengisi dicampurkan dengan setiap jenis bitumen pada nisbah pengisi ke bitumen 0.75, 1.0 dan 1.25 mengikut berat. Dari itu, 18 campuran telah disediakan.

Sifat-sifat campuran bitumen yang telah disediakan itu berserta kandungan optima bitumen (OBC) telah ditentukan menggunakan Ujikaji Marshall. Kandungan optima bitumen tersebut kemudiannya digunakan untuk menyediakan spesimen bagi ujikaji prestasi. Ujikaji prestasi termasuk ujikaji perubahan bentuk kekal menggunakan ujikaji-ujikaji creep dan penjejakan roda, dan ujikaji alur lesu untuk menentukan ciri-ciri lesu.

Keputusan-keputusan ujikaji tersebut menunjukkan bahawa partikel sfera mengurangkan peratusan lowong dan kandungan OBC campuran, justeru meningkatkan prestasi campuran bitumen. Partikel tak sebentuk didapati meningkatkan konsistensi sistem pengisi-bitumen dan, kestabilan dan kekukuhan campuran bitumen melalui mekanisma saling mengunci. Kandungan silika dan aluminium di dalam pengisi didapati mempengaruhi kualiti turapan bitumen dengan meningkatkan kekerasan campuran dan oleh itu turapan menjadi lebih tahan terhadap perubahan bentuk kekal. Bagaimanapun, peningkatan kekerasan menyebabkan turapan menjadi rapuh lebih cepat, maka keretakan lesu boleh terjadi lebih awal dalam jangkahayat turapan. Kombinasi bitumen gred penusukan 80-100 yang dicampurkan dengan simen biasa Portland pada nisbah pengisi-bitumen 1.0 (80/cmt/1.0) dianggap sebagai campuran berprestasi terbaik berdasarkan ketahanan kepada ciri lesu, sementara kombinasi bitumen gred penusukan 50-60 yang dicampurkan dengan abu cerobong pada nisbah pengisi-bitumen 1.25 (50/fa/1.25) berprestasi terbaik berdasarkan kepada perubahan bentuk kekal.

Kata kunci
Pengisi mineral, konkrit berasfalt, perubahan bentuk kekal, lesu

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ABBREVIATION

AC	Asphaltic Concrete
ASTM	American Society for Testing Material
AV	Air Voids
BS	British Standard
FA	Fly Ash
JKR	Jabatan Kerja Raya
LVDTs	Linear Variable Displacement Transducers
OBC	Optimum Bitumen Content
OPC/ CMT	Ordinary Portland Cement
QD	Quarry Dust
SEM	Scanning Electron Microscopy
UTM	Universal Testing Machine
VFB	Voids Filled with Bitumen
VMA	Voids in Mineral Aggregate
XRF	X-Ray Fluorescence

CHAPTER 1

INTRODUCTION

1.1 Background

Highway pavements have been subjected to increasing traffic loading, which creates severe pavement deterioration. The common deteriorations in flexible pavement are permanent deformation and fatigue cracking. They occur within the service life with pavement failure occurring before the end of the pavement design life. Environmental conditions also propagate pavement deterioration especially in extreme conditions, such as overly high or low temperatures. These problems could be mitigated by improving the design and quality of bituminous pavement mixtures.

Bituminous paving mixture is a composite material. It consists of large percentage of coarse and fine aggregate and a small percentage of bitumen and additive material. Different types and proportion of the material used produces mixtures with different properties. The physical and chemical properties of material such as particle shape and gradation of coarse and fine aggregate, consistency of bitumen and chemical constituent of materials may influence the mixtures properties. On the other hand, the proportion of material, such as composition of total aggregate and bitumen and the aggregate gradation can also influence the properties of the mixtures. The challenge to achieve the best mixture combination has drawn great interest among researchers involved in this area.

Although bitumen and additives make up a small percentage in the mixture, however they play an important role in determining many aspects of pavement performance particularly resistance to permanent deformation and fatigue cracking. Several types of additive materials have been used in pavement mixture such as fillers, fibers, antioxidants, thermoplastic polymers and chemical modifiers [1].

Fillers are defined as fine material passing a 75 µm or no. 200 sieve size. Several types of filler have been used in pavement construction including ordinary Portland cement (OPC), quarry dust (QD), limestone dust, hydrated lime, sludge ash, and fly ash (FA) [2-5]. Several studies have confirmed that fillers incorporated in bituminous mixtures improve the properties and performance of bituminous pavement mixtures [6-9]. The properties and performance of bituminous pavement mixtures are largely influenced by the type and proportion of filler used [2, 3, 5, 8].

Fillers have been found to change the rheological behavior of the binder. A filler stays suspended in bitumen and forms a mastic system that binds the aggregates and fills the void in the mixtures [10, 11]. It affects the properties of the mixtures such as stability, density, air voids and flow [2-5]. Consequently, the resulting optimum bitumen content of mixtures is also affected [5]. The mixture stability and density increase with the addition of filler, while the air voids and flow tend to decrease. The resulting optimum bitumen content (OBC) of bituminous mixtures also tends to decrease. Some researchers believe that filler could replace a certain amount of bitumen in the mix [7].

On the performance criteria, filler incorporated in bituminous mixture has been found to decrease the permanent deformation [4, 12, 13], but did not improve the resistance on fatigue distress [13, 14]. The resulting performance of bituminous paving mixture is believed to depend on the physical and chemical properties of fillers [2, 7, 9].

Although many researchers have observed the effect of filler in the bituminous paving mixtures, however the exact relationship of the specific filler property on the properties and performance of the bituminous mixture has not been clearly defined. Thus, this study is undertaken in order to find the effect of filler properties namely physical and chemical properties and the filler composition to the performance of the resulting mixtures. This result may be used further for the consideration of alternative material selection used for filler in bituminous mixtures.

1.2 Objectives

The objectives of this study are:

i. To determine the properties of filler used in Asphaltic Concrete (AC) mixtures and the most significant parameters affecting the properties of the mix.
ii. To determine the best filler type and composition that exhibits the best performance on permanent deformation and fatigue characteristic.

1.3 Scope of Study

The scope of this study includes the preparation of material, mixture preparation and characterization, performance test on permanent deformation and fatigue, and lastly mixture optimization. Three types of filler namely; Ordinary Portland cement (OPC), quarry dust (QD) and fly ash (FA) and two types of bitumen i.e. bitumen penetration grade 50-60 and 80-100 were used in the mixture. The proportions of filler to bitumen used were 0.75, 1.0 and 1.25 by weight of the mix giving a total of 18 mixture variations. The asphaltic concrete (AC) mixture used in this study was designed based on the Jabatan Kerja Raya (JKR) Malaysia Standard. The best mixture combination was evaluated based on the optimized engineering mixture properties, and the mixture performance studied there of were permanent deformation and fatigue.

1.4 Thesis Outline

This thesis consists of 5 (five) chapters include introduction, literature review, methodology, results and discussion, and finally conclusions and recommendations. A whole range of systematic experimental works had been performed to meet the objective of this study.

Chapter 1 describes the background of this study, objectives, scope of study and thesis outline.

Chapter 2 describes filler information on bituminous mixtures cited from many studies on filler behavior. A brief information of other materials such as bitumen and aggregate are also included.

Chapter 3 presents the general steps of the experimental works as well as specific testing procedures conducted in this study.

Chapter 4 presents the results and discussion of the analyses that have been conducted in this study including the properties of filler, filler-bitumen (mastic) system characteristics, mixtures properties (i.e. density, voids in mineral aggregate (VMA), voids filled with bitumen (VFB), air voids, stability, flow, and stiffness), and performance on permanent deformation and fatigue characteristic.

Chapter 5 presents the conclusions of this study based on the results and discussion from chapter 4 and also recommendations for further study on filler.

CHAPTER 2

LITERATURE REVIEW

2.1 Bitumen Additives

Bitumen plays an important role in bituminous mixtures. It binds all material that composes the bituminous mixture and is responsible for the visco-elastic behavior of the mix. It also plays a large part in determining many aspects of the pavement performance. Improving the quality of bitumen can potentially improve the performance of highway pavement.

The concept of modifying bitumen in bituminous mixture has been used for many years. It has become prominent in the latest years since the demands of high performance pavement arise along with the increasing number of traffic. There are several reasons for modifying bituminous mixture using additive materials. These include [15]:

i. The increasing traffic intensity also includes higher volume, heavier loads and high tire pressures.
ii. Higher construction and maintenance costs require improvements on material characteristics to improve pavement performance and extend its service life.
iii. Environmental and economic reasons, the disposal problems of industrial waste materials can be overcome by converting them into bituminous mixture additives.

Several materials have been used as bituminous mixture additives. The types of additive material used in the industry are shown in Table 2-1. Each type of additives has specific characteristics and advantages. Therefore, the selection of the type and proportion of additives in the composite materials are dependent upon the specific goal or desired characteristic of the resulting mixtures. Material additives such as filler, fibers, antioxidant and adhesion improvers are believed to offer a certain benefit on bituminous paving mixtures.

Table 2-1 Types of Additive [1]

Type of Additive	Example
Filler	Ordinary Portland Cement (OPC) Carbon black Lime Fly ash Quarry dust Hydrated lime
Fibers	Polyester Polypropylene Asbestos Cellulose
Thermoplastic elastomer	Natural rubber Polybutadiene (PBD) Polyisoprene
Adhesion Improvers	Organic amines Amides
Chemical Modifiers	Sulphur Lignin Organo-metallic compounds
Antioxidant	Amines Phenol

Fillers can improve resistance to permanent deformation [4, 12, 13], while fibers can improve the fatigue characteristic of the resulting mixtures [16]. On the other hand, antioxidant and adhesion improvers are usually used to improve the resistance of pavements due to ageing and moisture damage [1].

The materials used as additive in bituminous mixture should be effective both practically and economically. The material availability, temperature susceptibility and cost of material must be considered before the material is being decided to be used in bituminous mixture [1].

2.2 Mineral Filler

According to the JKR standard [17], filler is defined as any fine material that is not less than 70% by weight which passes the 75 µm or no. 200 B.S sieve. Several materials have been used as mineral filler in bituminous mixtures such as rock dust, limestone, hydrated lime, ordinary Portland cement, fly ash, hematite and other suitable materials.

Fillers have been found to improve the properties of bitumen and performance of bituminous mixtures. Several studies on the effect of fillers in bituminous mixture performance conducted by a number of researches have found that the addition of filler can decrease the penetration, increased the softening point, caused ductility loss and also increased the viscosity of the bitumen used [7, 18-21]. Warden et al [7] found that the log penetration is approximately a linier function of filler concentration in the filler-bitumen system or mastic. A relationship exists between the logarithm of viscosity of the filler-bitumen systems and the volume percent of filler used which was found to be linear by Traxler [21].

2.2.1 Background

The earliest study on filler has been done by Richardson [22]. He postulated that the function of filler is more than void filling, but may involve a physical-chemical reaction in the mixtures. On the other hand, Traxler [21] found that the physical properties of filler i.e. size and size distribution are the fundamental filler parameters that affect the void content and average void diameter of packed powders. The study about the physico-chemical properties of fillers was also conducted by Crush, Ishai and Sides [23]. They found that different mineral fillers have different effects on the same bitumen. The geometrical irregularity, surface activity and the physico-chemical characteristics of fillers affect the performance of the resulting mixtures.

Tunnicliff [11] defined fillers as part of fine aggregate which influences the characteristic of bitumen as a binder agent. He suggested that the influence of the fillers surface may be extended into the bitumen through a surface energy gradient. In another paper, he stated that filler should be defined as a material that remains suspended in bitumen. His postulation was proven by Puzinauskas [10] who found that fillers have a double function. The small particle sizes of fillers increase the contact points between the aggregates and bitumen which contributes to increasing the stability of bituminous mix. The incorporation of fillers into bitumen also increases the consistency of the binder.

The activity of the filler depends largely on its packing properties, which is a function of the filler physical characteristic such as size, size distribution and geometric irregularity [18]. Besides the physical characteristic, the type of filler is also found to influence the characteristic of filler-bitumen mixes significantly [19].

2.2.2 Filler properties

The properties of bituminous mixture are critically dependant on the interphase between the filler and bitumen. The type of interphase depends on the character of interaction which may be either a physical force or a chemical reaction. Both types of interaction contribute to the reinforcement of bituminous mixture. The physical and chemical properties of filler are described in detail as follows.

2.2.2.1 Physical properties

The physical properties of filler include density, particle shape, particle size, and particle size distribution.

i. Density

Density of filler varies depending upon the type of filler. It influences the density of the mixtures either by increasing or decreasing this property [24]. The effect of filler density on the density of filled material as in bituminous mixture can be closely approximated by the additivity rule. The influence of filler concentration on the density of polymer or bitumen can be calculated from the following Equation 2-1,

$$d_{p/bit} = \frac{d_c - d_{MF} \times V_{MF}}{1 - V_{MF}} \quad \text{.....................................} 2\text{-}1$$

where; $d_{p/bit}$ = density of polymer/bitumen

d_c = density of composite

d_{MF} = density of filler

V_{MF} = volume fraction of filler

Composite density can be expected to vary because of uneven distribution of filler particle. The density variation also could be due to air voids in the material, which is related to the method of filler incorporation.

ii. Particle shape

Filler has several types of particle shape, i.e. spherical, elongated, flaky, cubic and irregular. Each type of particle shape has specific advantages in the filled materials. According to Wypych [24], in general spherical particle shape give the highest packing density, a uniform distribution of stress, increase the melt flow and lower viscosity, while the cubic and tabular shapes give good reinforcement and packing density. The flaky particles can lower the permeability of liquids, gases and vapors of filled material. The elongated particles give superior reinforcement, reduce shrinkage and thermal expansion. However, irregular particle does not seem to posses any special advantages.

Based on another study conducted by Sayed [18] on cement fillers having irregular particle shape, it was found that the very irregular particle shape and their rough surface texture increased the porosity of the mix and lowered the filler-bitumen consistency. However, these were compensated by the increase in the stability of the bituminous mixture, since they provide a good interlocking mechanism or contact point effect [11]. Filler particle shape can be determined by using the Scanning Electron Microscopy.

iii. Particle size and particle size distribution

The filler particle size ranges from a few nanometers to tenths of a millimeter which depends on the filler type. Normally, the fillers used in the bituminous mixtures meet the passing 63 or 75 micrometer sieve. The JKR standard specifies that filler used in the asphaltic concrete mixture should obtain 70-100% passing this sieve size.

The activity of filler in the bituminous mixes depend largely on the particle size and particle size distribution [18, 19]. However, particle size distribution does not influence stiffening markedly because the fine dust acted in much the same manner as the coarse dust [20]. Filler particle size and its distribution can be determined by using sieve analysis and/or the hydrometer tests.

2.2.2.2 Chemical properties

The chemical composition of filler is believed to influence the bituminous mixture [22, 23]. The inherent characteristic and proportion of the chemical constituent are responsible for the different characteristic of filler. Thus, the type of filler affects the consistency of filler-bitumen system and properties of bituminous mixes [18]. The chemical composition of fillers can be predicted by using the X-ray fluorescence (XRF) apparatus.

2.2.3 Properties and performance of asphaltic concrete mixtures

Studies on the effect of filler on asphaltic concrete have been carried out by many researchers. The effect of filler on the properties of mixtures namely density, voids, stability, etc, and the performance on permanent deformation and fatigue resistance are discussed in the following section.

2.2.3.1 Mixture properties

The correlation between filler and the mixture properties have been established by several researchers. Hudson and Vokac [25], and Kallas et al [26], conducted studies on the effect of filler on the Marshall stability of bituminous mixtures and found that the Marshall stability is a function of both filler concentration and filler type. It is related to the voids in the solid phase and the stone content of the mix. When filler is incorporated in the mix, the relative increase in stability can't be attributed solely to the cohesion of the filler-bitumen phase, but also the interlocking or contact point effects [11]. The shape of filler particles, size distribution and surface texture are rather important factors that affect a good stable pavement [18]. Jacobs [27] found that Marshall stability correlate very well with the softening point of the filler-bitumen system.

The density of the mixtures is strongly related to the degree of compaction. The same effort of compaction on different material will result in different densities. Studies conducted by Al-suhaibani et al [8], Sayed [18], and Kallas et al [26] have found that initial compaction and subsequent densification of asphalt paving mixture are strongly dependent on the type and concentration of filler. The compaction characteristic is influenced not only by the viscosity of filler-bitumen, but also by filler particle shape, size and surface texture.

Sayed [18] also found that the porosity of the bituminous mix is influenced by the volumetric of filler to bitumen. The type of fillers also influences the porosity of bituminous mixtures.

The properties of filler namely particle size distribution, specific surface area, shape and surface characteristic have been suggested as possible factors affecting the voids in mineral aggregate (VMA) of the mixtures [3].

2.2.3.2 Fatigue resistance

Laboratory fatigue tests have demonstrated that the harder bitumen and higher filler content have no significant effect on fatigue life [1]. The addition of filler increased the stiffness of filler-bitumen system [8, 18-20]. However, stiff filler-bitumen mastic may result in brittle mixtures that adversely affect pavement performance under low temperature conditions. The fatigue characteristic of bituminous mixtures is strongly related to bitumen content. In order to obtain the longest fatigue life, the volume of bitumen should be as high as possible, but it is limited according to the permanent deformation [28]. A one percent reduction of bitumen content have been found to reduce fatigue life by 70% [29].

Bolk et al [12] in the study on effect of filler on mechanical properties of asphaltic concrete mixture, found that the effect of type and nature of the filler upon the fatigue behavior of the surfacing is not relevant.

2.2.3.3 Permanent deformation resistance

Evaluation of permanent deformation indicates that permanent deformation may occur by combination of densification (volume change) and shear deformation resulting from high shear stress in the upper layer of the pavement over repeated traffic loadings [30]. It is believed that permanent deformation is influenced by both the nature of the constituent materials used and the materials composition [31]. The continuously graded mixes offer better resistance to permanent deformation rather than gap graded mixes [32].

Resistance of bituminous mixture to permanent deformation can be favorably influenced by using a high viscosity binder. Filler type is found to affect the susceptibility of bituminous mixtures to permanent deformation [18, 33]. This is due to the fact that different fillers have different effects on the viscosity of binder [3, 6, 10, 19].

2.3 Filler Type

Several types of filler have been used in pavement construction including ordinary Portland cement (OPC), quarry dust, limestone dust, hydrated lime, sludge ash, and fly ash [2-5]. Each filler type has certain characteristic that is believed to influence the bituminous mixture performance. Some types of filler such as OPC, quarry dust and fly ash are described follows.

2.3.1 Ordinary portland cement (OPC)

Portland cement is derived from the combustion of limestone and clay at very high temperature range of 1400-1600^{o}C. It can be used as mineral filler with asphalt binder in flexible pavement and due to its fineness, it can fill the void resulting in a viscous mastic system. The principal constituents of OPC are compounds of lime, iron, silica and alumina. With these compositions, mixture incorporating OPC is found more resistant in term of stripping [34].

Incorporation of OPC into bitumen was found to result in a low consistency binder reflected by higher penetration, lower softening point temperature and viscosity compare to the fillers such as hydrated lime, fly ash, limestone and silt [18].

2.3.2 Quarry dust (QD)

Quarry dust or quarry-by-product materials are produced during the processing of crushed stone as aggregates. During the crushing and washing operation, quarry-by-products are formed. There are three types of quarry-by-product resulting from these operation i.e. screenings, pond fines and baghouse fines.

The principal constituent of quarry dust is similar with the parent crushed rock. Granite rock is usually used as the coarse aggregate in pavement mixtures. It is composed of high percentage of silica and alumina. Several studies have been carried out to investigate the use of quarry dust as filler in bituminous mixes. Quarry baghouse fines have been used as mineral filler in asphalt mixtures as long as the size complies with the standards for used as filler. It may also improve the engineering properties of resulting bituminous mixture [6, 19].

2.3.3 Pulverized fuel ash (PFA/FA)

Pulverized Fuel Ash (PFA) or fly ash (FA) is the product of coal combustion. Its composition is dominantly silicon, aluminum and iron constituent. The overall color is cream to dark grey, depending on the proportion of carbon, iron and moisture content. Physically, fly ash is a fine powder with almost the same appearance as Portland cement in fineness and also in color.

There are two types of fly ash i.e. fly ash class C and class F. They are classified according to ASTM C-618 [35]. Fly ash is classified into class C if it composes a minimum 50% of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron (III) oxide (Fe_2O_3). It is classified into class F if it composes a minimum 70% of those constituents.

Fly ash has been found to improve the mixture properties. Adding 4 % of fly ash produces high stability and flow, and lower the air voids [36]. Fly ash improves the strength and stripping resistance of asphaltic concrete, but there are no indication that incorporation of fly ash reduces pavement distress and improve field performance of an asphalt pavement [14].

2.4 Mixture Design

2.4.1 Materials

Bituminous mixtures are composed of small percentage of bitumen that binds the high percentage of aggregates in the mixture. The characteristic of bitumen and aggregate and their functions in the mixture are described as follows.

2.4.1.1 Bitumen

Bitumen is defined by BS 3690: Part 1: 1989 [37] as a viscous liquid, or a solid, consisting essentially of hydrocarbons and their derivatives which is soluble in trichloroethylene and is substantially nonvolatile and softens gradually when heated. It is black or brown in color and possesses waterproofing and adhesive properties. It is obtained by the refinery processes from petroleum, and is also found as a natural deposit or as a component of naturally occurring asphalt, in which it is associated with mineral matter. However, currently the most commonly used binder for highway construction is petroleum bitumen.

Bitumen is a complex material, with varying chemical compounds. There are 4 (four) broad chemical group inside bitumen i.e. asphaltenes, resins, aromatics, and saturates. Harder bitumen has a higher asphaltenes from the same crude oil. Asphaltenes are brown/black amorphous solids which comprise 5-25% by weight of bitumen [38]. Proportion of chemical inside bitumen may influence the performance of bitumen in the mixture.

Bitumen is a visco-elastic material and its deformation under stress is a function of both temperature and loading time. At high temperatures or long times of loading they behave as a viscous liquids, whereas at very low temperature or short times of loading they behave as elastic (brittle) solids. At the intermediate range of temperature and loading times, typical of conditions in service, bitumen behaves in a visco-elastic manner.

Bitumen plays an important role in bituminous mixtures. It binds the aggregate material, responsible for the visco-elastic behavior of mixes and generates a stable mixture. The types of bitumen influence the compaction of mixes. It is expected that the softer bitumen will achieve better compaction than the harder bitumen when the same filler type and compaction effort are used in both cases [4, 39].

2.4.1.2 Aggregate

Aggregate is a fundamental component in asphalt mixtures, it has predominant percentage by weight and contributes to the strength of the mix, and is bonded with bitumen. Thus, a consideration of the origins and properties of aggregate is absolutely necessary. Since it must support stress and strain due to traffic loading in the surface layer as well as in underlying layers, it should have certain properties that should meet the requirements of the specification of the project.

Aggregate is classified into coarse aggregate and fine aggregate. In general, granite crushed rock is used as coarse aggregate and sand is used as fine aggregate. The aggregate size distribution influences the mixture stiffness. A dense graded aggregate produces a stiff mixture than that produced by an open or gap graded material [40].

The studies conducted by Stephens [41] and Kalcheff [42] found that the aggregate particle shape and size have an influence to the properties of bituminous mixtures.

2.4.2 Asphaltic concrete design mixture

Asphaltic concrete is a type of design mixture that has a continuously graded mineral aggregate and filler. In general, it is designed to produce materials with minimum voids. The main structure contributor in asphaltic concrete mixtures is aggregate interlocking that contributes to strength and performance, while the bituminous binder plays a minor role. Hence, the percentage of bituminous binder is relatively low. Generally, asphaltic concrete has good resistance to permanent deformation [32].

The gradation specification of asphaltic concrete varies from one country to another. The specification includes the percentage range of aggregate sizes and the suggested ranges of bitumen content. The Jabatan Kerja Raya (JKR) Malaysian Standard [17] for asphaltic concrete design mixture will be used in this study. The suggested gradation limits and design bitumen content are shown in Table 2-2.

Table 2-2 JKR Gradation Limits and Design Bitumen Content For Asphaltic Concrete Mixture [17]

Mix Type	Wearing course
Mix Designation	ACW 20
B.S. Sieve	% Passing by weight
37.5 mm	
28.0 mm	100
20.0 mm	76-100
14.0 mm	64-100
10.0 mm	56-81
5.0 mm	46-71
3.35 mm	32-58
1.18 mm	20-42
425 um	12-28
150 um	6-16
75 um	4-8
Design Bitumen Content	4.5-6.5 %

2.5 Mixture Properties and Performance Test

The mixture properties test consists of the Marshall test and the performance tests on both permanent deformation and fatigue. The performance tests consist of the creep test, wheel tracking test and beam fatigue test.

2.5.1 Marshall test

The Marshall test provides the measurement of resistance to plastic flow of cylindrical specimens of bituminous mixtures loaded on the lateral surface by means of the Marshall apparatus. Two parameters are obtained i.e. stability (kN) and flow (mm). Marshall stability is the maximum load that a specimen can withstand at a loading rate of 50.8 mm/minute tested at a temperature of 60°C. The flow value is the total deformation of the specimen at the maximum load. One of the easiest ways to increase the stability of bituminous mixture is by increasing the viscosity grade of bitumen by the addition of mineral filler [19].

Both stability and flow are used to determine the optimum bitumen content (OBC) of bituminous mixtures. The percentages of bitumen at maximum stability and flow at the considered value as recommended standard are used in the OBC determination. The other engineering properties used in OBC such as density, air voids (AV), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB) are determined by data of weight in air and water, and the height of the Marshall specimens. The bitumen percentages at the maximum/minimum or recommended value of a number of engineering properties are averaged and it is considered as optimum bitumen content.

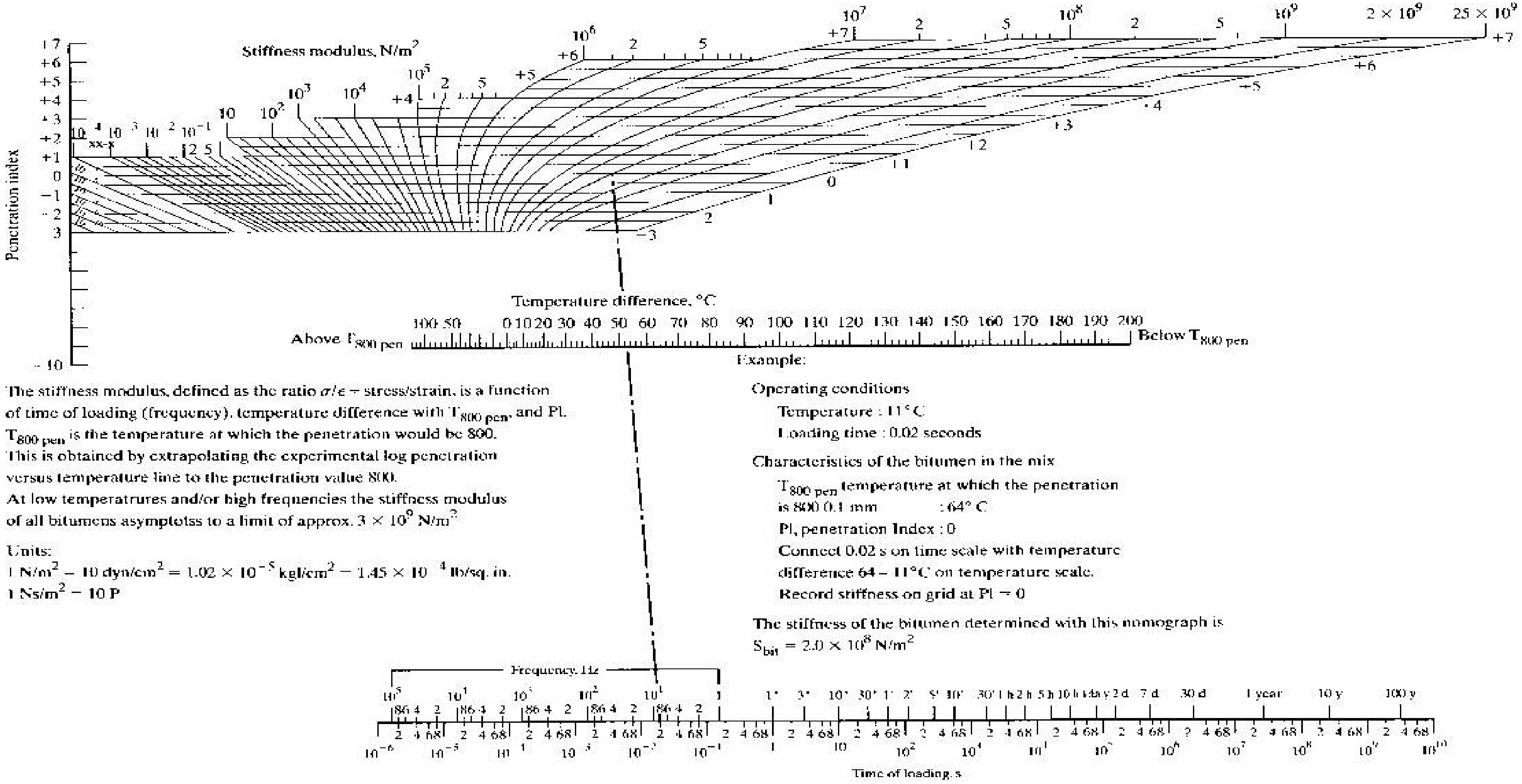
Voids in mineral aggregate (VMA) is the space between the aggregate particles of bituminous mixture. It is expressed as the percentage of volume voids to the total volume of mix. VMA is important as it provides sufficient space between the aggregates that can be filled by bitumen in order to obtain maximum strength of the design mixture. Void filled with bitumen (VFB) represent the percentage of voids filled by bitumen, while air voids (AV) is the percentage of air volume to the total volume of compacted bituminous mixtures.

Marshall stiffness, which is Marshall stability divided by flow is used to characterize the stiffness of bituminous mixture. In a study on design of improved asphalt road mixture, Brien [43] found a reasonable correlation between the Marshall stiffness and wheel tracking test results. Bolk et al [12] also found the optimum bitumen content decreased with the addition of filler in the bituminous mixture.

2.5.2 Creep test

One of the tests used to determine the permanent deformation of bituminous mixture is the creep test. The creep test is a test that applies a repeated pulsed uniaxial stress/load onto the bituminous mixture specimen and measures the resulting deformations in the same axis and/or radial axis using Linear Variable Displacement Transducers (LVDTs). The duration of the test is 1800 load cycles with specific time of loading, rest period and applied stress as specified by the selected standard. According to British Standard DD226 [44], the proposed test parameters are pulse width 1,000 ms, rest period 1,000 ms and contact stress 2 kPa.

The results are plotted as deformation versus time of loading. The reversible part of the total deformation may also be determined by removing the load, which is usually equal to the loading time, and measuring the deformation after recovery time [45]. Another way of expressing the creep test results is to plot Log S_{mix} versus Log S_{bit}. S_{mix} is determined by dividing the stress by the strain, calculated from creep test measurements, while S_{bit} parameter is determined using Van der Pool Nomograph [46] as shown in Figure 2-1. Both S_{mix} and S_{bit} are independent of temperature, time of loading and stress levels. This implies that the slope and intercept of the S_{mix} -S_{bit} line will only depend on the composition of the mixture and its inherent characteristics [47].



The stiffness modulus, defined as the ratio σ/ε = stress/strain, is a function of time of loading (frequency), temperature difference with $T_{800\ pen}$, and PI.
$T_{800\ pen}$ is the temperature at which the penetration would be 800.
This is obtained by extrapolating the experimental log penetration versus temperature line to the penetration value 800.
At low temperatrures and/or high frequencies the stiffness modulus of all bitumens asymptotss to a limit of approx. 3×10^9 N/m²

Units:
$1\ N/m^2 = 10\ dyn/cm^2 = 1.02 \times 10^{-5}\ kgf/cm^2 = 1.45 \times 10^{-4}$ lb/sq. in.
$1\ Ns/m^2 = 10$ P

Example:

Operating conditions
Temperature : 11° C
Loading time : 0.02 seconds

Characteristics of the bitumen in the mix
$T_{800\ pen}$ temperature at which the penetration is 800 0.1 mm : 64° C
PI, penetration Index : 0
Connect 0.02 s on time scale with temperature difference 64 – 11°C on temperature scale.
Record stiffness on grid at PI = 0

The stiffness of the bitumen determined with this nomograph is
$S_{bit} = 2.0 \times 10^8$ N/m²

Figure 2-1 Van der Pool nomograph for S_{bit} determination [46].

2.5.3 Wheel tracking test

Wheel tracking test is used to assess the resistance to rutting of bituminous materials under simulated traffic conditions. A loaded wheel tracks a sample under specified conditions of load, speed and temperature while the development of the rut profile is monitored continuously during the test. Test specimens can be either slabs prepared with a laboratory compactor or cores cut from the highway. The test measures the rutting under the wheel over a period of time.

An actual wheel of 200 mm diameter and 50 mm width with applied load of 520 N is used in this test. It runs backward and forward across a bituminous specimen and forms a longitudinal rut in the specimens. The rut depth is not uniform along the wheel track. The deepest rut depth appears at two ends of the track while the shallowest appears in the midpoint of the track. The rut depth is influenced by temperature and speed of loading of the test [48].

In bituminous mixture, rut depth or wheel tracking rate is affected significantly by binder content and binder penetration [49]. Since fillers affect the resulting mastic in the bituminous mixtures, it can also thus be considered to influence the rut depth.

2.5.4 Beam fatigue test

The fatigue characteristic is typically determined by using a simple beam with three point loading. The advantage of the three point loading is the existence of a bending moment over the middle third of a specimen.

As shown in Figure 2-2, there are two parameters that could be controlled in a fatigue test i.e. either the stress or the strain. For a constant stress test, the strain is increased with the number of repetition, and for a constant strain, the load of stress is decreased with the number of repetition. A constant stress is usually applied to thick pavement (more than 152 mm or 6 in) and a constant strain is usually used for thin pavement (less than 51 mm or 2 in). While, for pavement that has intermediate thickness, either constant stress or constant strain could be applied. Failure occurs quicker with constant stress, because both stress and strain are normally larger for constant stress than constant strain, and the failure is easy to define using constant stress. For arbitrary failure criterion, for example stress is equal to 50% from the initial stress, constant strain is used. In this test, it is necessary to select the range of sufficient stress that could make the specimens fail in the range of 1,000 to 1,000,000 repetitions.

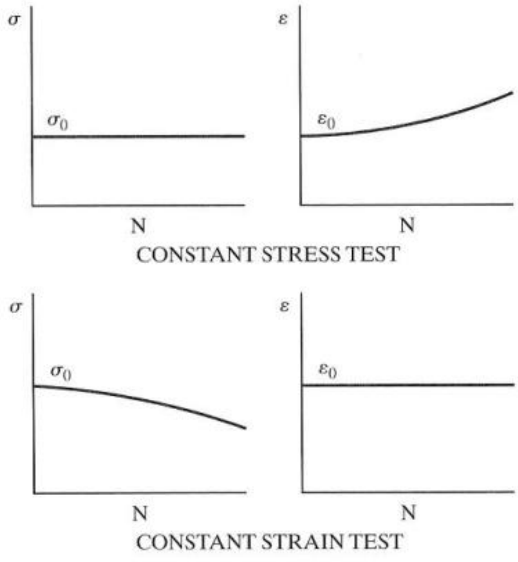


Figure 2-2 Types of controlled loading for fatigue test [46].

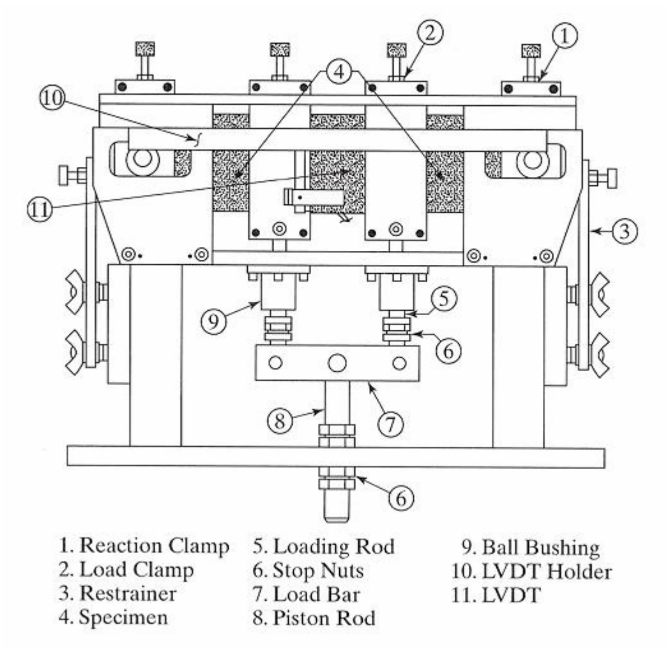


Figure 2-3 Fatigue testing equipment [46].

Loading of beam fatigue test can be haversine or sinusoidal waves with pulse width entered in millisecond and can range from 10 (100Hz) to 50,000 millisecond (0.02Hz). The specimens for this test are beam specimens with 310 mm (15 in) length, and width and depth not exceeding than 76 mm (3 in). In order to determine the dynamic deflection, LVDTs (Linear Variable Displacement Transducers) are arranged in midspan of the beam specimen. Figure 2-3 is a schematic diagram of the fatigue testing equipment.

The results of this test are plotted either as the initial strain or stress versus number of repetition of loads. The plots approximate straight lines as shown in Figure 2-4. For the constant stress loading, the number of repetitions to failure, N_f can be expressed as in Equations 2-2.

$$N_f = c_2(\varepsilon_t)^{-f2} \quad \text{.....................................2-2}$$

Where N_f is the number of repetitions to failure, c_2 is a fatigue constant that is the value of N_f when $\varepsilon_t = 1$, and f_2 is the inverse slope of the straight line.

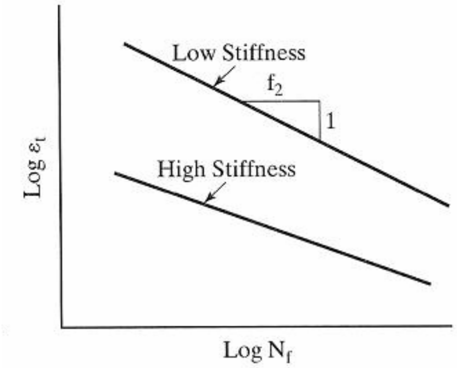


Figure 2-4 Relationship between strain and number of repetitions to failure [46].

2.6 Pavement Distresses

The two most common structural distresses that occur in flexible pavements are rutting and cracking. Rutting normally occurs during the first few years after construction, while cracking occurs after a critical number of repetitions of loading and grows rapidly when the strength of the pavement decreases.

2.6.1 Rutting

Rutting is apparent at the surface in the wheel paths repeatedly tracked by vehicle wheels. Rutting stems from a permanent deformation in any of the pavement layers or in the sub grade, one usually caused by a consolidation or lateral movement of the materials due to traffic loads.

Rutting can be caused by plastic movement of asphalt mix either in hot weather or from inadequate compaction. An element of the deformation that is induced under the application of a vehicle load is therefore, irrecoverable and with repeated load applications, this permanent deformation accumulates leading to the formation of ruts [50]. Overstress on the underlying base generates rutting throughout the entire asphalt pavement structure. It can be the result of inadequate thickness design for the applied traffic or for the strength properties of the underlying materials [51]. A sample of rutting in pavement is shown in Figure 2-5.

Figure 2-5 Rutting in pavement [52].

2.6.2 Alligator or fatigue cracking

Fatigue failures begin from the bottom layer of asphalt surface due to maximum tensile strain that generates the fatigue cracking. This phenomenon is associated with the temperature changes. Cracks originating from the bottom layer propagate to the upper layer and become connected like an alligator skin. Fatigue cracking occurs only in areas that are passed by repeated traffic loading and is considered as a major structural distress. Fatigue cracking is shown in Figure 2-6.

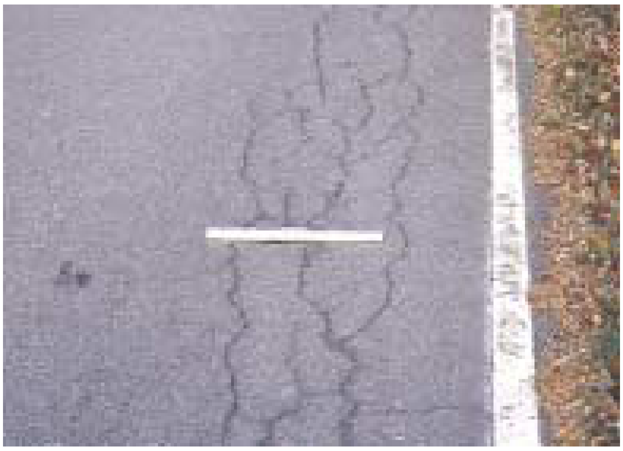


Figure 2-6 Alligator or fatigue cracking [52].

2.7 Summary

The summary of the previous study of the filler in the bituminous mixture is presented in the Table 2-3. Many researchers have confirmed that filler has an important role in the bitumen properties and also bituminous mixture properties and performances. Filler may increase the stability and lowered the voids of the bituminous mixture. On the mixture performance, filler can increase the resistance to permanent deformation, even though there is no indication to improve fatigue resistance. However, the effect of physical and chemical properties of filler and the filler of composition to the mixture performance has not clearly defined by previous study. In order to find this gap, this study is undertaken with emphasis to find the effect of filler properties to the resulting mixtures properties and performances.

Table 2-3 Summary of Literature Review

Results from Previous Study	
Bitumen Characteristic	The addition of filler can decrease the penetration, increased the softening point, caused ductility loss and also increased the viscosity of the bitumen used. (Traxler (1937), Warden (1961), Eick et al (1978), Sayed (1988), Anderson (1992))
Mixture Properties	Marshall stability is a function of both filler concentration and filler type. (Hudson and Vokac (1962), Kallas et al (1962)) The size distribution, specific surface area, shape and surface characteristic of fillers is factor that affecting the voids in mineral aggregate (VMA) of the mixtures. (Puzinauskas and Kallas (1961)) The volumetric of filler to bitumen influence the porosity of the bituminous mix. (Sayed (1988))
Mixture Performance	The geometrical irregularity, surface activity and the physico-chemical characteristics of fillers affect the performance of the resulting mixtures. (Crush et al (1978)) Fillers can improve resistance to permanent deformation. (Heukelom (1965), Bolk et al (1982), Brown (1990)) The harder bitumen and higher filler content have no significant effect on fatigue life. (Read (2003)) The effect of type and nature of the filler upon the fatigue behavior of the surfacing is not relevant. (Bolk (1982))
Filler Type	Spherical particle shape gives the highest packing density, and lower viscosity to the filled materials, whilst elongated particles give superior reinforcement. However, irregular particle does not seem to posses any special advantages. (Wypych (1999))

CHAPTER 3

METHODOLOGY

3.1 Introduction

The general scheme of this study is described in detail in this chapter. The study started with material preparation followed by mixture preparation, performance tests and mixtures optimization. The material preparations included material selection and characterization of materials properties. The materials were selected based on JKR standard and were then characterized in term of density (for aggregate, bitumen and filler), physical appearance and chemical constituents (for filler only).

The mixture preparation included the determination of mixture variation and specimen preparation, the consistency test of the filler-bitumen system and characterization of mixture properties. The consistency of the filler-bitumen system was tested by using three different tests including the penetration, softening point and ductility tests. The properties of the bituminous mixtures were characterized by using the Marshall test where the optimum bitumen content was obtained by optimization of several of the mixture properties. The optimum bitumen content was then used for the performance test of the bituminous mixtures.

The performance tests of the mixture specimens include the permanent deformation and fatigue characteristics of the mix. Permanent deformation is determined by using two different tests i.e. dynamic creep test and wheel tracking test, while fatigue characteristic were determined by using the beam fatigue test. In order to determine the best mixture combination, several aspects including properties of mixture and mixture performance on permanent deformation and fatigue were used. The flowchart of this study is shown in Figure 3-1.

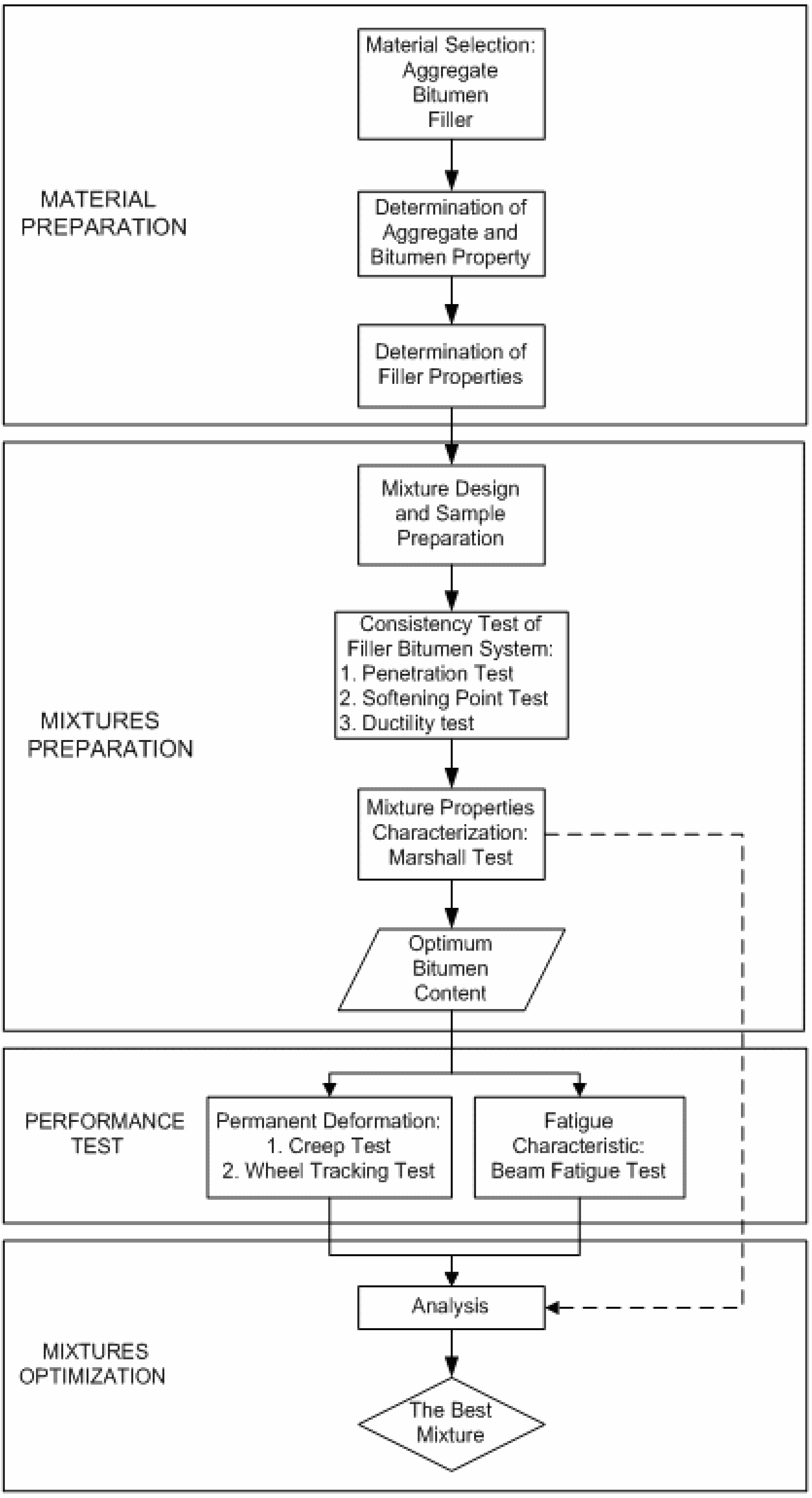


Figure 3-1 Research flowchart.

3.2 Material Preparation

The material preparations included the material selection and the material properties test on aggregate, bitumen and filler. The details of the material preparation are presented as follow.

3.2.1 Material selection

The selections of material and mixture design was referred to the JKR standard [17]. In this study, asphaltic concrete (AC) mixture designated as ACW 20 was used. The maximum aggregate size used was that retained on size 20 mm British Standard (B.S) sieve and the bitumen content ranged from 4.5% to 6.5%. The aggregate was subjected to sieving to ensure that the aggregate used in the mixtures conforms to the standard.

3.2.1.1 Bitumen

Two types of bitumen penetration grades were used in this study, i.e. bitumen penetration grade 50-60 and 80-100. Bitumen penetration grade 80-100 was used in accordance to the specification from JKR standard for asphaltic concrete mixture, while bitumen penetration grade 50-60 was used in order to observe the effect of filler in harder bitumen. The Effect of filler in different bitumen types was then compared with the effect of filler in different filler composition. Both bitumen penetration grade 50-60 and bitumen penetration grade 80-100 are manufactured from refined crude oil. The bitumen was heated to approximately 160^{o}C before it was mixed with the aggregate and filler.

3.2.1.2 Filler

Three types of different filler were used in this study namely ordinary Portland cement (OPC), quarry dust (QD) and fly ash (FA). The parameter of ratios filler to bitumen by weight were used in this study. The ratios of filler to bitumen were selected in accordance to JKR standard specifications for bitumen that ranged from

4.5% to 6.5% and the ratios were then adjusted to the specification for filler that ranged from 4% to 8%. Thus, it was giving filler proportion variations of 0.75, 1.0 and 1.25 of filler to bitumen by weight.

The fillers used in this study obtained 100% passing through the 75 μm B.S sieve. The fillers were dried in the oven at 160^{o}C for 24 hours before mixing with the aggregate and bitumen to produce a homogenous bituminous mix.

3.2.1.3 Aggregate

Two different aggregate materials were used in this study, i.e. granite crushed rock for coarse aggregate and river sand for fine aggregate. 5 mm B.S sieve size was used as the limit of aggregate classifications. The aggregates that were retained on 5 mm B.S sieve were categorized as coarse aggregate, while those that passed the sieve size were classified as fine aggregate.

The range of JKR gradation specification and aggregate gradations used in this study are shown in Table 3-1. The gradations of this study, as shown in Table 3-1, were divided into gradation (a) and (b). The gradation (a) was used for mixture variations composed of filler equal to or lower than 6.25% by weight of total aggregate, while gradation (b) was used for mixture variations composed of filler more than 6.25% of total aggregate. These gradations were subjected to the variation of F/B ratio, as it mentioned earlier.

Both coarse and fine aggregates were sieved by using the sieve shaker. The aggregates were then washed and dried in the oven for ± 24 hours. They were put in the containers and classified based on their particle size. Each aggregate particle size was weighted based on the aggregate gradation proportion in every mixture in order to meet the aggregate gradation requirements in all the bituminous mixture specimens. In other words, there is no aggregate gradation variation in this study except the filler content.

Table 3-1 Aggregate Gradation

	JKR Standard	Gradation aggregate (a)	Gradation aggregate (b)
B.S. Sieve	% Passing by weight		
28.0 mm	100	100	100
20.0 mm	76-100	97.9	97.9
14.0 mm	64-100	72.9	72.9
10.0 mm	56-81	60.4	60.4
5.0 mm	46-71	52.1	52.1
3.35 mm	32-58	50	50
1.18 mm	20-42	41.7	41.7
425 µm	12-28	16.7	16.7
150 µm	6-16	6.25	x
75 µm	4-8	x	x

3.2.2 Aggregate and bitumen property

The densities of composed material were required in the determination of mixture properties. The coarse and fine aggregates densities were determined by using the Ultrapycnometer 1000, while the bitumen density was determined by using the 25 ml pycnometer.

3.2.3 Filler properties test

The tests on filler properties include determining the physical and chemical characteristics of the filler. The physical characteristic of filler such as particle density and physical appearance of filler were determined by using the Ultrapycnometer 1000 and the scanning electron microscopy (SEM) respectively with 300 and 2000 times magnifications, while the chemical constituents were determined by X-ray fluorescence (XRF) technique. All filler samples used passes the 75 µm B.S sieve totally.

3.3 Mixture Preparation

The mixture preparations include mixture design and preparation, determination of the consistency of the filler-bitumen system and mixture properties. The mixture preparations were conducted to perform the basic characteristics of mixture that were used in the analysis of mixture performance.

3.3.1 Mixture design and specimen preparation

3.3.1.1 Mixture design

Two bitumen grades i.e. penetration grade 50-60 and 80-100 were used in the preparation of the mixtures. All three fillers were used in the preparation and the amount of each filler was varied in the filler/bitumen ratio of 0.75, 1.0 and 1.25 by weight. Hence, a total of 18 mixtures were prepared. Each mixture was assigned a designated code based on the bitumen penetration grade, filler type and filler to bitumen ratio by weight as listed on Table 3-2 and Table 3-3.

3.3.1.2 Specimen preparation

The sample preparation for the penetration, softening point and ductility tests were similar. The bitumen was first heated at ±160^{o}C for approximately 1 hour, and then mixed with filler based on the mixture design. After the mixture has been mixed properly, it was poured into a mould or container and allowed to harder for approximately 2 hours.

For the Marshall specimen preparation, 1200 gram of aggregates including coarse aggregates, fine aggregates and filler were mixed with bitumen ranging from 4.5% to 6.5% with increment of 0.5% for each mixture design variation. Three specimens were prepared for each percentage of bitumen content. The heated and mixed sample was poured into a heated mould with diameter 100 mm and compacted by Marshall compactor for 75 blows. This correspond with the design of Asphalt Institute Manual MS2 [53]. The Marshall compactor is shown in Figure 3-2.

The creep specimen has a similar dimension to the Marshall specimen. 1200 gram of coarse aggregate, fine aggregate and filler were mixed with certain bitumen based on the optimum bitumen content (OBC) results obtained from the Marshall test. The sample was then compacted by using a Marshall compactor for 75 blows on each side. Three specimens were prepared for each mixture variation. Thus the total creep specimens were 54. The creep test specimen is shown in Figure 3-3.

The wheel tracking specimens were prepared by mixing approximately 10 kg of aggregates at the optimum bitumen content. The materials were mixed by using a mixer at a controlled temperature of 160°C, as shown in Figure 3-4. The sample was then poured into a 305 mm x 305 mm x 50 mm mould and was then compacted by a hand compactor as shown in Figure 3-5. All wheel tracking specimens were compacted in two layers with the same power of hand compactor. Two samples were prepared for each mixture variation, thus total wheel tracking specimens were 36. The specimen for wheel tracking is shown in Figure 3-6

Table 3-2 Mixture Design Variations Using Bitumen Penetration Grade 50-60

Mixture Variations			
Bitumen	Penetration Grade 50-60		
(Filler type)/ (F/B ratio)	Cement	Quarry Dust	Fly Ash
0.75	50/cmt/0.75	50/qd/0.75	50/fa/0.75
1	50/cmt/1.0	50/qd/1.0	50/fa/1.0
1.25	50/cmt/1.25	50/qd/1.25	50/fa/1.25

Table 3-3 Mixture Design Variations Using Bitumen Penetration Grade 80-100

Mixture Variations			
Bitumen	Penetration Grade 80-100		
(Filler type)/ (F/B ratio)	Cement	Quarry Dust	Fly Ash
0.75	80/cmt/0.75	80/qd/0.75	80/fa/0.75
1	80/cmt/1.0	80/qd/1.0	80/fa/1.0
1.25	80/cmt/1.25	80/qd/1.25	80/fa/1.25

Figure 3-2 Marshall compactor.

Figure 3-3 Creep test specimen.

Figure 3-4 Mixer.

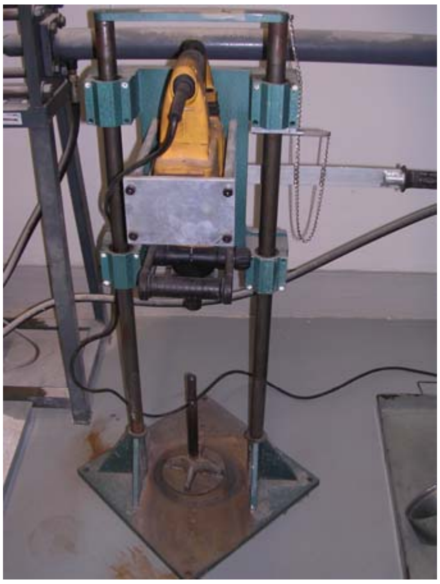


Figure 3-5 Hand compactor.

Figure 3-6 Wheel tracking specimen.

The beam fatigue specimens were prepared by mixing of approximately 7600 gram of total aggregates with bitumen at the optimum bitumen content and mixed in big mixer as shown in Figure 3-4. The samples were poured into the 100 mm x 100 mm x 500 mm mould and were compacted by a hand compactor as shown in Figure 3-5. All the beam fatigue specimens were compacted in two layers with the same power of hand compactor. The samples were then cut to obtain a dimension of approximately 50 mm x 65 mm x 380 mm for the fatigue test. The process of cutting and the beam fatigue specimens after cut are shown in Figure 3-7 and Figure 3-8 respectively. Two samples were prepared for each mixture variation. The total number of specimens for the beam fatigue test was 36.

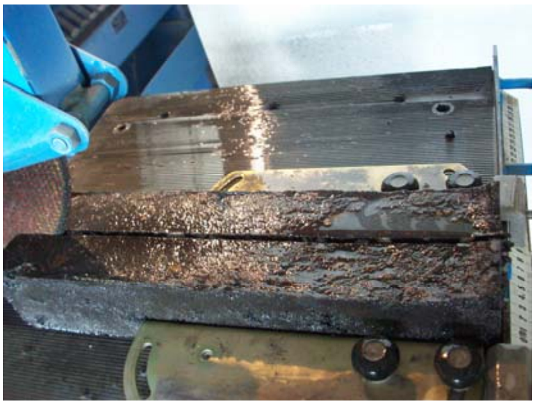


Figure 3-7 Cutting process of specimen.

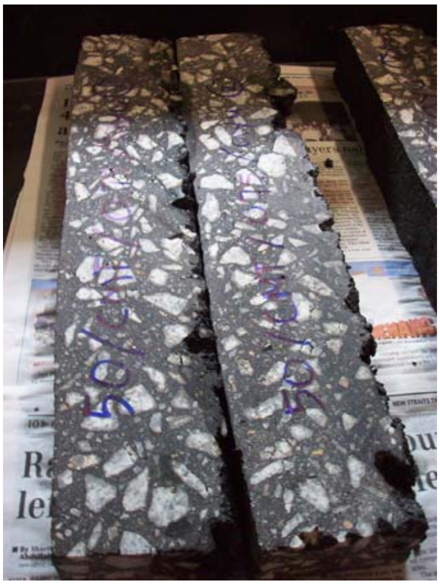


Figure 3-8 Beam fatigue specimen.

3.3.2 Consistency of filler-bitumen system

The consistencies of filler bitumen system were tested by using penetration test, softening point test and ductility test. They were determined in order to investigate the effect of filler properties and filler proportion on the bitumen characteristic.

3.3.2.1 Penetration test

The Penetration was conducted in accordance to B.S 2000: Part 49: 1983 [54]. In this test a needle with specified dimensions is allowed to penetrate into the sample of filler-bitumen mix under 100 gram loads, at a temperature of 25°C for 5 second. The distance penetrated by the needle into the sample of bitumen is termed the penetration. It is measured in a unit of tenth millimeter (dmm). The penetrometer apparatus and illustration of the penetration test are shown in Figure 3-9 and Figure 3-10 respectively.

Two samples were prepared for each mixture variation and 3 tests were conducted for each sample. The penetration value is compared against the difference between the highest and lowest determination as tabulated in Table 3-4. The penetration value should lie within a specified range. If the differences are exceeded, the test is repeated by using the second sample.

Table 3-4 Penetration Specification [54]

Penetration	0-49	50-149	150-249	>250
Maximum difference between highest and lowest determination	2	4	6	8

Figure 3-9 Penetrometer.

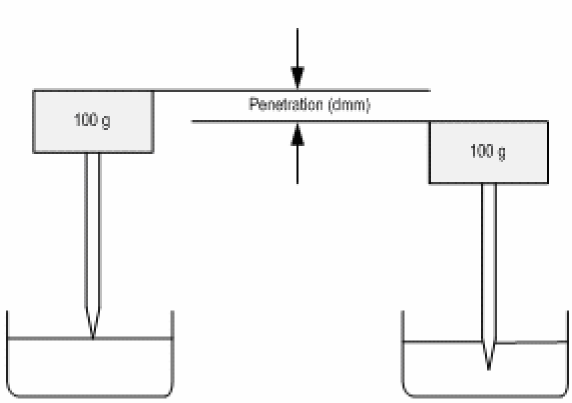


Figure 3-10 Illustration of penetration test.

3.3.2.2 Softening point test

The softening point test conducted is referred to BS 2000: Part 58: 1983 [55]. A steel ball (3.5 g) is placed on a sample of mixed filler-bitumen mortar contained in a brass ring and suspended in water. The bitumen softens and eventually deform slowly with the ball through the ring. The temperature of the water is recorded, at the moment the bitumen and steel ball touches the base plate 25 mm below the ring.

The test is performed in duplicate and the mean of the two measured temperatures is reported. If the difference between the values obtained in the duplicate determination exceeds 1°C, the test was repeated. The softening point apparatus and the illustration of softening point test are shown in Figure 3-11 and Figure 3-12.

Figure 3-11 Softening point apparatus.

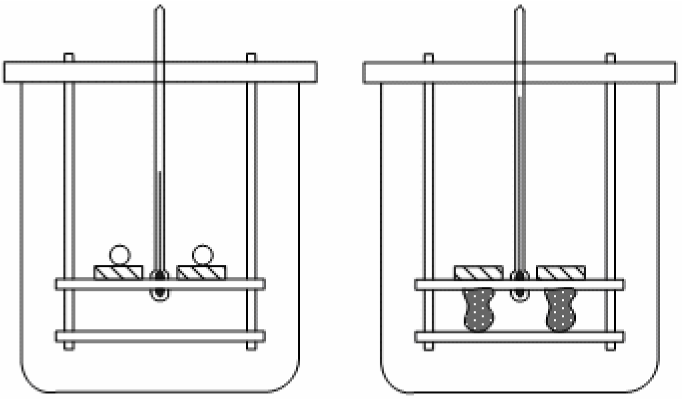


Figure 3-12 Illustration of softening point test.

3.3.2.3 Ductility test

The cohesive strength of penetration grade bitumen is characterized by its ductility. This test was referred to ASTM D 113 [56]. Two dump-bells of bitumen were immersed in a water bath with a standard test temperature of 25^{o}C and were stretched at a constant speed of 50 mm per minute until fracture occurs. The distance the specimen stretched before failure was reported as the ductility. The ductility apparatus or ductilometer and ductility illustration are shown in Figure 3-13 and Figure 3-14.

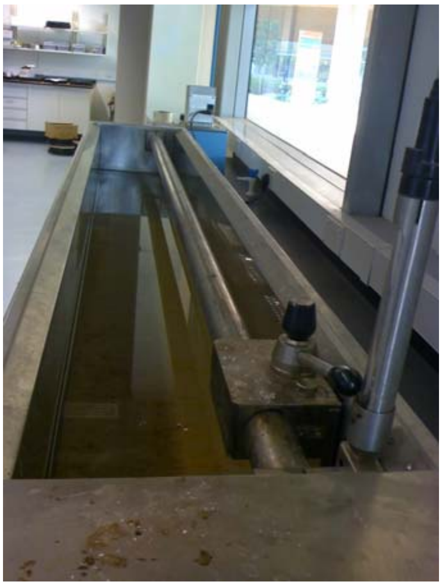


Figure 3-13 Ductilometer.

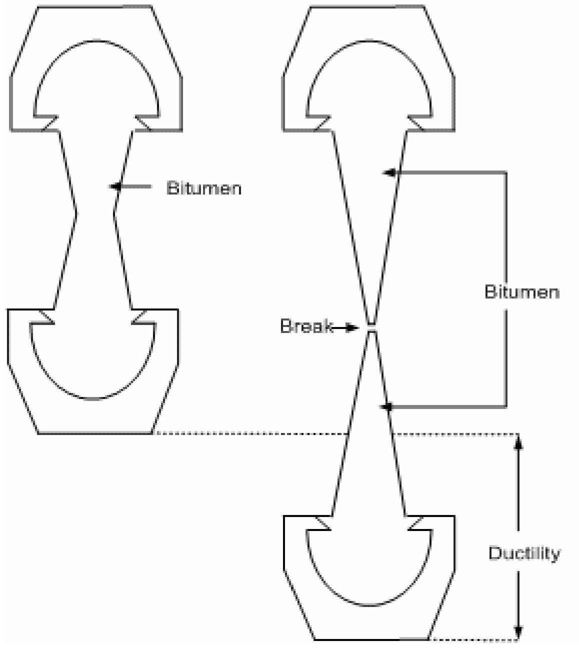


Figure 3-14 Illustration of ductility test.

3.3.3 Mixture properties

The mixture properties i.e. stability and flow were determined by using the Marshall test. The Marshall specimen height and weight in air and water were taken to determine the other mixture properties such as density, air voids (AV), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB). Marshall stiffness which is Marshall stability divided by flow is used to characterize the stiffness of the bituminous mixture. All mixture properties were optimized to obtain the optimum bitumen content of mixture.

The density, VMA, VFB, AV and Marshall stiffness are determined by data obtained from the Marshall specimen with the following equations. The equation assumed that $V_G + V_B + V_A = 1$ m^3.

$$Density = \frac{W_{air}}{W_{air} - W_{water}} \qquad \text{……..……………………..3-1}$$

$$VMA = (\frac{V_A + V_B}{1}) \times 100\% \qquad \text{…………………………..3-2}$$

$$VFB = (\frac{V_B}{V_B + V_A}) \times 100\% \qquad \text{…………………………..3-3}$$

$$AV = (1 - (V_G + V_B)) \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \; 3\text{-}4$$

$$MarshallStiffness = \frac{Stability}{Flow} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.3\text{-}5$$

where: W_{air} = Weight in air (gram)

W_{water} = Weight in water (gram)

V_G = Volume of aggregate (m^3)

V_B = Volume of bitumen (m^3)

V_A = Volume of air (m^3)

The Marshall test conducted was in accordance to BS 598:1985 [57]. It was conducted at room temperature. The sample was first immersed in water bath for 30 minute at 60^oC and then it was set up in the breaking head that has also been previously heated at 60^oC in the oven. Then the data of stability and flow were recorded. The Marshall apparatus is shown in Figure 3-15.

Figure 3-15 Marshall apparatus.

3.4 Performance Test

3.4.1 Permanent deformation

Permanent deformation of mixture variations were characterized by 2 different test i.e. creep test and wheel tracking test. The creep test and wheel tracking test were performed at different loads, simulation and they were subjected for the different types of specimens.

3.4.1.1 Creep test

The creep test was conducted by using the Universal Testing Machine (UTM) 4-19. It applies a repeated pulsed uniaxial stress/load to a mixture specimen and measures the resulting deformations in the same axis using Linear Variable Displacement Transducers (LVDTs). The data of the creep test were plotted to show the relationship between permanent deformation (mm) versus cycles.

This test was referred to British Standard DD226 with the following specifications:

i. Preload Option
   - Stress: 12 kPa
   - Holding Time: 120 s

ii. Loading Options
   - Wave shape: square pulse
   - Pulse width: 1,000 ms
   - Rest Period: 1,000 ms
   - Contact Stress: 2 kPa
   - Deviator Stress: 100 kPa

iii. Termination Option
   - Axial load reaches 30,000 micro-strain or 0% (if strain displayed as a percentage (%))
   - 1,800 loading cycles

The creep test was conducted at 40°C for 1 hour loading. The specimen was kept at the same temperature approximately 1 hour before testing. After setting up the specimen on the jig of the creep test apparatus, the specimen was preloaded at the test temperature for 2 minutes with a conditioning load of 12 kPa, and any axial deformation was recorded by the using the Universal Testing Machine (UTM) 4-19 software. The apparatus for the creep test is shown in Figure 3-16.

Figure 3-16 Creep test apparatus.

3.4.1.2 Wheel tracking test

The Wessex Wheel Tracker apparatus was used to determine the permanent deformation characteristic of the mixtures. It provides a fully automated test with automatic calculation of the tracking rates. The testing procedures conform to the specification of BS 598-110: 1998 [58]. The results are plotted as the rut depth versus cycles of loading.

An actual wheel of 200 mm diameter and 50 mm width with applied load of 520 N was used. The wheel run backward and forward across a bituminous specimen at the frequency setting of 42 wheel passes/minute for 45 minute loading. The total rut depth after a number of wheel passes was determined and recorded by the wessex software. The apparatus of wheel tracking are shown in Figure 3-17.

This test was carried out at 40°C. This temperature was used in order to evaluate the low stiffness response of the mixture that causes the permanent deformation or rutting. The wheel tracking results were compared to the creep results in order to verify the effect of filler on the permanent deformation of the bituminous mixture.

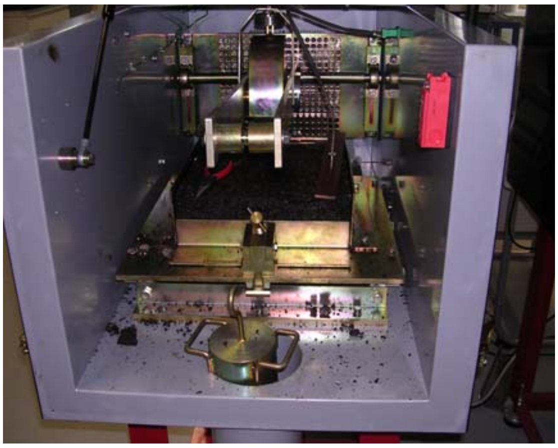


Figure 3-17 Wessex wheel tracker.

3.4.2 Fatigue

The investigation of bituminous mixture variations on the fatigue characteristic was determined by using the beam fatigue test of the Universal Testing Machine (UTM 4-21). This test applies repeated flexural bending to a bituminous specimen and measures the applied force and the resulting beam deflection using an on-specimen Linear Variable Displacement Transducers (LVDTs).

This test was conducted at 20°C and a control strain mode was used. The test temperature 20°C was chosen since the effect of air void content on fatigue life is more pronounced than at lower temperatures [59]. In the strain control mode, the deflection of the specimen is measured and the load is adjusted so that the specimen experiences a constant level of strain on each load cycle. A thin pavement with thickness of less than 60 mm is suggested for use in the control strain mode because failure will be more noticeable in this mode [60].

The parameters used in this test were:

i. Default poison ratio: 0.4

ii. Loading conditions:
  - Control mode: Sinusoidal strain
  - Pulse width: 200 ms
  - Frequency: 5 Hz
  - Peak to peak: 100 micro strain
  - Conditioning: 50 cycles

iii. Termination conditions
  - Termination stiffness: 50% of the initial stiffness or
  - Stop test after 1,000,000 cycles

The tabulated test data of the load and deformation were updated every 10th cycle by the UTM 4-21 software. The apparatus for the beam fatigue test is shown in Figure 3-18.

Figure 3-18 Beam fatigue apparatus.

3.5 Mixture Optimization

The optimization of mixtures was undertaken by ranking the mixtures according to their performance based on the engineering mixture properties and mixture performances.

The mixtures were ranked from 1 as the best to 18 as the worst. In the engineering mixtures properties ranking 1 was given to the mixtures with the high value of density, stability and stiffness, and low value of VMA and OBC. With respect to mixture performance, ranking 1 was given to the mixture with the lowest permanent deformation and lowest gradient on fatigue performance. The ranking of all aspects were then summarized.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter includes the presentation of test results along with the discussion for various properties investigated that includes property of constituent materials, followed by the consistency of the filler-bitumen system and lastly the characteristics and performances of the mixtures. The data analysis emphasized on the effect of the filler physical-chemical properties and the role of the filler on the permanent deformation and fatigue distress characteristics.

4.2 Aggregate and Bitumen Properties

The properties of aggregate and bitumen determined in this study were density and bitumen consistency. Both properties were used in either calculation or analysis for other parameters.

4.2.1 Density of aggregate and bitumen

The density of fine and coarse aggregate was determined using the Ultrapycnometer 1000, while the density of bitumen was determined using the calibrated pycnometer 25 ml volume. The density results of the aggregates and bitumen used are presented in Table 4-1. It was found that the granite crushed rock as coarse aggregate has a lower density than river sand which was used as fine aggregate. It was also noted that density of bitumen penetration grade 50-60 higher than that of bitumen penetration grade 80-100.

4.2.2 Bitumen Properties

The bitumen was observed in term of consistency tests namely penetration, softening point and ductility. The results of the consistency test are shown in Table 4-2. It indicates that the penetration value determined by the laboratory test have confirmed the specification of bitumen obtained from the bitumen company. This result ensures bitumen used in this study was still in good condition. The softening point results show that bitumen penetration grade 50-60 needs higher temperature to soften than bitumen penetration grade 80-100. The ductility results indicate that bitumen grade 80-100 has higher value than bitumen penetration grade 50-60. The entire consistency tests prove that bitumen penetration grade 50-100 has higher consistency than bitumen penetration grade 80-100.

4.3 Filler Properties

The physical and chemical properties of fillers are described separately in this section. The physical properties of filler include particle shape and density, while the chemical property is the chemical composition identification. The filler shape was characterized using the scanning electron microscopy (SEM) with 300 and 2000 times magnifications. These magnifications were used in order to obtain the convinced characteristic of filler particle shape. The fillers densities were measured using the Ultrapycnometer 1000, the chemical constituents were identified using the X-ray fluorescence (XRF) technique.

Table 4-1 Density of Constituent Materials

	Fine Aggregate	Coarse Aggregate	Bitumen Pen Grade 50-60	Bitumen Pen Grade 80-100
Density (g/cm^3)	2.76	2.71	1.036	1.033

Table 4-2 Consistency of Bitumen

	Penetration (dmm)	Softening Point (°C)	Ductility (cm)
Pen grade 50-60	55	57.1	100.7
Pen grade 80-100	90	46.3	128.1

4.3.1 Physical properties

According to studies conducted by Puzinauskas and Kallas [3], Heukelom [4], and some other researchers [6, 9, 12], they believed that the physical properties of filler influence the properties of bituminous paving mixtures. The filler densities contributes to the density of the composite bituminous mixture, while the shape of filler particle may influence the void filling mechanism [61].

4.3.1.1 Filler particle shapes

The physical appearance of cement, quarry dust and fly ash at 300 and 2000 magnifications are shown in Figure 4-1 to Figure 4-6. In general, cement has an irregular particle shape but somewhat spherical, flaky and elongated as shown in Figure 4-1 and Figure 4-2. On the other hand, Figure 4-3 and Figure 4-4 show that the particle shape of quarry dust is typically irregular and relatively big compared to the other fillers. However, fly ash particle looks somewhat spherical, with a small particle attached to the big particle as shown in Figure 4-5 and Figure 4-6. Therefore, cement and quarry dust can be categorized as irregular particles while fly ash as a spherical particle. These particle shape particular to each filler type is deemed to have an effect on the properties of the resulting bituminous mixtures.

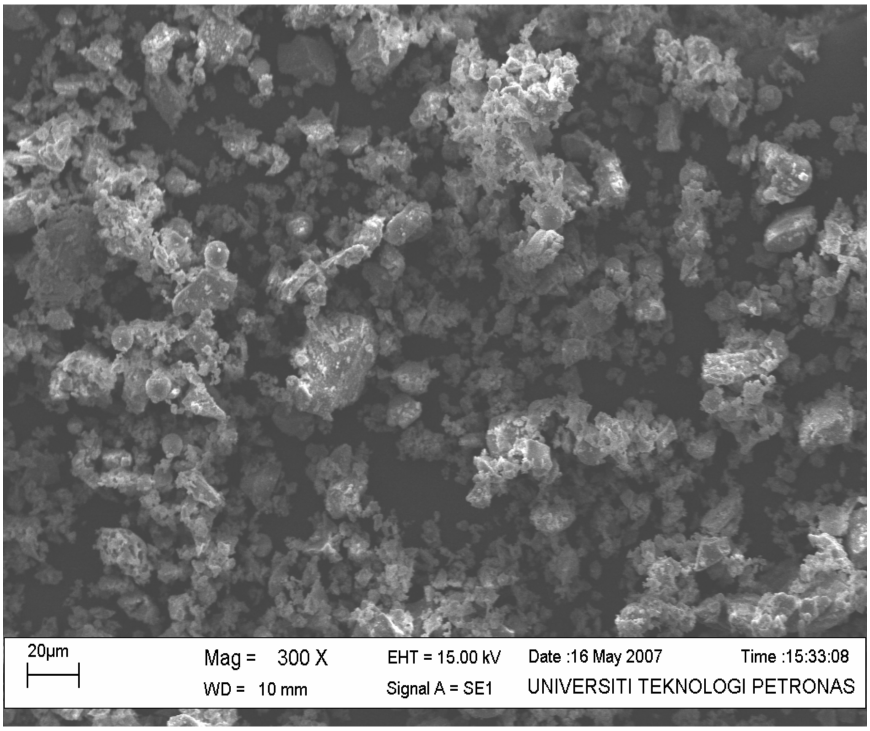


Figure 4-1 Physical appearance of cement (magnified 300x).

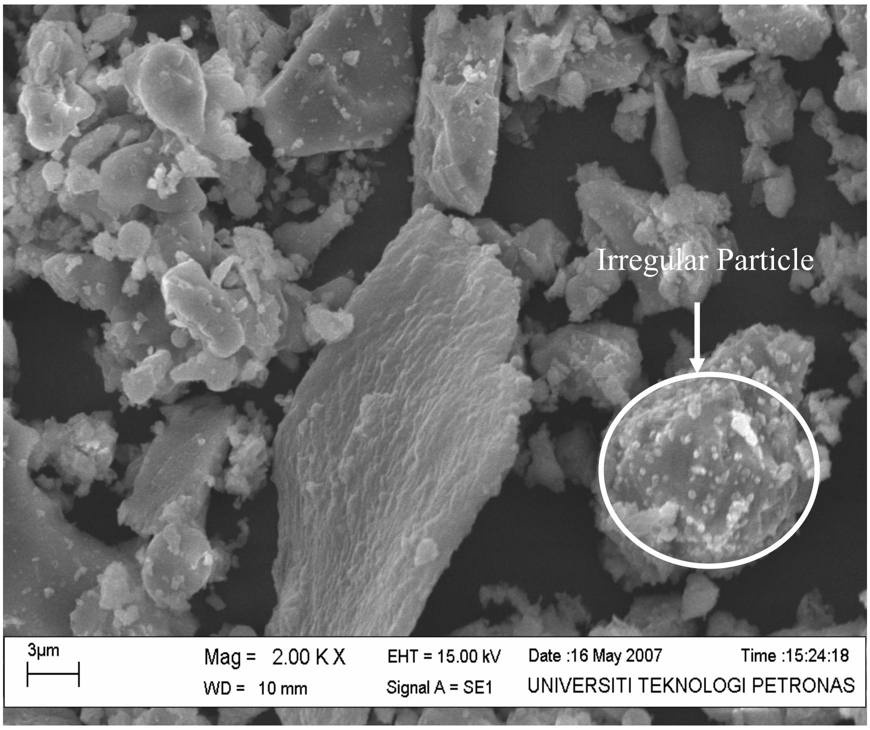


Figure 4-2 Physical appearance of cement (magnified 2000x).

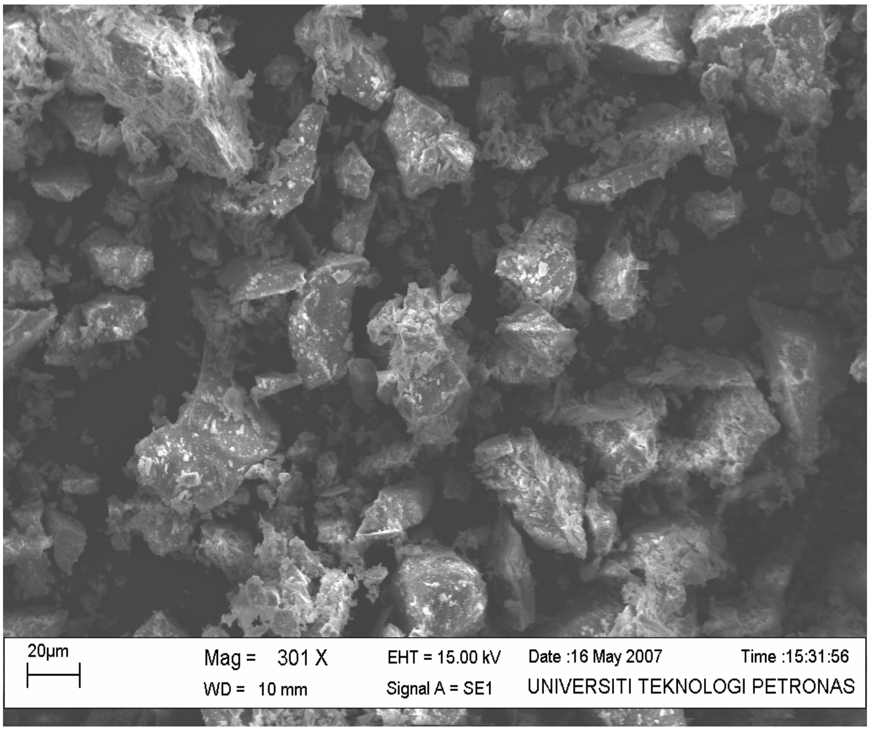


Figure 4-3 Physical appearance of quarry dust (magnified 301x).

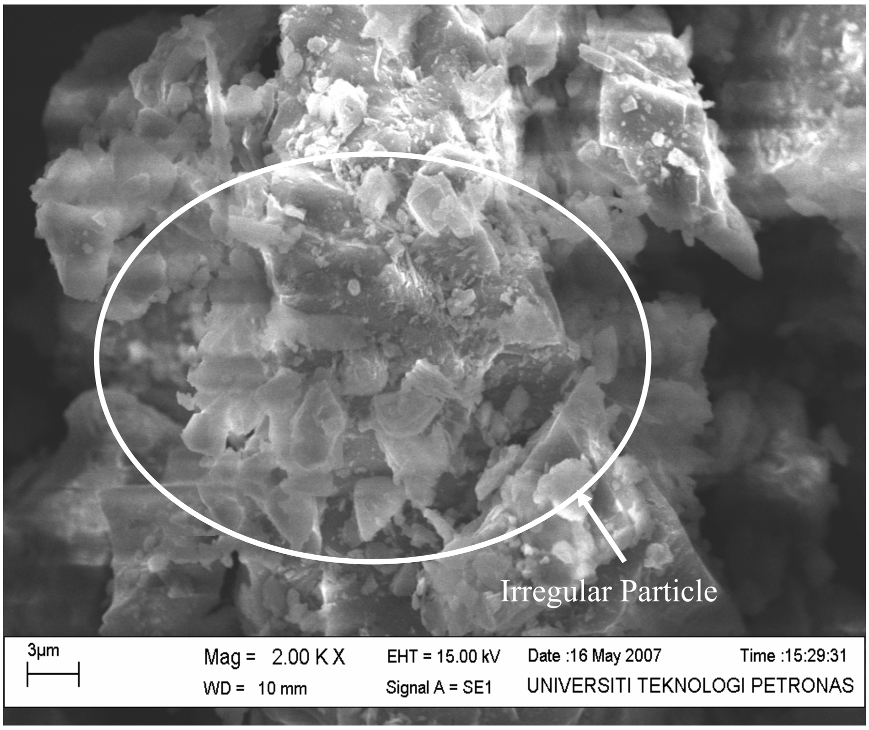


Figure 4-4 Physical appearance of quarry dust (magnified 2000x).

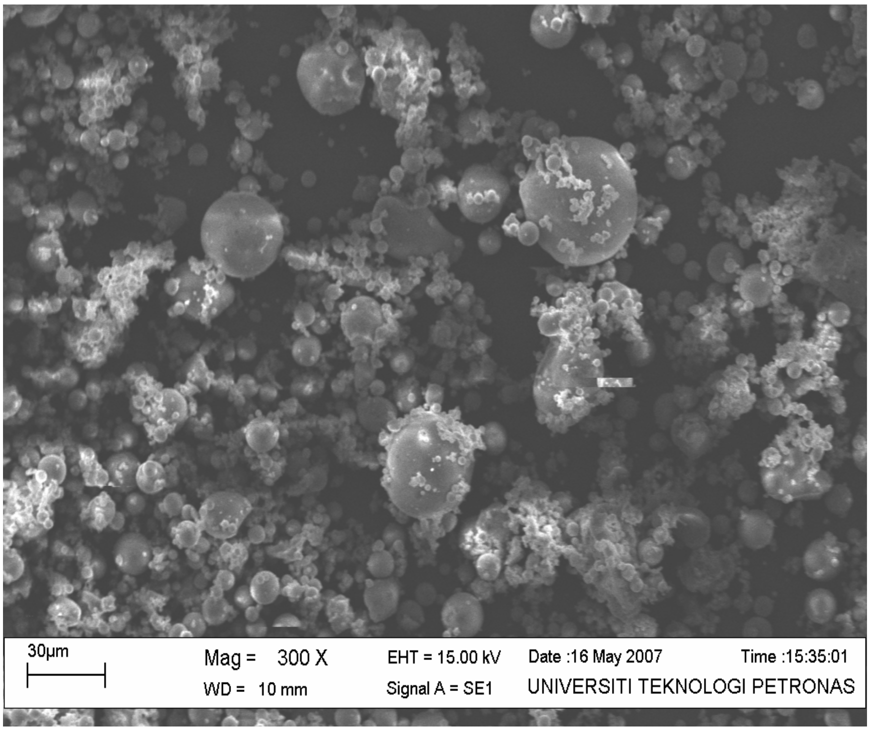


Figure 4-5 Physical appearance of fly ash (magnified 300x).

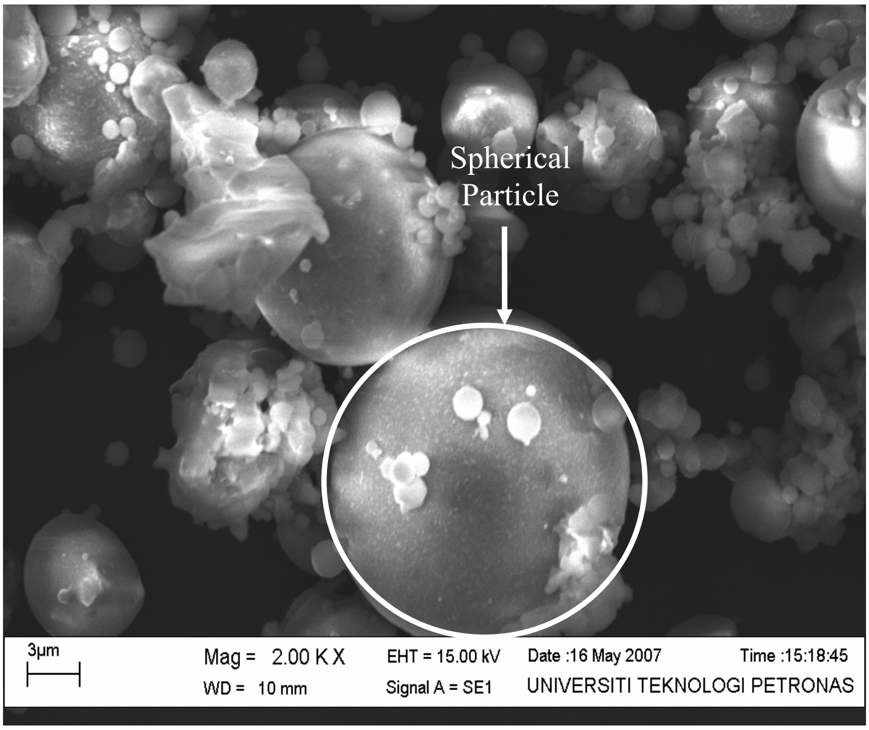


Figure 4-6 Physical appearance of fly ash (magnified 2000x).

4.3.1.2 Density of filler

Table 4-3 shows the density of the different fillers used. It can be seen that cement has the highest density, followed by quarry dust and fly ash. Those values indicate that with the same weight, fly ash has the largest volume, followed by quarry dust and cement. Warden et al [7] found that filler which has high density tends to produce bituminous mixtures that has high densities as well.

Table 4-3 Density of Fillers

Filler	Cement	Quarry Dust	Fly Ash
Density (g/cm^3)	3.21	2.78	2.45

4.3.2 Chemical properties

Like physical properties, the chemical composition of filler were also found to affect the properties and performance of bituminous paving mixtures [5]. The results of filler chemical composition of fillers are shown in Table 4-4. The results indicate that cement mainly consist of calcium oxide (CaO), whilst both quarry dust and fly ash mainly consist of silicon dioxide (SiO_2) or commonly known as silica. The other dominant compounds in cement are SiO_2, Al_2O_3 and Fe_2O_3, while those of quarry dust are Al_2O_3, K_2O and CaO, and those of fly ash are Al_2O_3, Fe_2O_3, CaO, respectively. Fly ash has the highest total percentage of SiO_2, Al_2O_3, and Fe_2O_3, i.e. 87.41% which is categorized as fly ash class F by ASTM C 618. While quarry dust consists 83.65% and cement consists 32.29% of SiO_2, Al_2O_3, and Fe_2O_3.

It is necessary to identify the dominant compound in fillers because the chemical characteristics of fillers strongly depend on the dominant characteristic of the compound. Based on the data in handbook of filler [24], the characteristic of each chemical compound that was identified in the fillers are shown in Table 4-5. CaO and K_2O are hydrophilic in nature, whilst SiO_2, Al_2O_3, and Fe_2O_3 are hydrophobic. Considering that bitumen is hydrophobic material, hydrophilic filler often has serious disadvantages. It tends to be susceptible in water and may cause an early stripping failure. Based on the hardness characteristic, alumina (Al_2O_3) has the highest hardness value, followed by silica (SiO_2) and hematite (Fe_2O_3). The hard constituents tend to increase the hardness of bituminous mixtures, hence increasing the stiffness of the mixtures. Thus, this study was emphasized to the effect of hydrophobic and high hardness constituent of filler which are silica and alumina on the properties and performance of the bituminous mixture.

From the data in Table 4-5, it is observed that hematite (Fe_2O_3) has the smallest particle size, followed by alumina (Al_2O_3) and silica (SiO_2). The size of particles also has some effect on the performance of paving mixtures. Smaller particle tend to decrease the void within the bituminous mixture, which consequently will increase the resistance to permanent deformation. The oil absorption property determines the effect of filler on the bitumen rheology. Alumina (Al_2O_3) has the highest oil absorption, followed by hematite (Fe_2O_3) and silica (SiO_2). Fillers that have low oil absorption characteristic have little effect on the viscosity. On the other hand, higher oil absorption makes the bitumen thicker. However, oil characteristic is not the only parameter that influences the viscosity, the particle shape also has an influence on this property.

Table 4-4 Filler Chemical Composition

Filler	CaO	SiO_2	Al_2O_3	Fe_2O_3	K_2O
Cement	61.20%	21.60%	5.41%	5.28%	0.54%
Quarry Dust	4.84%	67.70%	13.00%	2.95%	7.58%
Fly Ash	5.90%	51.80%	25.90%	9.71%	1.39%

Table 4-5 Characteristics of Compounds [24]

	Solubility in Water	Hardness (Mohr)	Particle Size (μm)	Oil Absorption (g/100g)
CaO	Hydrophilic	-	-	-
SiO_2	Hydrophobic	7	2-19	17-20
Al_2O_3	Hydrophobic	9	0.8-10	25-225
Fe_2O_3	Hydrophobic	3.8-5.1	0.013-0.105	10-35
K_2O	Hydrophilic	-	-	-

4.4 Filler-Bitumen System Properties

After material characterization, the effects of physical-chemical properties and proportion of fillers on the consistency of filler-bitumen system were analyzed. The consistencies of the system were tested in terms of its penetration, softening point and ductility properties. Each bitumen, grade 50-60 and 80-100 were mixed with the fillers, each in the F/B ratio of 0.75, 1.0, and 1.25 by weight. A total of 18 samples were prepared for the consistency tests.

4.4.1 Penetration

The penetration test results of filler-bitumen system are shown in Table 4-6 and are presented in graphs of penetration versus F/B ratio in Figure 4-7 and Figure 4-8. The penetration values are the average of three measurements for each test. It decreases with increasing F/B ratio for both bitumen grades, and proves that bitumen gets harder as the number of solid particle increases in the system. The results also indicate that penetration values for bitumen grade 50-60 are relatively lower than that for bitumen grade 80-100. This is related to the content of asphaltenes as a solid particle in bitumen penetration grade 50-60, which is higher than bitumen penetration grade 80-100. This inherently makes bitumen penetration grade 50-60 harder than that of bitumen 80-100.

Amongst the fillers, quarry dust is observed to have the lowest penetration value in both bitumen grades, followed by fly ash and cement respectively. In bitumen penetration grade 80-100, fly ash has almost the same penetration value with cement. However, fly ash incorporated bitumen penetration grade 50-60 produces a higher consistency than cement.

Quarry dust has irregular particle and high content of silica and alumina. It produces a high consistency as exhibited by the penetration of the resulting filler-bitumen system. On the other hand, fly ash with a high content of silica and alumina, and has spherical particles produces almost the same consistency on penetration in bitumen grade 80-100 as cement which has a lower content of silica and alumina and has irregular particles. It seems to suggest that both filler particle shapes and content of silica and alumina has an influence on the penetration values of the resulting filler-bitumen system. It was also found that either low compositions of silica and alumina were compensated in terms of the hardness (consistency) of the resulting filler-bitumen system with irregular particles or spherical particles with high content of silica and alumina. This indicates that silica and alumina which have high hardness value and the irregular particle which has good interlocking system can increase the consistency of filler-bitumen system.

The natural solid particles of penetration grade 50-60 bitumen were also found to significantly increase the consistency with the addition of fly ash. Based on this observation, it proves that the consistency of the filler-bitumen system on penetration is influenced by filler particles shape, filler chemical constituents and also bitumen types.

Table 4-6 Penetration Results of Filler-Bitumen System

	Penetration (dmm)					
Bitumen Type	Pen Grade 50-60			Pen Grade 80-100		
Filler/ Bitumen Ratio	0.75	1	1.25	0.75	1	1.25
Cement	36	31	26	46	46	43
Quarry Dust	32	24	23	46	42	39
Fly Ash	35	30	24	48	45	42

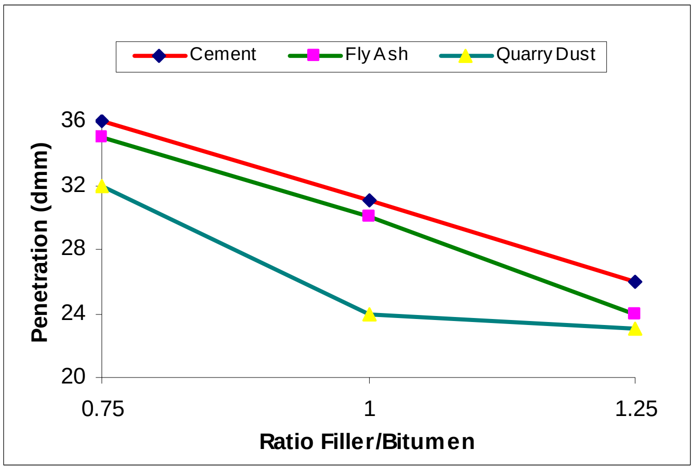


Figure 4-7 Penetration results for bitumen pen grade 50-60 mix.

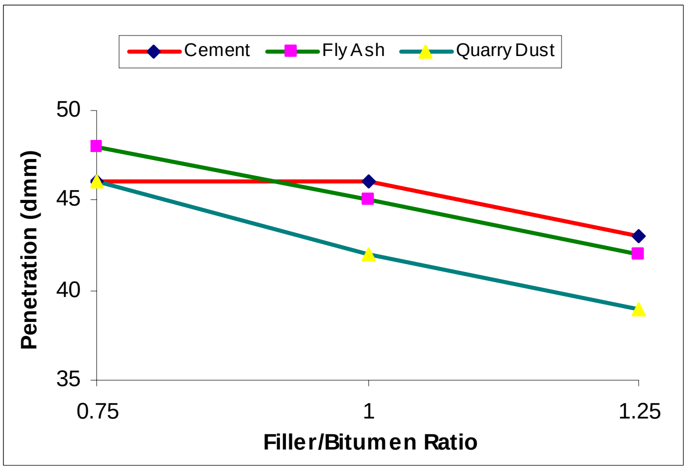


Figure 4-8 Penetration results for bitumen pen grade 80-100 mix.

4.4.2 Softening point

Another way of determining the consistency of bitumen is through the softening point test. The softening point results are shown in Table 4-7 and are presented graphically in Figure 4-9 and Figure 4-10. The results show that the softening point values increase with increasing F/B ratio for both bitumen penetration grades, since bitumen gets harder with increasing solid particle in the system. The results also indicate that the softening points of bitumen penetration grade 50-60 are relatively higher than bitumen penetration grade 80-100 except for the 50/cmt/0.75 mixture. This observation is attributed to the high content of solid particle (asphaltenes) in the grade 50-60 bitumen.

The cement bitumen system has the highest softening point (except at F/B 1.25) for penetration grade 80-100 bitumen, followed by quarry dust and fly ash. However, the consistency of fly ash mix increases greatly in penetration grade 50-60 bitumen. The fly ash-bitumen system displayed the highest softening point (except at F/B 1.25), followed by cement and quarry dust. A similar trend also appears in both bitumen penetration grades. Cement has a higher consistency than quarry dust. It seems that the irregularity of filler particle shape have an influence on the softening point trend.

Based on the observation, the irregular particles that are found in cement and quarry dust produce good consistency in softer bitumen as exhibited in the behavior of the penetration grade 80-100 bitumen. Spherical particles that are found in fly ash also produce good consistency in harder bitumen as shown in penetration grade 50-60 bitumen. It suggests that the consistency of the filler-bitumen system on softening point not only depends on the filler particle shape, but also on the bitumen grades.

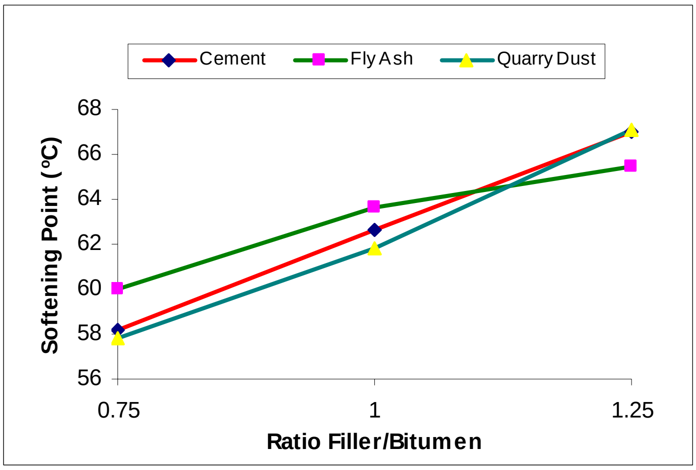


Figure 4-9 Softening point results for bitumen pen grade 50-60 mix.

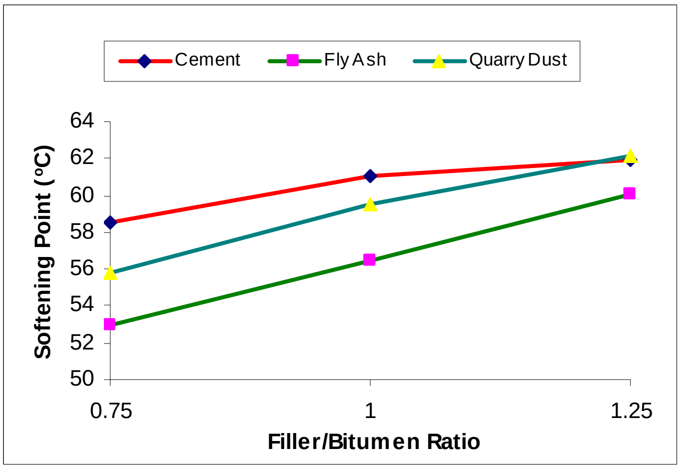


Figure 4-10 Softening point results for bitumen pen grade 80-100 mix.

Table 4-7 Softening Point Results of Filler-Bitumen System

	Softening Point (^oC)					
Bitumen Type	Pen Grade 50-60			Pen Grade 80-100		
Filler/ Bitumen Ratio	0.75	1	1.25	0.75	1	1.25
Cement	58.2	62.6	67	58.5	61	61.9
Quarry Dust	57.8	61.8	67.1	55.8	59.5	62.1
Fly Ash	60	63.6	65.5	53	56.5	60.1

4.4.3 Ductility

The cohesive strength of the bitumen system is exhibited by its ductility properties. It is the distance that the bitumen specimens stretched before undergoing failure, and was used as an alternative test in characterizing the filler-bitumen system. The ductility test results are shown in Table 4-8 and are presented graphically as the F/B ratio versus ductility for both bitumen grades used in this study in Figure 4-11 and Figure 4-12. The ductility values taken are the average of two specimens. The results indicate that ductility values decrease with increasing F/B ratio for both bitumen penetration grades. In general, the ductility of the filler-bitumen system using bitumen penetration grade 50-60 is lower than that of bitumen penetration grade 80-100. This observation can be attributed to the higher proportion of solid particle (asphaltene) in bitumen grade 50-60.

Quarry dust produces the lowest ductility values among the fillers. Deviation from the trend can be seen for 80/qd/0.75 and 50/qd/1.25. Portland cement and fly ash incorporated bitumen yield different results for both bitumen penetration grades 50-60 and 80-100. Fly ash produces the lowest consistency (or highest ductility) in bitumen grade 80-100 amongst all the fillers and cement has the lowest consistency in bitumen grade 50-60. The consistency of fly ash incorporated bitumen grade 50-60 increases significantly, and it makes the ductility of fly ash incorporated bitumen grade 50-60 lower than that in cement. This same trend was also found in the penetration test results.

Based on the ductility test results, the filler-bitumen system with quarry dust which is irregular particle and high content of silica and alumina produces the highest consistency. Using the bitumen penetration grade 80-100, cement that has irregular particles and low content of silica and alumina have the second highest consistency, followed by fly ash that has spherical particle shape and high content of silica and alumina. However, cement and fly ash in bitumen penetration grade 50-60 produced the opposite results. This suggests that filler particle shape, filler chemical composition and bitumen types also have an influence on the ductility results. The irregular particles shape tend to produce a high consistency filler-bitumen system in bitumen penetration grade 80-100 even though the filler has a low content of silica and alumina. However, in bitumen penetration grade 50-60, the compositions of silica and alumina have more significant effect than filler particle shape. This ascertains that the natural solid particles of bitumen affect the consistency of filler-bitumen system.

Deviation from the general trend that can be seen from the 50/qd/1.25 samples can be explained with the different slope of the ductility versus F/B ratio graph. Quarry dust seemed to have the lowest slope amongst the fillers, which means the variation of F/B ratio only slightly affects the ductility value. Quarry dust has a lower consistency (higher ductility) at the 50/qd/1.25 proportion than fly ash which exhibited higher slope. However, the exception to the trend in F/B 0.75 can't be clarified with this data. A study with a wider range of F/B ratio may explain this trend.

Table 4-8 Ductility Results of Filler-Bitumen System

	Ductility					
Bitumen Type	Pen Grade 50-60			Pen Grade 80-100		
Filler/ Bitumen Ratio	0.75	1	1.25	0.75	1	1.25
Cement	55.1	30.8	16.2	36.5	30	23.5
Quarry Dust	24.7	16.1	8.6	37.6	24.3	18.6
Fly Ash	31.1	19.3	6.8	39.5	35.7	30.3

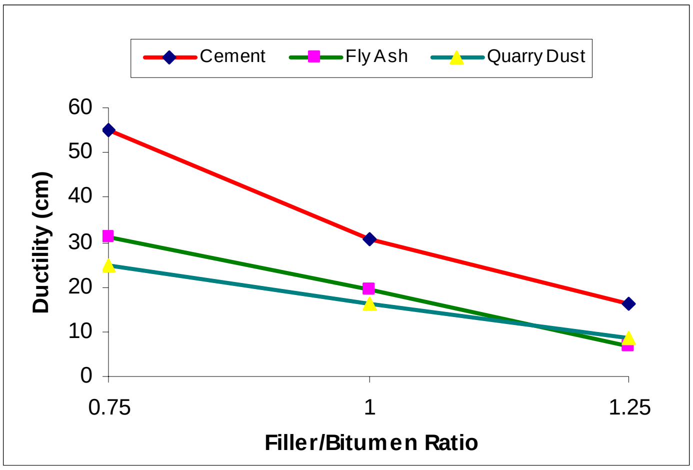


Figure 4-11 Ductility results for bitumen pen grade 50-60 mix.

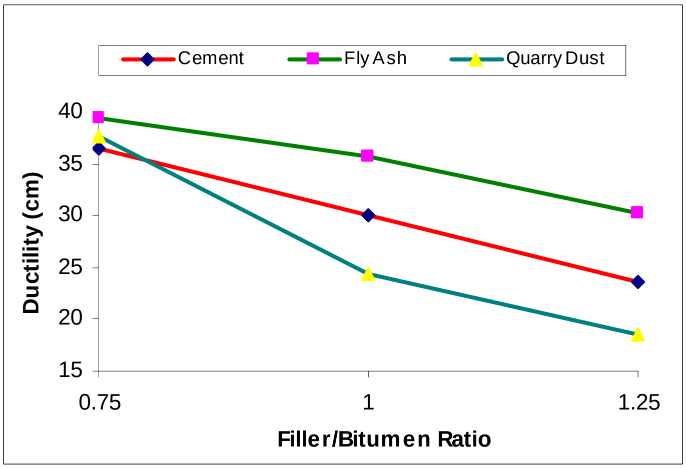


Figure 4-12 Ductility results for bitumen pen grade 80-100 mix.

Table 4-9 JKR Requirements for Asphaltic Concrete Mixtures Parameters [17]

Parameter	Wearing Course
Stability (S)	> 8000 N
Flow (F)	2.0-4.0 mm
Stiffness (S/F)	> 2000 N/mm
Air void in mix	3-5%
Void in aggregate filled with bitumen	70-80%

4.5 Properties of Mixture

The effect of filler physical-chemical properties and proportions on bituminous mixture properties are discussed in this sub-chapter. The percentage of bitumen used in the mixtures ranged from 4.5% up to 6.5%. The mixtures physical parameters i.e. density, voids in mineral aggregate (VMA), air voids (AV), voids filled with bitumen (VFB), stability, flow and stiffness were analyzed. The requirements for asphaltic concrete mixture parameters as set by Jabatan Kerja Raya (JKR) Malaysia Standards [17] are shown in

Table **4-9**. However, the JKR standard does not provide for the VMA requirements. Thus, the limitation of VMA in this study is referred to the Asphalt Institute Design Criteria [53] subjected to 5% air voids as shown in Table 4-10.

Table 4-10 Asphalt Institute Design Criteria for VMA subjected to 5% Air Voids [53]

Maximum Size of Aggregate (mm)	Minimum Voids in Mineral Aggregate (%)
25	13
19	14
12.5	15
9.5	16
4.75	18
2.36	21
1.18	23.5

4.5.1 Density

The resulting densities of the prepared bituminous paving mixture are presented in Figure 4-13 and Figure 4-14. As observed from both figures, the density increases with increasing bitumen content until a maximum density is reached and then it starts to decrease at higher bitumen content. However, in several mixture variations i.e. 50/cmt/0.75, 50/cmt/1, 50/qd/0.75, 80/cmt/0.75, 80/cmt/1, 80/cmt/1.25, 80/qd/0.75 and 80/qd/1, the resulting density is still increasing at 6.5% of bitumen content.

The maximum density of each mixture variation is summarized in Table 4-11. The results show that all the mixtures densities ranged between 2.312 to 2.381 (g/cm^3). The maximum density of the mixture is observed to have just slightly increased with increasing F/B ratio, bitumen hardness, and filler density. This suggests that different fillers, F/B ratios and bitumen types do not influence the density of mixture significantly.

The bitumen content at maximum density of all mixture variations is shown in Table 4-12. The results indicate that the bitumen content at maximum density decreased with increasing F/B ratio. The mixtures using the penetration grade 50 bitumen was found to have lower bitumen requirement than mixtures using bitumen penetration grade 80-100 except for 50/fa/0.75 and 50/fa/1.0 mixes. Comparing the filler types used, cement needed the highest amount of bitumen, followed by quarry dust and fly ash in order to obtain the maximum density. Cement and quarry dust that have irregular particles require higher bitumen than fly ash that has spherical particles. From these results, it can be concluded that different filler, F/B ratios and bitumen types affects the required bitumen content of mixtures at maximum density, even though they do not influence the mixture density significantly.

Table 4-11 Maximum Density of Bituminous Mixtures

Maximum Density (g/cm^3)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	2.321	2.345	2.366	2.312	2.330	2.352	2.320	2.323	2.342
Pen 80-100	2.350	2.375	2.381	2.319	2.340	2.352	2.317	2.326	2.339

Table 4-12 Bitumen Content at Maximum Density of Bituminous Mixtures

Bitumen Content at Maximum Density (%)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	6.50	6.5	6.1	6.5	6.3	6.1	6.4	6.3	5.8
Pen 80-100	6.50	6.5	6.5	6.5	6.5	6.25	6.3	6.15	5.85

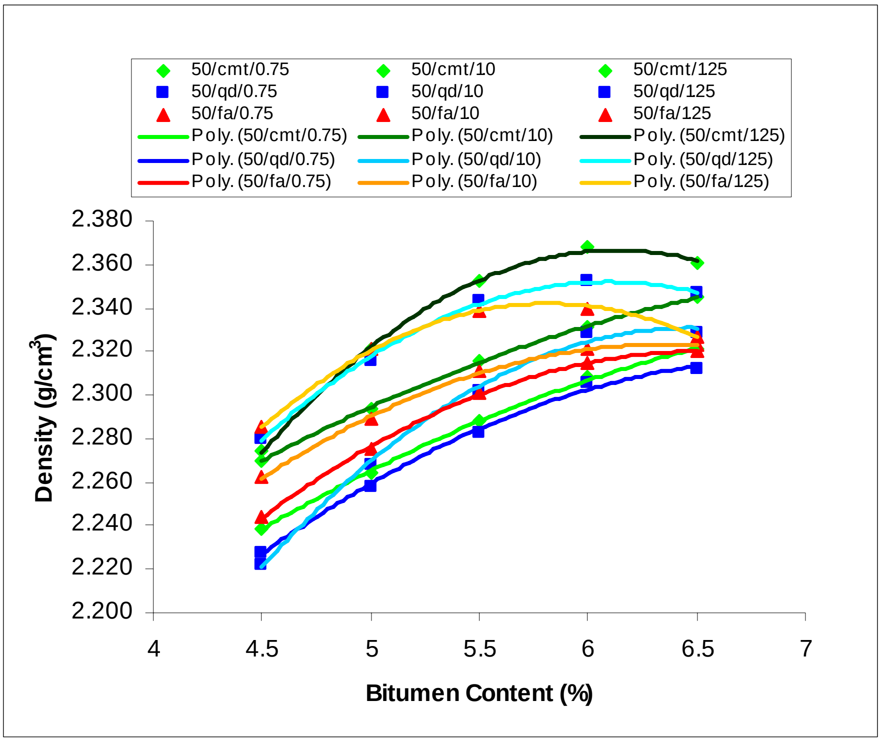


Figure 4-13 Density of bituminous mixtures for bitumen pen grade 50-60.

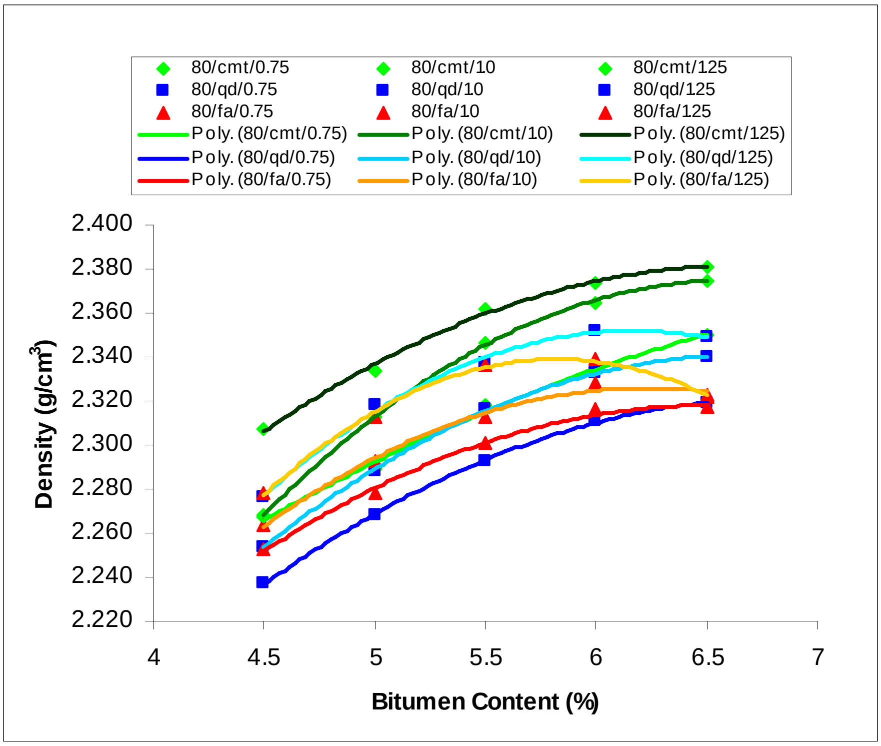


Figure 4-14 Density of bituminous mixtures for bitumen pen grade 80-100.

4.5.2 Voids in mineral aggregate (VMA)

Voids in mineral aggregate (VMA) is the percentage of voids volume to the total volume of mix. VMA is important to provide sufficient space between aggregate that can be filled by bitumen in order to obtain maximum strength of the design mixture. Since JKR standard does not provide the VMA requirements of bituminous mixtures, therefore the standard by Asphalt Institute is used in the VMA characterization of asphaltic concrete mixture. According to the standard, a minimum 13% of VMA is required for the ACW20 mix design that has 25 mm of maximum aggregate size.

The VMA results for all mixtures are shown in Figure 4-15 and Figure 4-16. The results show that all the mixtures meet the VMA requirements of the Asphalt Institute. Both figures exhibit a decreasing trend of VMA with increasing bitumen content until minimum VMA values are reached and then it continues to increase for the higher bitumen content.

The minimum VMA for all mixtures is presented in Table 4-13. It is observed that the minimum VMA decreases with increasing F/B for both bitumen penetration grades. It also exhibits that bitumen grade 50-60 mixes have a higher VMA than bitumen grade 80-100 mixes, except for 50/qd/1.25 and 50/fa/1.25 mixes. Among the different filler types, fly ash incorporated bituminous mixtures has the lowest VMA. Quarry dust incorporated with bituminous mixtures has lower VMA than cement, except for 80/qd/0.75 and 80/qd/1.0 mixes.

The higher proportion of fine material in the mixture is found to decrease the VMA in the mixture. The spherical particles of fly ash that is believed to produce lower viscosity filler-bitumen system and low viscosity of bitumen grade 80-100 produce low VMA mixtures. These results seem to conclude that VMA is greatly influenced by the viscosity of the filler-bitumen system. However, this study does not include the viscosity test. The addition of viscosity test for further study is required to verify the VMA results and may also describe some exceptions in the VMA results. This VMA results prove the study conducted by Puzinauskas and Kallas [3], which has suggested the shape of filler as possible factors affecting the VMA results.

The bitumen content at minimum VMA for all mixtures are shown in Table 4-14. The results show that bitumen content decreases with increasing F/B ratio. Fly ash incorporated bituminous mixture indicates the lowest required bitumen content followed by quarry dust and cement for all ratios. Spherical particle of fly ash may cause the reduction of the required bitumen content. In general, the results exhibit low VMA in the bituminous mixtures requires low bitumen content. Study by Dukatz and Anderson [6] indicated that the required amount of bitumen is possibly replaced by filler material.

Table 4-13 Minimum VMA of Bituminous Mixtures

Minimum Voids in Mineral Aggregate (%)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	21.2	20.6	19.5	20.9	20.2	19.1	20.0	19.6	18.5
Pen 80-100	20.3	19.4	19.3	20.6	19.9	19.2	20.0	19.4	18.6

Table 4-14 Bitumen Content at Minimum VMA of Bituminous Mixtures

Bitumen Content at Minimum VMA (%)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	6.4	6.1	5.7	6.15	6.05	5.65	5.95	5.75	5.5
Pen 80-100	6.4	6	5.75	6.05	6	5.7	5.85	5.7	5.55

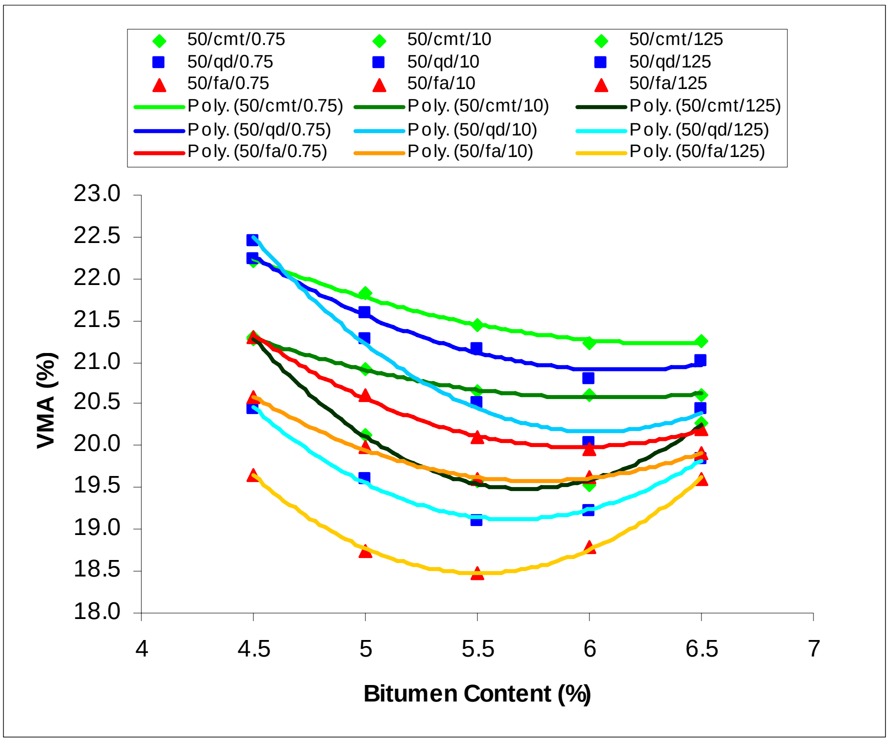


Figure 4-15 VMA of bituminous mixtures for bitumen pen grade 50-60.

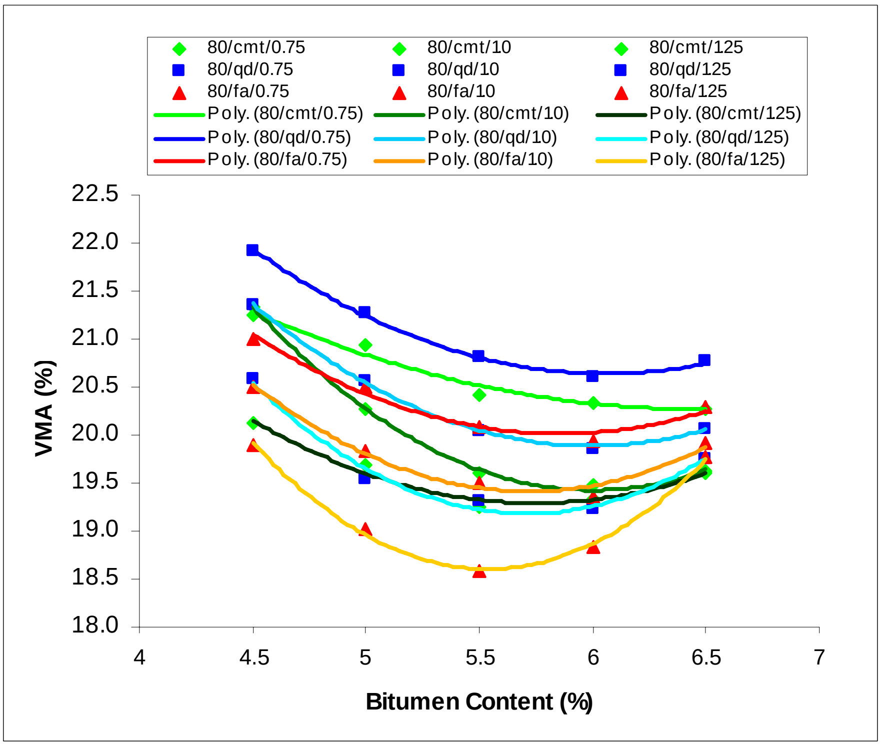


Figure 4-16 VMA of bituminous mixtures for bitumen pen grade 80-100.

4.5.3 Voids filled with bitumen (VFB)

Void filled with bitumen (VFB) is the percentage of voids filled by bitumen. The requirement of VFB according to JKR standard is in the range of 70-80%. For the purpose of this study, a VFB of 70% was selected.

The VFB results of all mixtures are shown in Figure 4-17 and Figure 4-18. An increasing trend of VFB is observed with increasing bitumen content for all mixtures. In order to fulfill the 70% requirement for VFB, different bitumen content is required for each mixture. The required bitumen content for every mixture variations is shown in Table 4-15. As can be observed from the table, generally the required bitumen content decreases with increasing F/B ratio. The results also show that the mixtures of bitumen penetration grade 50-60 require slightly higher bitumen content than the mixtures using bitumen penetration grade 80-100 and a significant difference is observed in cement incorporated bituminous mixtures. Among the three types of filler used, fly ash incorporated bituminous mixtures have the lowest required bitumen content. Cement and quarry dust however show different behaviors for different bitumen grades. Cement incorporated mixture of bitumen penetration grade 50-60 require higher bitumen content than quarry dust. While the opposite is observed for bitumen penetration grade 80-100 mixture variations.

The results prove that the proportion of filler can replace certain amount of bitumen in the mixtures. It is observed that spherical particle generally reduces the bitumen requirement for the mixture at the same percentage of VFB i.e. 70%. For mixtures with irregular particles of fillers, it is observed that the required bitumen content is higher than the spherical particle shape particles. These observations are consistent with the VMA results which indicate lower requirement for bitumen for spherical shaped particles mixture.

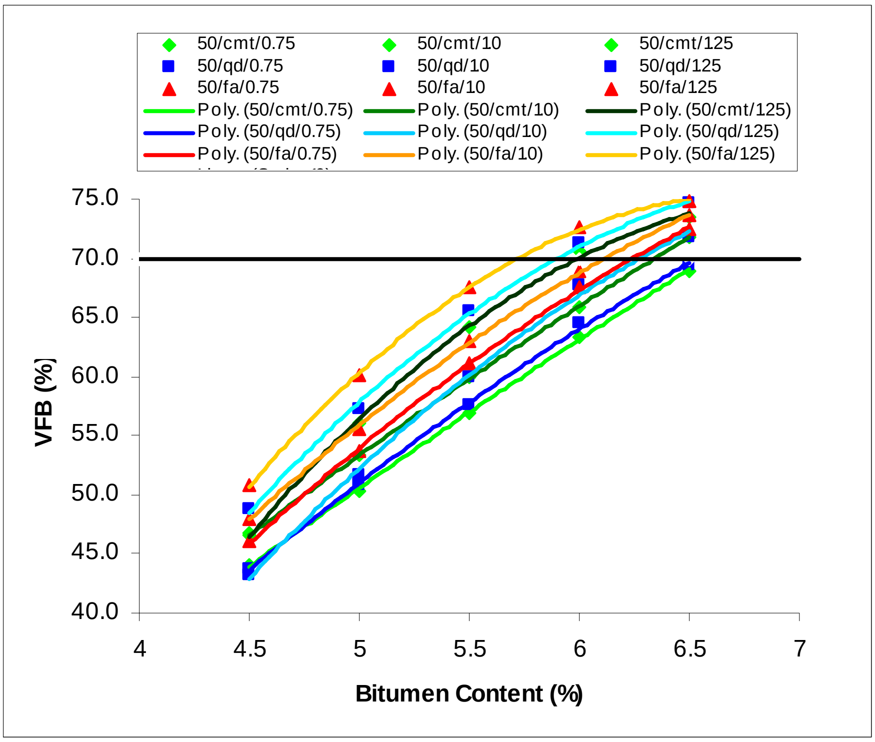


Figure 4-17 VFB results of bituminous mixtures for bitumen pen grade 50-60.

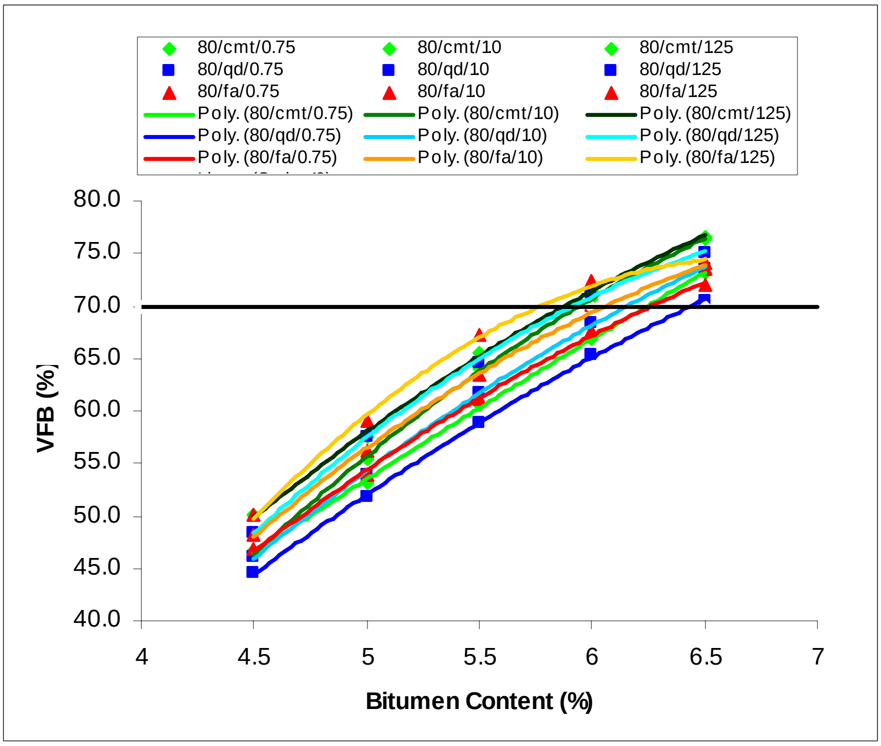


Figure 4-18 VFB results of bituminous mixtures for bitumen pen grade 80-100.

Table 4-15 Bitumen Content at 70% VFB of Bituminous Mixtures

Bitumen Content at 70% VFB (%)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	6.5	6.35	6	6.5	6.25	5.9	6.25	6.1	5.7
Pen 80-100	6.25	5.95	5.85	6.45	6.15	5.9	6.25	6.05	5.75

4.5.4 Air voids (AV*)*

Air voids (AV) is the percentage of air volume to the total volume of compacted bituminous mixtures. High air voids tend to decrease the performance of bituminous mixtures. JKR standard sets the requirement of air voids from 3% up to 5%. However, all the design mixtures prepared in this work, with the exception of a few, have air voids more than 5%. Therefore, the air voids was not used in the OBC determination. Those mixtures that have air voids below 5% are 50/qd/1.25, 50/fa/1.25, 80/cmt/1, 80/cmt/1.25, and 80/qd/1.25.

The air voids results for all mixture variations are presented in Figure 4-19 and Figure 4-20. It is observed that air voids decrease with increasing bitumen content and F/B ratio. Bitumen grade 50-60 mixtures are observed to have higher air voids than bitumen grade 80-100 mixtures if incorporated with cement and quarry dust. However, the opposite result is observed for fly ash mixtures. Comparing the filler types at 6.5% bitumen content, fly ash incorporated bitumen grade 50-60 mixtures and cement incorporated bitumen grade 80-100 mixtures have produced the lowest air voids in all F/B ratios.

The results prove that fineness of the material help decrease the mixture air voids. The spherical particles of fly ash produce the lowest air voids in bitumen grade 50-60, while the irregular particles of cement produce the lowest air voids in bitumen grade 80-100. These trends are similar with the softening point results, where cement and quarry dust have good consistency in softer bitumen i.e. bitumen penetration grade 80-100, while spherical particles that are found in fly ash have a good consistency in harder bitumen i.e. bitumen penetration grade 50-60. It seems to suggest that softening point results may correlate well the air voids results. The air voids are observed not only to depend on filler type but also on the bitumen type. Spherical particles of fly ash incorporated with harder bitumen (grade 50-60) produce lower air voids while the irregular particles of cement and quarry dust need softer bitumen to produce lower air voids.

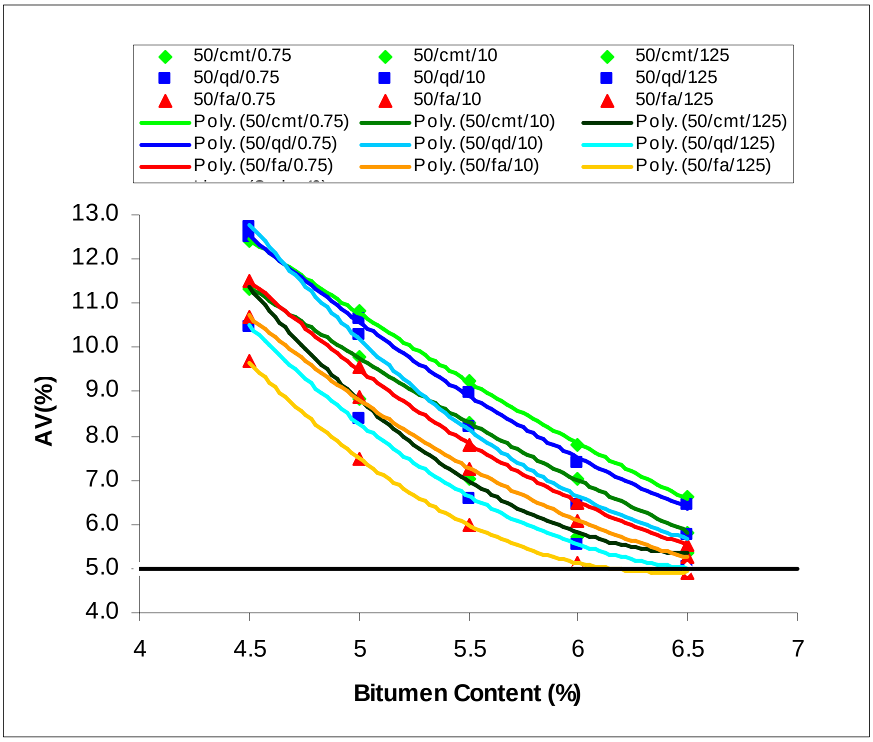


Figure 4-19 Air voids of bituminous mixtures for bitumen pen grade 50-60.

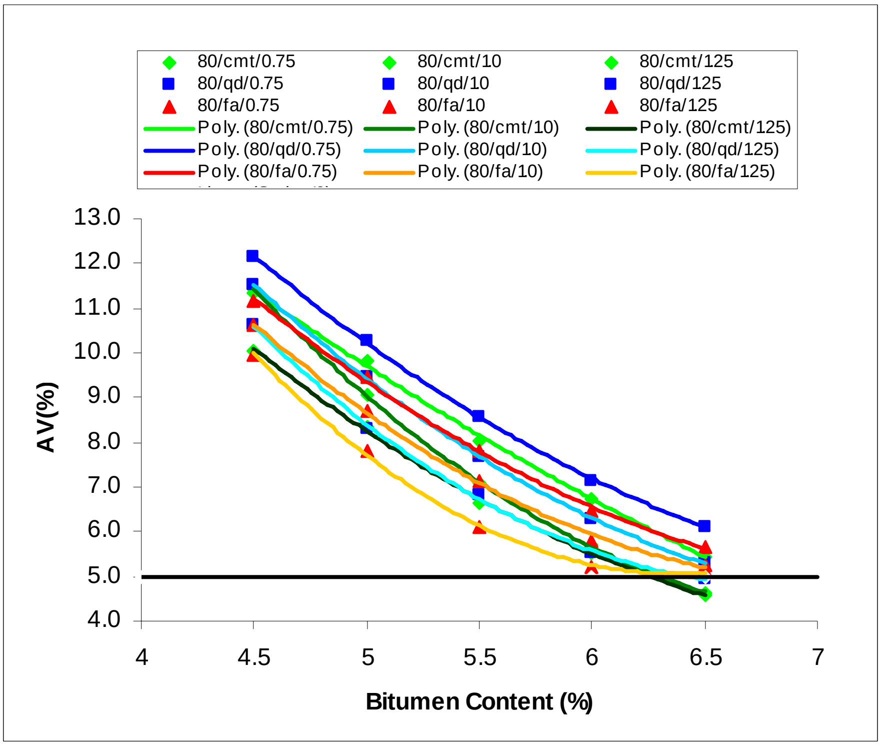


Figure 4-20 Air voids of bituminous mixtures for bitumen pen grade 80-100.

4.5.5 Stability

Stability is the parameter that expresses the strength of compacted mixtures. It is determined by the maximum load that the specimens could withstand at a loading rate of 50.8 mm/minute (2 inch/minute). JKR standard sets the requirement of stability higher than 8 kN for high traffic loading design. The stability results of all the mixtures are shown in Figure 4-21 and Figure 4-22. From both figures, it can be observed that stability increases with increasing bitumen content until it reaches an maximum value and then it starts to decrease at much higher bitumen content.

The maximum stability values of all mixtures are shown in Table 4-16. As can be seen from this table, the maximum stability of the mixture does not exhibit a consistent behavior with increasing F/B ratio. The maximum stability against F/B ratio have three different trends. First, the maximum stability increases with increasing F/B ratio for fly ash incorporated of both bitumen grades and quarry dust incorporated mixtures of bitumen grade 50-60. Second, the maximum stability have minimum value at F/B 1.0 for cement incorporated bituminous mixtures for penetration grade 50-60 bitumen and quarry dust incorporated bituminous mixtures for penetration grade 80-100 bitumen. Third, the maximum stability has maximum value for F/B 1.0 for the cement incorporated bituminous mixtures for penetration grade 80-100 bitumen.

The bituminous mixtures for bitumen grade 50-60 are observed to have higher maximum stability than bituminous mixtures for bitumen grade 80-100, except for 50/qd/0.75 mixtures. The highest stability of mixtures with bitumen grade 50-60 for different F/B ratios is observed for different type of filler. Cement has the highest maximum stability for F/B 0.75, fly ash for F/B 1.0, and quarry dust for F/B 1.25. However, in bitumen grade 80-100 mixtures, consistent results are observed, quarry dust mixes have the highest maximum stability, followed by cement and fly ash except for 80/cmt/1.25 mixture, which has a lower maximum stability than fly ash.

However, in general fly ash has the highest maximum stability in bitumen grade 50-60 mixtures, while quarry dust has the highest maximum stability in bitumen grade 80-100. This behavior also occurs from the softening point test and air voids results. The results prove an earlier study conducted by Jacobs [27] which suggest that Marshall stability correlate very well with the softening point. This behavior suggests that filler particle shape, chemical composition and types of bitumen influence the mixture stability. The effect of bitumen type to mixture stability is attributed to the natural solid particle (asphaltenes) of the bitumen.

The bitumen content of all the mixtures was compared against the maximum stability. The data are tabulated in Table 4-17. It is observed that the bitumen content decreases with increasing F/B ratio. The mixtures for bitumen grade 80-100 require less bitumen than mixtures for bitumen grade 50-60 except for 80/cmt/1.0 and 80/qd/1.25 mixtures. Comparing the fillers, fly ash incorporated bituminous mixtures require the lowest bitumen content at maximum stability, followed by quarry dust and cement. Fly ash that has spherical particles required the least bitumen. On the other hand, quarry dust and cement that have irregular particles have almost the same requirement for bitumen. This trend is also observed in other mixture properties such as density, VMA and VFB. This observation suggests that the shape of filler particles has a significant influence on the required bitumen in order to obtain maximum stability.

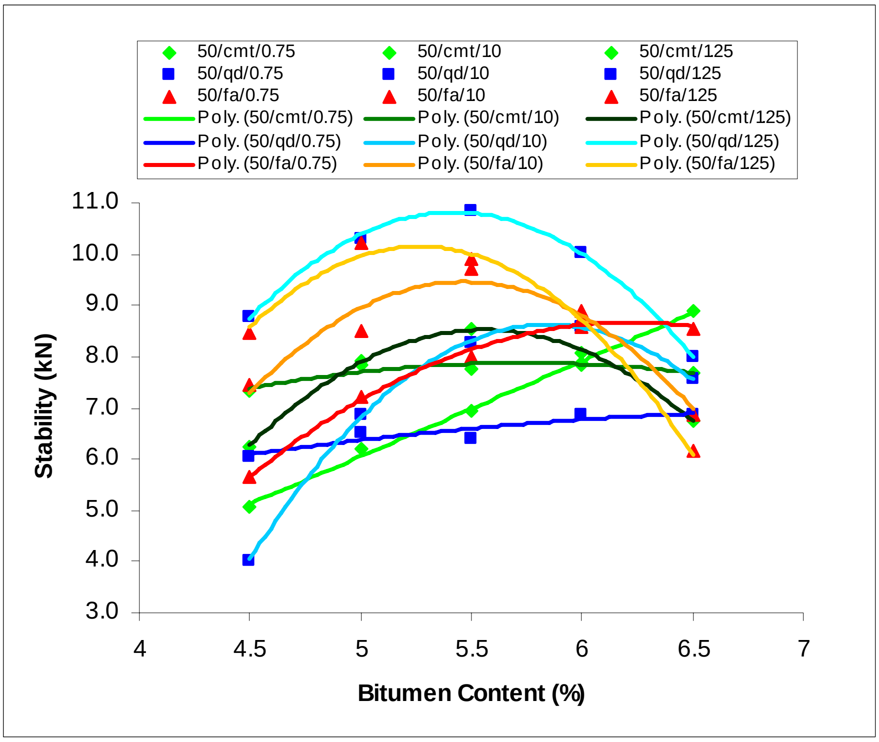


Figure 4-21 Stability of bituminous mixtures for bitumen pen grade 50-60.

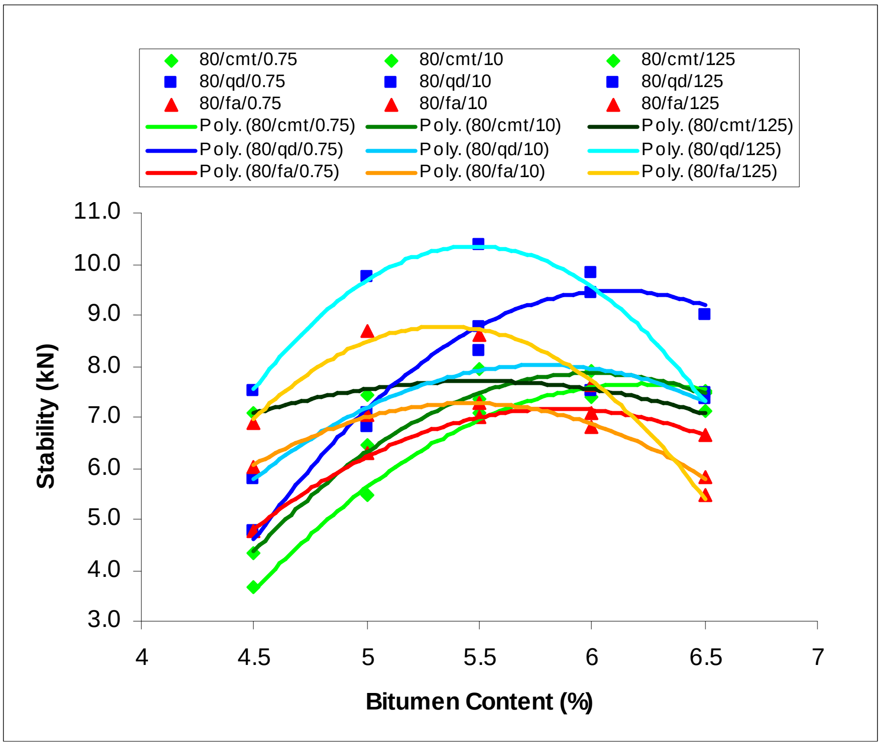


Figure 4-22 Stability of bituminous mixtures for bitumen pen grade 80-100.

Table 4-16 Maximum Stability of Bituminous Mixtures

Maximum Stability (kN)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	8.9	7.9	8.5	6.9	8.6	10.81	8.7	9.5	10.15
Pen 80-100	7.65	7.86	7.70	9.48	7.94	10.35	7.16	7.27	8.78

Table 4-17 Bitumen Content at Maximum Stability of Bituminous Mixtures

Bitumen Content at Maximum Stability (%)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	6.5	5.75	5.55	6.5	5.85	5.45	6.2	5.45	5.25
Pen 80-100	6.2	6	5.5	6.1	5.55	5.5	5.85	5.45	5.35

4.5.6 Flow

Flow is the deformation on the highest strength of specimen at a loading rate of 50.8 mm/minute (2 inch/minute). However, it does not represent permanent deformation performance since it does not perform the analogous loading mechanism of permanent deformation. It is only used as one of the considered parameters to determine the OBC of the bituminous mixtures. The JKR standard sets the flow requirement range from 2 up to 4 mm. The flow for all mixtures was set at 2 mm.

The flow results of all bituminous mixtures are shown in Figure 4-23 and Figure 4-24. The results indicate that generally flow increases with increasing bitumen content. The required bitumen content at 2 mm flow for all mixtures is listed in Table 4-18. In order to achieve 2 mm flow, the required bitumen content for mixtures with bitumen grade 80-100 are observed to be lowerr than that of mixtures with bitumen grade 50-60. The flow results compared against the F/B ratio exhibits two different trends. First, the required bitumen is minimum for F/B 1.0 for quarry dust incorporated bitumen grade 50-60 mixture and fly ash incorporated bitumen grade 80-100 mixture.

The rest of the mixtures exhibit the required bitumen content decreasing with increasing F/B ratio. Among the filler incorporated bituminous mixtures, fly ash mixtures have the highest required bitumen content to achieve 2 mm flow, except 50/fa/1.25 and 80/fa/1.0 mixtures. This trend is opposite to that found in density, VMA, VFB and stability results where the spherical particle of fly ash required low bitumen content than the irregular particle of cement and quarry dust.

In order to achieve 2 mm flow, bitumen grade 80-100 which is softer than bitumen grade 50-60, requires lower amount of bitumen. The composition of asphaltene or natural solid particle which controlled the hardness of bitumen is suggested to affect this result. Based on Figure 4-23 and Figure 4-24, fly ash mixtures require more bitumen to achieve the required 2 mm flow. Cement and quarry dust however portrayed the opposite trend. Based on these results, it is suggested that spherical particle shape fly ash mixtures produce lower flow than mixtures incorporating irregular particles of filler. Thus, in order to obtain the same 2 mm flow, fly ash needs higher bitumen content than cement and quarry dust. The results prove that flow is influenced by filler particle shape and bitumen grade.

Table 4-18 Bitumen Content of 2 mm Flow

Bitumen Content of 2 mm Flow (%)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	6.05	5.65	5.65	6.05	5.25	5.65	6.4	5.85	5.65
Pen 80-100	5.8	5.15	4.9	-	5.6	5.1	6.3	5.45	5.1

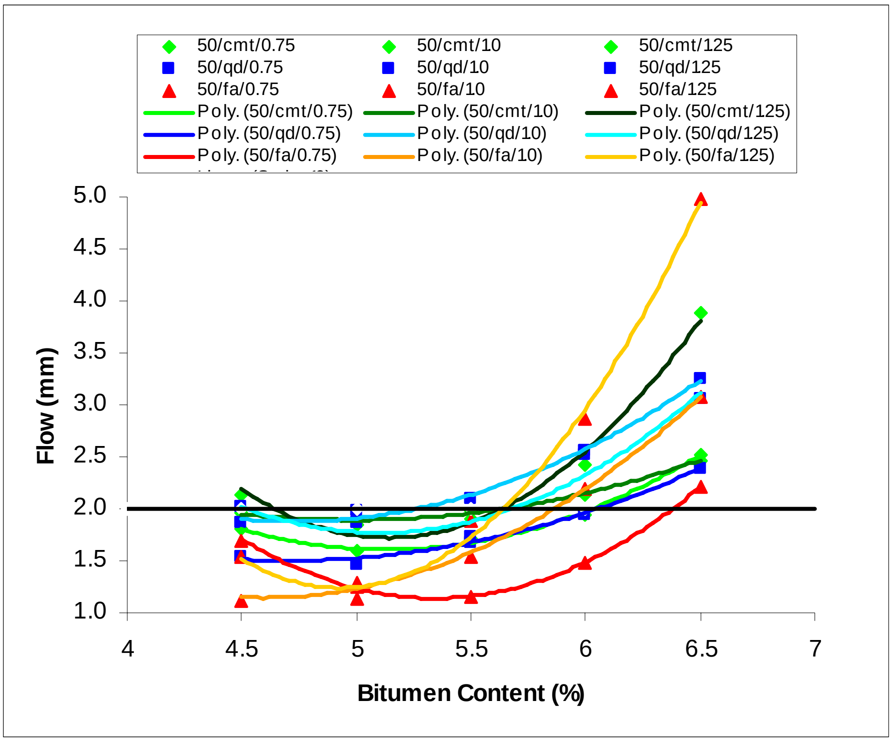


Figure 4-23 Flow of bituminous mixtures for bitumen pen grade 50-60.

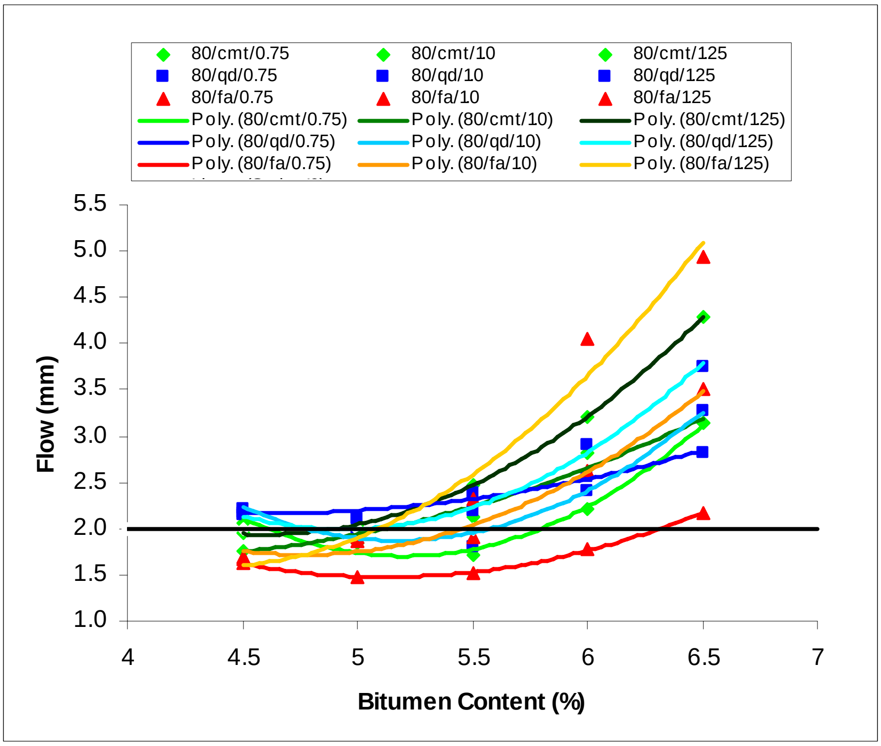


Figure 4-24 Flow of bituminous mixtures for bitumen pen grade 80-100.

4.5.7 Stiffness

The stiffness parameter is considerably reliable for determining the mixtures characteristic besides the stability and flow. The stiffness results for all mixtures are shown in Figure 4-25 and Figure 4-26. The results show that stiffness increases with increasing bitumen content until it reaches a maximum stiffness and then starts to decrease.

The maximum stiffness values of all mixtures are tabulated in Table 4-19. The bitumen grade 50-60 mixtures are observed having higher stiffness than bitumen grade 80-100, except for 50/cmt/0.75 and 50/qd/1 mixtures. The mixtures show that minimum stiffness is reached at F/B 1.0, except for cement-bitumen grade 50-60 mixtures and quarry dust-bitumen grade 80-100 mixtures. Among the fillers used, fly ash-bitumen grade 50-60 and quarry dust-bitumen grade 80-100 mixtures have the highest stiffness, while cement incorporated bituminous mixtures have the lowest stiffness for both grades. This behavior is also observed when analyzing the softening point, air voids and stability results. The highest mixture stiffness is observed for the 50/fa/1.25 mix.

The fact that spherical particles produce high stiffness mixture if incorporated with high asphaltene bitumen, and the irregular particles produce high stiffness if incorporated with low asphaltene bitumen, seems to suggest that the filler particle shape and natural solid particle of bitumen influence the stiffness results. On the other hand, the highest stiffness of bituminous mixtures incorporated with quarry dust and fly ash seemed to be attributed to the high percentage of silica and alumina. The high percentage of alumina and silica is observed to increase the consistency of the resulting filler-bitumen system as shown in penetration test results. The high consistency filler-bitumen is believed to increase the stiffness of mixtures. Thus, it can be concluded that stiffness of the mixtures is influenced not only by filler particle shapes and type of bitumen, but also the chemical composition of the filler used.

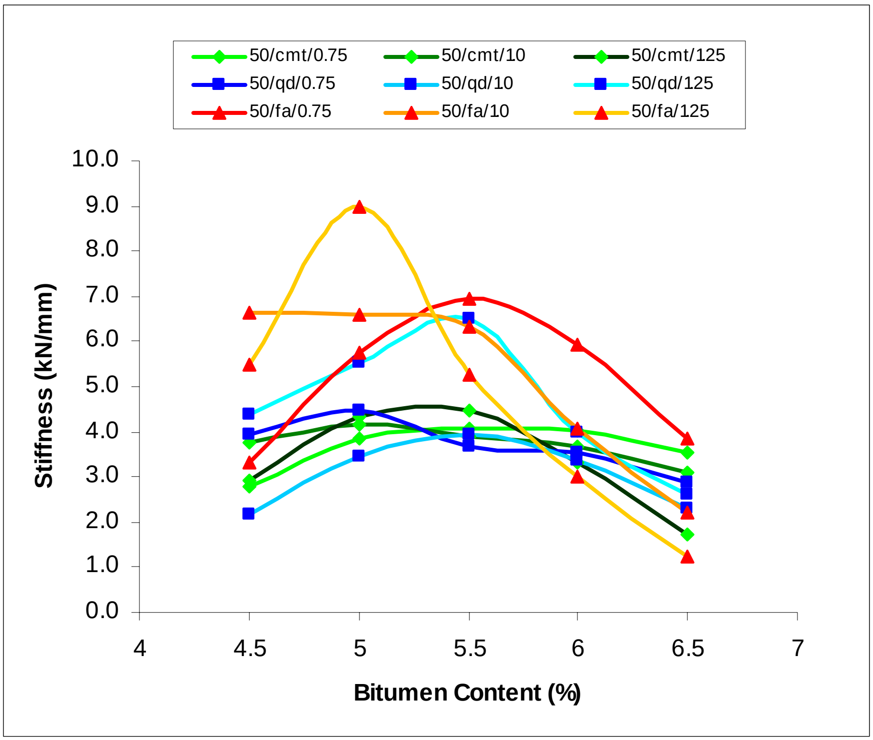


Figure 4-25 Stiffness of bituminous mixtures for bitumen pen grade 50-60.

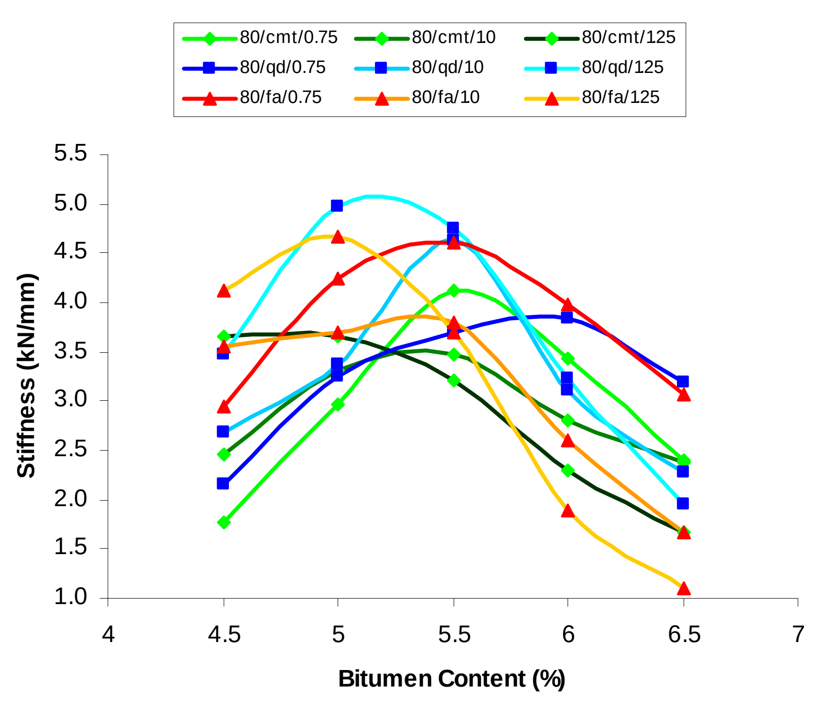


Figure 4-26 Stiffness of bituminous mixtures for bitumen pen grade 80-100.

Table 4-19 Maximum Stiffness of Bituminous Mixtures Incorporated with Filler

Maximum Stiffness (kN/mm)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	4.07	4.18	4.49	4.45	3.96	6.50	6.93	6.64	8.99
Pen 80-100	4.12	3.48	3.65	3.84	4.62	4.97	4.61	3.80	4.67

4.6 Optimum Bitumen Content

The determination of optimum bitumen content (OBC) is a fundamental step in bituminous mixtures design. It is determined by optimization of the bitumen content on several mixture parameters. In this study, the mixture parameters used are density, stability, VMA and VFB. These parameters except for VMA are as recommended by the JKR Standards [17], while VMA is used in accordance to the requirement by the Asphalt Institute [53].

The OBC results are summarized in Table 4-20 and Table 4-21 and are also presented in the form of bar charts as shown in Figure 4-27 and Figure 4-28. The bar charts clearly indicate that OBC is inversely proportional to the F/B ratio. All of the mixtures exhibit a decreasing OBC with increasing filler proportion in bituminous mixer. T-test analysis on averaged OBC between F/B ratios shows that the differences are quite significant. These results prove that filler can lower the optimum bitumen content which is in accordance with an earlier study by Bolk et al [12]. The T-test results are shown in appendix A.

Among the fillers used, fly ash incorporated bituminous mixtures have the lowest OBC, followed by quarry dust and cement. This result is attributed to the particle shape, density and chemical composition of fillers. These parameters have been shown to influence the density, stability, VMA and VFB results.

Comparing the bitumen penetration grades, the OBC results indicate that bitumen grade 50-60 mixtures always have higher OBC than bitumen grade 80-100 mixtures, except for F/B ratio of 1.25. All the considered parameters, i.e. stability, VMA and VFB have the same trend, except for stability and VFA for 50/cmt/1.25 mixture. This trend is highlighted in the OBC against F/B ratio bar charts. Bitumen grade 80-100 has lower slope than bitumen grade 50-60, which means the OBC much more decreased with increasing F/B for bitumen pen grade 50-60 compared to bitumen pen grade 80-100 mixtures. Thus, even though bitumen grade 80-100 mixtures have lower OBC than bitumen grade 50-60 mixtures at F/B 0.75 and 1.0, bitumen grade 80-100 mixtures at F/B 1.25 has higher OBC than bitumen grade 50-60 for the same F/B ratio. However, T-test shows that the differences caused by filler and bitumen types are not significant. The T-test results are shown in appendix A.

Table 4-20 Summarized OBC of Bitumen Pen Grade 50-60 Mixtures

	Bitumen Pen Grade 50-60 (%)								
Filler Type	Cement			Quarry Dust			Fly Ash		
F/B	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Density	6.50	6.5	6.1	6.5	6.3	6.1	6.4	6.3	5.8
Stability	6.5	5.75	5.55	6.5	5.85	5.45	6.2	5.45	5.25
VFB/70	6.5	6.35	6	6.5	6.25	5.9	6.25	6.1	5.7
VMA	6.4	6.1	5.7	6.15	6.05	5.65	5.95	5.75	5.5
Average	6.48	6.18	5.84	6.41	6.11	5.78	6.20	5.90	5.56

Table 4-21 Summarized OBC of Bitumen Pen Grade 80-100 Mixtures

	Bitumen Pen Grade 80-100 (%)								
Filler Type	Cement			Quarry Dust			Fly Ash		
F/B	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Density	6.50	6.5	6.5	6.5	6.5	6.25	6.3	6.15	5.85
Stability	6.2	6	5.5	6.1	5.55	5.5	5.85	5.45	5.35
VFB/70	6.25	5.95	5.85	6.45	6.15	5.9	6.25	6.05	5.75
VMA	6.40	6	5.75	6.05	6	5.7	5.85	5.7	5.55
Average	6.34	6.11	5.90	6.28	6.05	5.84	6.06	5.84	5.63

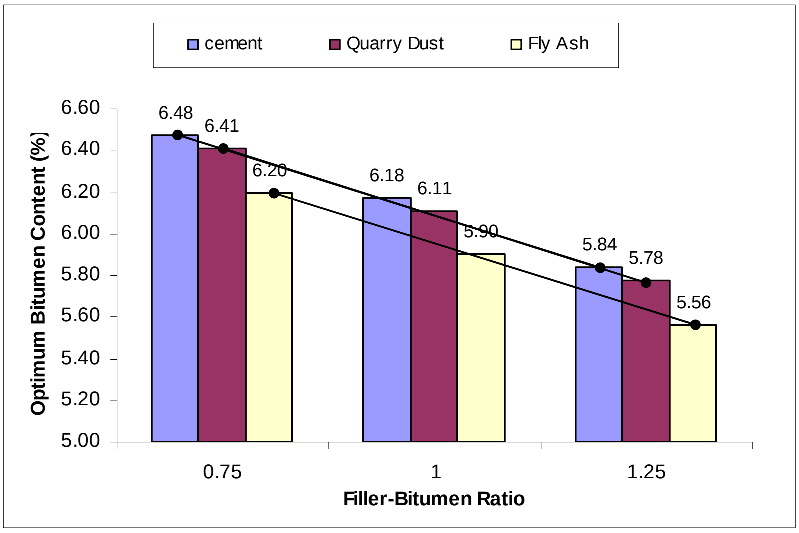


Figure 4-27 Optimum bitumen contents of bitumen pen grade 50-60 mixtures.

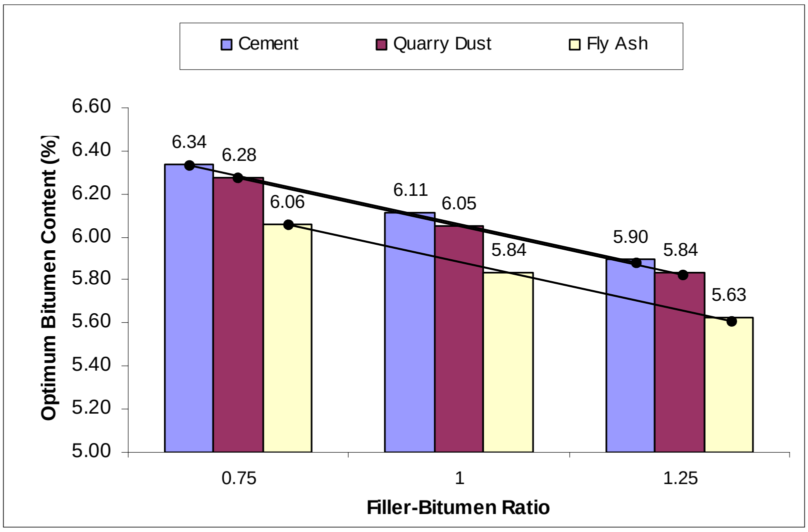


Figure 4-28 Optimum bitumen contents of bitumen pen grade 80-100 mixtures.

4.7 Mixture Performance on Permanent Deformation

Permanent deformation is one of the structural distresses in flexible pavements. It is caused by plastic movement of the asphalt mix either in hot weather (environment related) or from inadequate compaction (load related). It creates rutting in the pavements. It is therefore important to investigate the resistance of bituminous mixtures to permanent deformation. Both creep and wheel tracking tests have been used in this study to determine the effect of fillers on the resistance bituminous mixtures to permanent deformation.

4.7.1 Creep test

In this study, the creep test was conducted at 40°C on cylindrical specimens, identical to the Marshall specimens. Each specimen was compacted by the Marshall compactor for 75 blows on each side which corresponds to the design of highways. Three specimens were used for each mixture variation. The specimens were prepared based on the OBC results obtained from the previous experiments.

The creep test results are shown in Figure 4-29 and Figure 4-30. The graphs indicate that permanent deformation increases with increasing loading cycles. The values of permanent deformation at the end of the 1800 cycles in the test of all bituminous mixtures are listed in Table 4-22. The table shows different trends of permanent deformation at this condition. In general, the results show that permanent deformation decreases with increasing F/B ratio, but bitumen grade 50-60 mixtures incorporated with cement and quarry dust show the minimum permanent deformation at F/B 1.0. It seems to suggest that within the F/B ratio range used, increasing the filler in the bituminous mixture decreased the permanent deformation. However, this is not the case for cement-incorporated and quarry dust-incorporated bitumen grade 50-60 mixtures. Minimum permanent deformation is reached at F/B 1.0. This may be caused by the irregular particles of cement and quarry dust which has good interlocking mechanism with harder bitumen. Thus, less filler is required to satisfy the minimum deformation criterion than other filler-bitumen combination.

Amongst the fillers, cement and quarry dust generally have the lowest permanent deformation for bitumen grade 50-60 mixtures, while fly ash has the lowest permanent deformation for bitumen grade 80-100 mixtures. This result is inconsistent with the filler-bitumen consistency from the softening point test and the stiffness results from the Marshall test. The softening point and stiffness results show that fly ash has the highest consistency and highest stiffness in bitumen grade 50-60 mixtures, while cement and quarry dust have the highest consistency and highest stiffness in bitumen grade 80-100 mixtures. The high consistency and high stiffness mixture are expected to have low permanent deformation, however the permanent deformations resulted from creep test show the opposite results. These results will be verified further with the wheel tracking test result.

Bitumen grade 50-60 mixtures are observed to have lower permanent deformation than bitumen grade 80-100 mixtures. This result is expected, since the bitumen grade 50-60 is harder than bitumen grade 80-100, and creates stiffer mixture. However, fly ash mixtures show the opposite. This opposite result can not be explained with these data. It will be confirmed further with wheel tracking test results.

Another parameter acquired from the creep test is stiffness modulus. The stiffness modulus results are displayed in Figure 4-31 and Figure 4-32. From the figures, it can be observed that stiffness modulus decreases with increasing loading cycles for both type of bitumen. The stiffness modulus at 1800 cycle or failure of all mixtures is listed in Table 4-23. It can be observed that quarry dust mixtures has the highest stiffness for bitumen grade 50-60 and fly ash mixtures has the highest stiffness for bitumen grade 80-100 mixture. These results are opposite to the stiffness results obtained by Marshall test, but it seems stiffness results are consistent with permanent deformation results.

Overall, conclusion can not be drawn from creep test result alone, since the results are not consistent with the other mixtures properties. The wheel tracking test should help verify the mixture resistance to permanent deformation.

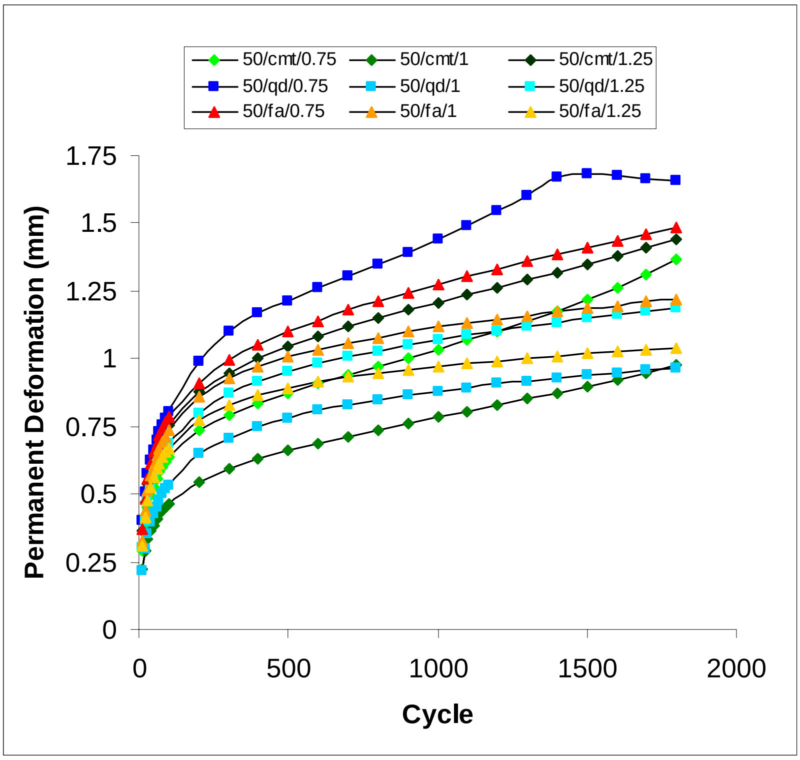


Figure 4-29 Permanent deformations of bitumen pen grade 50-60 mixtures.

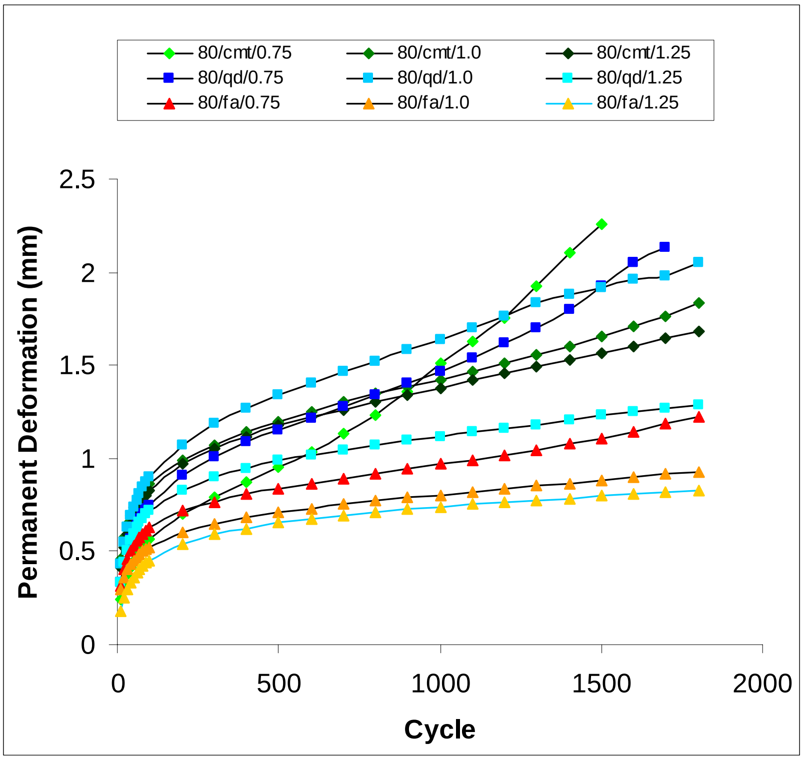


Figure 4-30 Permanent deformations of bitumen pen grade 80-100 mixtures.

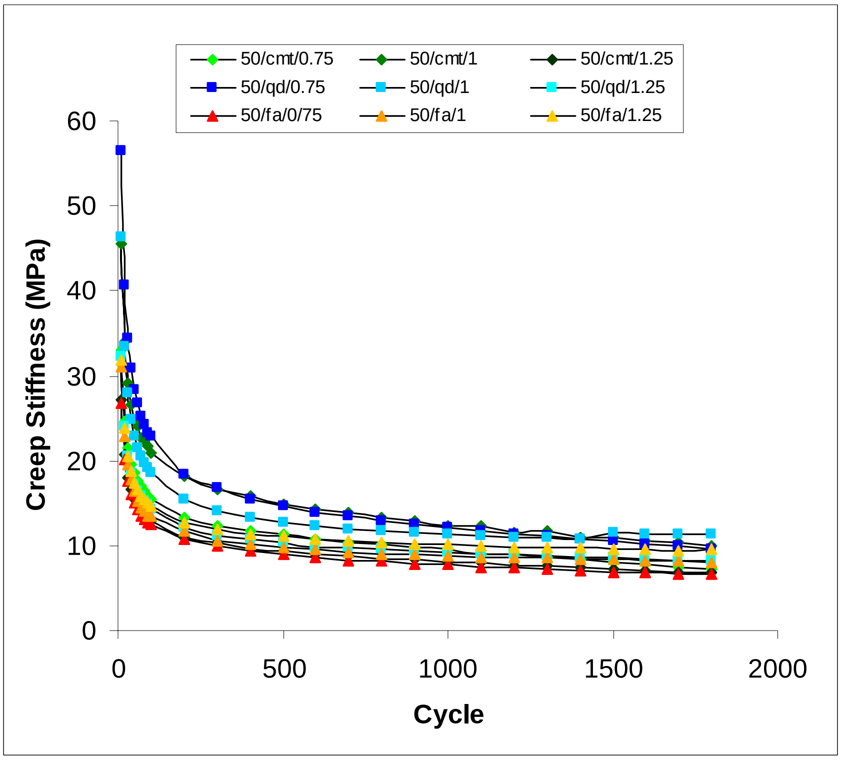


Figure 4-31 Creep Stiffness of bitumen pen grade 50-60 mixtures.

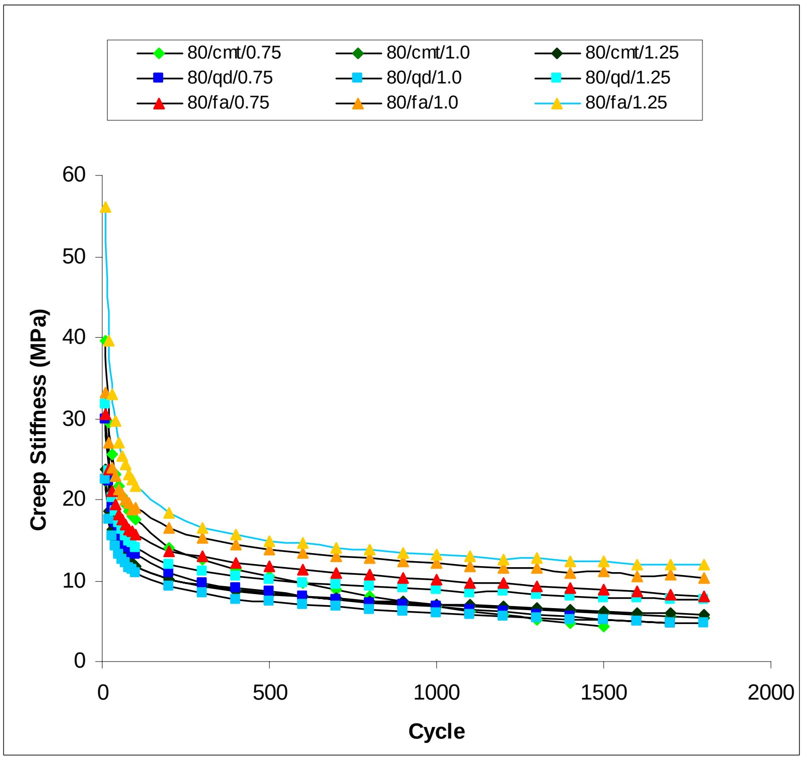


Figure 4-32 Creep Stiffness of bitumen pen grade 80-100 mixtures.

Table 4-22 Permanent Deformation of Creep Test at 1800 or Failure Cycles

Permanent Deformation (mm)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	1.37	0.97	1.44	1.66	0.97	1.19	1.48	1.22	1.04
Pen 80-100	2.25	1.72	1.68	2.41	2.05	1.31	1.36	1.01	0.83

Table 4-23 Creep Stiffness at 1800 or Failure Cycle

Creep Stiffness (MPa)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	7.22	9.96	6.78	9.54	11.3	8.36	6.64	8.05	9.51
Pen 80-100	4.36	5.77	5.82	4.25	4.81	7.56	7.38	9.92	11.87

4.7.2 Wheel tracking test

Another method of determining pavement resistance to permanent deformation is through the wheel tracking test. This test is categorized as a simulative test. The test uses an actual wheel with a load of 520 N applied to the bituminous mixture slab specimen, which measures 305 mm (L) x 305 mm (W) x 50 mm (H). The tests were carried out at a temperature of 40°C. The low stiffness response of the mixture can be determined. The performance of pavement is evaluated by the total rut depth after a number of wheel passes. In this study, a frequency of 42 wheel passes/minute for 45 minutes loading was used.

The wheel tracking test results which show the total rut depths against cycle are exhibited in Figure 4-33 and Figure 4-34. The rut depth value at maximum cycle is shown in Table 4-24. Based on the table, the rut depth of bituminous mixtures is observed to decrease with increasing F/B ratio. However, cement-bitumen grade 50-60 mixtures reach minimum rut depth at F/B ratio 1.0. These results are in agreement with the results from the creep test. It seems to suggest that within the F/B ratio range used, increasing the filler in the bituminous mixture decrease the permanent deformation. The bituminous mixtures of bitumen grade 50-60 are observed to have lower rut depth than bitumen grade 80-100 mixtures. The lowest rut depth for all bituminous mixtures is observed for the 50/fa/1.25 mix. Combination of bitumen grade 50-60, spherical particles and high F/B ratio create the best resistance to permanent deformation.

Among the fillers used, fly ash incorporated bituminous mixtures have the lowest rut depth for both bitumen penetration grades. Quarry dust incorporated bituminous mixtures have the second lowest rut depth, and cement incorporated bituminous mixtures as the third. This result is generally similar with the OBC results. Lower OBC results in lower rut depth. It can be seen that OBC greatly influence the mixture resistance to permanent deformation. The results proves the previous study, which suggest that rut depth or wheel tracking rate is affected significantly by binder content and binder penetration [49].

The results obtained by the wheel tracking test is consistent with the filler-bitumen consistency and mixture properties results. The inconsistency of the creep test results with the filler-bitumen consistency and mixture properties proves that creep test does not have any direct correlation with permanent deformation. This was also suggested by Hills [47].

Table 4-24 Rut Depths at the Maximum Cycle

Rut Depth (mm)									
Filler	Cement			Quarry Dust			Fly Ash		
(F/B ratio)/ (Bitumen Grade)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Pen 50-60	5.71	2.93	3.69	3.91	3.15	2.88	3.5	2.81	2.17
Pen 80-100	5.62	4.1	3.12	4.77	3.9	2.8	4.01	3.21	2.31

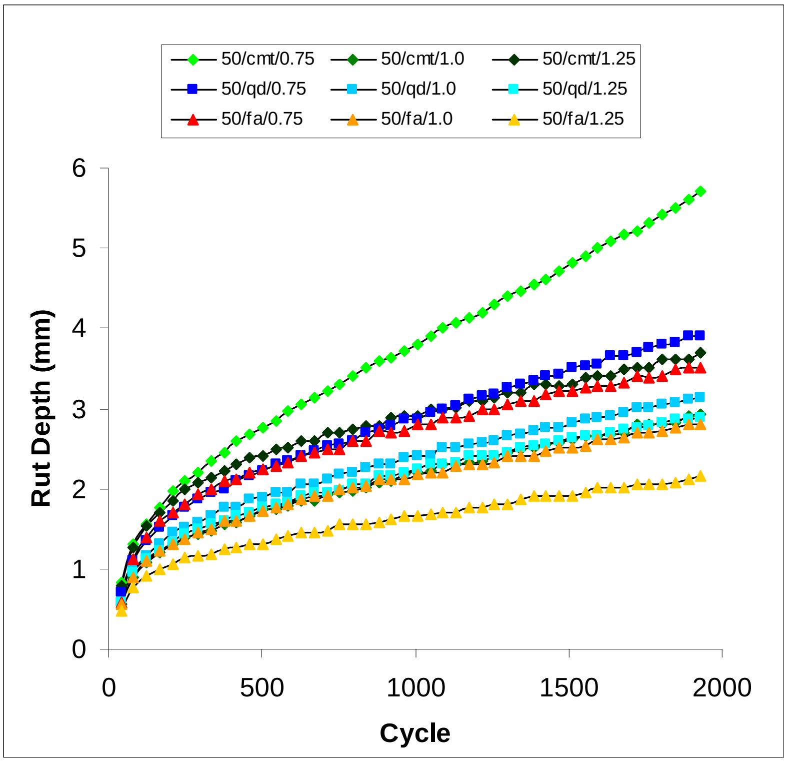


Figure 4-33 Rutting in bitumen pen grade 50-60 mixture variations.

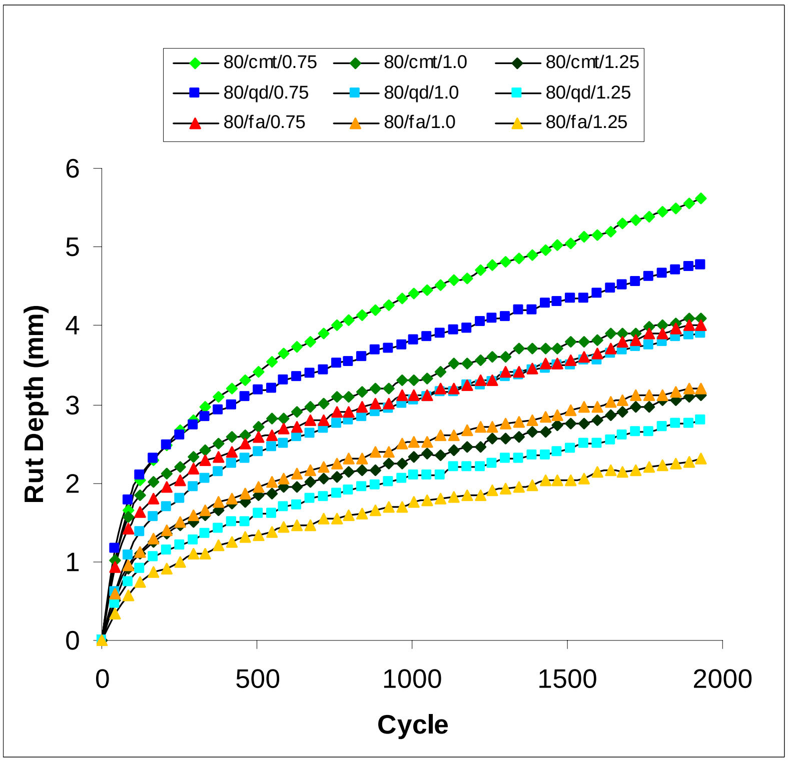


Figure 4-34 Rutting in bitumen pen grade 80-100 mixture variations.

4.8 Mixture Performance on Fatigue

Fatigue distress generates cracking in road pavements. Cracking occurs as a result of excessive tensile stress by a combination of low temperature and fluctuating traffic loading. Thus the resistance of bituminous mixtures to fatigue distress depends on its tensile strength. In this study, a three point beam bending fatigue test was used to determine the bituminous mixture resistance to fatigue distress.

The study used the control strain mode, thus the results of the beam fatigue test are expressed in the form of a graph of stress versus load cycles and are presented in Figure 4-35 and Figure 4-36. The resulting equations of stress and cycle for bituminous mixtures are tabulated in Table 4-25. The trend line of the graph is observed as logarithmic, and the general equation is expressed as,

$$y = -a\ln(x) + b \quad \text{..4-1}$$

or

$$\sigma = -a\ln(N) + b \quad \text{..4-2}$$

where; $y = \sigma =$ stress

$x = N =$ cycle

$a =$ equation gradient/slope factor

$b =$ constant

In this study, the beam fatigue test results are analyzed based on the slopes obtained from the graphs. The bitumen grade 80-100 mixtures are observed to have lower slope than bitumen grade 50-60 mixtures, except for the 80/qd/1.25 mixture. This suggests that bitumen grade 80-100 mixtures have a better fatigue resistance than bitumen grade 50-60 mixtures. This result is consistent with the consistency of filler-bitumen results where the bitumen grade 80-100 has lower consistency than bitumen grade 50-60. The soft or low consistency bitumen tends to have a better resistance to fatigue than harder bitumen. For mix with proportion of fillers used F/B ratio 1.25, it is observed that the slopes of the stress and load cycle for both bitumen grades mixtures are almost the same. This result concludes that bitumen type does not a significant influence on the fatigue characteristic of mixture with high filler proportion.

In bitumen penetration grade 50-60 mixtures, fly ash incorporated bituminous mixtures have the best performance on resistance to fatigue distress, followed by cement and quarry dust. However, bitumen pen grade 80-100 mixtures show the different trend. Cement incorporated bitumen pen grade 80-100 has the best resistance to fatigue distress followed by cement and quarry dust. It seems that bitumen hardness significantly influenced the fatigue behavior. This result can be correlated with the ductility results data. The spherical particles and low content of silica and alumina in the fillers are observed to have low consistency of filler-bitumen system, and cement produce low consistency of filler bitumen system in bitumen pen grade. Low consistency/hardness of filler-bitumen tends to have better resistance to fatigue distress.

In general, the slopes obtained from the graphs decrease with increasing F/B ratio, except for cement incorporated in both bitumen grades. Cement incorporated in bituminous mixture has the lowest slope at F/B 1.0. It may be correlated to the stiffness results which show some mixtures have the lowest stiffness at F/B 1.0. In term of cycle of load failure, it decreases with increasing of F/B ratio. It signifies that high F/B ratio increases the brittleness of pavement. Quarry dust incorporated bituminous mixtures have the lowest cycle of failure among the other filler. Fly ash and cement incorporated bituminous mixture using bitumen penetration grade 80-100 indicate relatively similar cycles of failure. On the other hand, mixtures using bitumen penetration 50-60 indicate inconsistency trend of cycles to failure among fillers since the failures occur in the early stage (less than 10^5 cycles). However, the best mixture variation due to fatigue resistance is the combination of bitumen grade 80-100, fly ash and F/B ratio 1.0 (80/cmt/1.0).

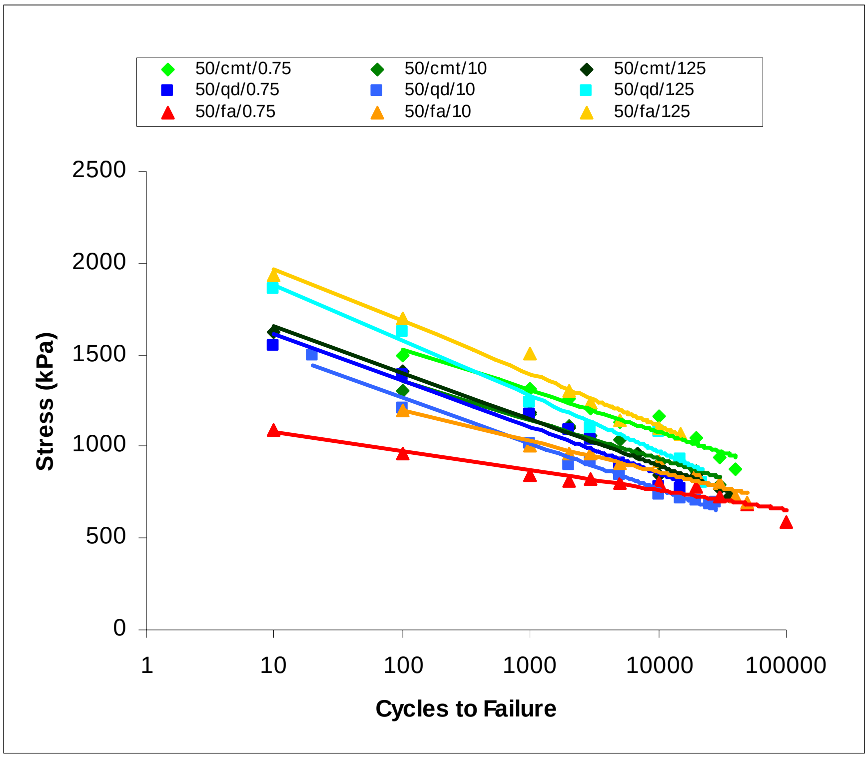


Figure 4-35 Fatigue Characteristic of bitumen pen grade 50-60 mixture variations.

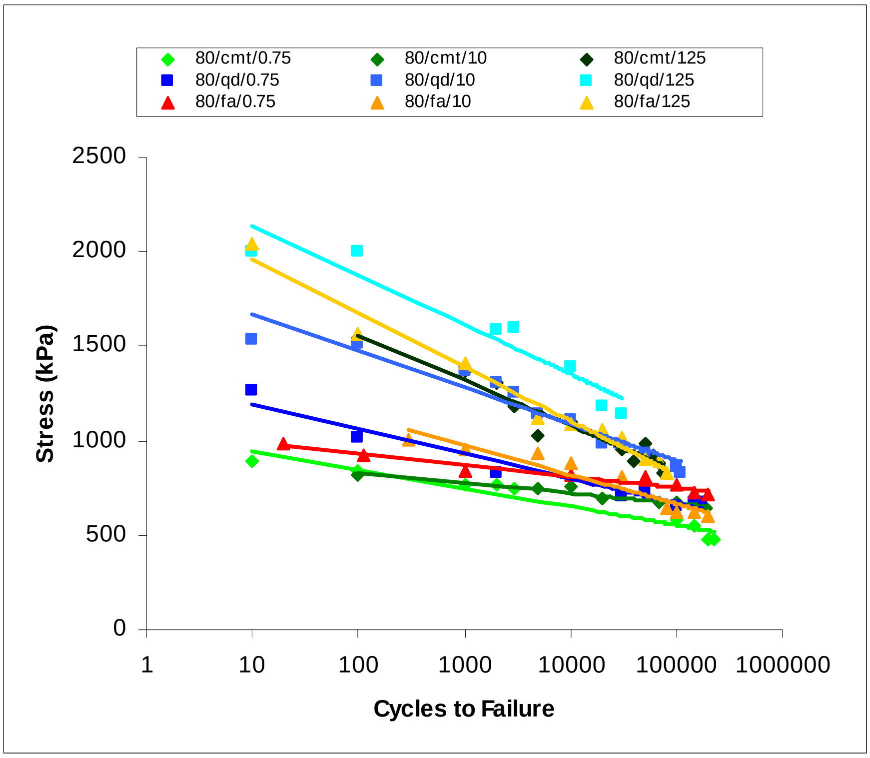


Figure 4-36 Fatigue Characteristic of bitumen pen grade 80-100 mixture variations.

Table 4-25 Fatigue Characteristic Equations

Mixture Variation	Equation of Fatigue Characteristic	R^2
50/cmt/0.75	y = -97.827Ln (x)+1981.2	0.95
50/cmt/1.0	y = -91.246Ln(x) + 1773.4	0.95
50/cmt/1.25	y = -109.94Ln(x) + 1908.6	0.99
50/qd/0.75	y = -109.64Ln(x) + 1864.4	0.96
50/qd/1.0	y = -107.6Ln(x) + 1759.8	0.98
50/qd/1.25	y = -131.41Ln(x) + 2184.8	0.98
50/fa/0.75	y = -46.499Ln(x) + 1190.2	0.94
50/fa/1.0	y = -72.781Ln(x) + 1531.1	0.94
50/fa/1.25	y = -124.08Ln(x) + 2255.4	0.97
80/cmt/0.75	y = -42.02Ln(x) + 1038.7	0.94
80/cmt/1.0	y = -22.939Ln(x) + 929.09	0.98
80/cmt/1.25	y = -103.94Ln(x) + 2037.6	0.94
80/qd/0.75	y = -56.917Ln(x) + 1324.7	0.95
80/qd/1.0	y = -83.589Ln(x) + 1857.8	0.93
80/qd/1.25	y = -151.33Ln(x) + 2735.4	0.98
80/fa/0.75	y = -26.645Ln(x) + 1060.8	0.96
80/fa/1.0	y = -68.161Ln(x) + 1441.7	0.93
80/fa/1.25	y = -123.19Ln(x) + 2240.2.2	0.98

4.9 Summary

Mixtures that have better performance on permanent deformation are most likely to perform worse on fatigue characteristic. A hard pavement is needed to reduce permanent deformation at high temperatures. However, such mixtures generate brittle pavement that can easily cause cracking at low temperatures. Thus, both criteria need to be optimized to obtain best overall mixture performance

The experimental results obtained in this work were compared in order to determine the optimum composition of bituminous mixtures for different fillers, bitumen grades and F/B ratios. The bituminous mixtures were analyzed from 3 different aspects of mixture parameters i.e. engineering properties, permanent deformation and fatigue performance. The optimization of mixtures is undertaken by ranking the mixtures according to their performance under each category of mixture parameter.

The mixtures are ranked from 1 (as the most desired characteristic) to 18 (as the least desired characteristic). Ranking 1 is given to the mixtures with the high value of density, stability and stiffness and low values of VMA and OBC. As for mixture performance, ranking 1 is given to the mixture with the lowest permanent deformation which was obtained from the wheel tracking test and the lowest slope as defined by the relationships of stress and cycles to failure in the fatigue tests. The ranking of all the mixtures were then summarized and tabulated in Table 4-26.

Table 4-26 Ranking of Mixture According to Performance

	Mixture Variation	Mixture Properties	Permanent Deformation	Fatigue
		Rank		
1	50/cmt/0.75	17	18	10
2	50/cmt/1.0	12	6	9
3	50/cmt/1.25	5	11	14
4	50/qd/0.75	18	13	13
5	50/qd/1.0	13	8	12
6	50/qd/1.25	2	5	17
7	50/fa/0.75	9	10	4
8	50/fa/1.0	6	4	7
9	50/fa/1.25	1	1	16
10	80/cmt/0.75	14	17	3
11	80/cmt/1.0	10	15	1
12	80/cmt/1.25	7	7	11
13	80/qd/0.75	16	16	5
14	80/qd/1.0	8	12	8
15	80/qd/1.25	3	3	18
16	80/fa/0.75	15	14	2
17	80/fa/1.0	11	9	6
18	80/fa/1.25	4	2	15

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Several mixtures of Asphaltic Concrete –ACW20 with different types of filler and in various proportions were evaluated with emphasis on their resistances to permanent deformation and fatigue distresses. The laboratory tests, which included the Marshall test, dynamic creep test, wheel tracking test and beam fatigue tests have resulted in the following conclusions:

i. The filler particle shapes influence the properties and performance of bituminous pavements. The spherical particles can reduce the percentage of voids and optimum bitumen content in the mixtures, thus influencing the final performance of pavement. The irregular particles of fillers produce high consistency filler-bitumen system and increase the stability and stiffness of the resulting mixtures.
ii. The content of silica and alumina in fillers affects the quality of bituminous pavement by increasing the hardness of the mix and hence the pavement becomes more resistant to permanent deformation. However, increase in hardness causes the pavement to brittle faster, promoting fatigue cracking to occur early in the pavement life.
iii. Based on the finding, it is proposed that for 80/cmt/1.0 mixtures shows the high superiority in term of fatigue, while for 50/fa/1.25 mixtures was the most superior in term of permanent deformation. It is therefore recommended that the construction of the surface layer of the pavement with incorporate these two layers, with the 80/cmt/1.0 mix being used as the binder course, whilst the 50/fa/1.25 mix is being used as the wearing course. These would help mitigate the phenomena of cracking at the underside of the binder layer while at the same time provide a material which is most resistant to permanent deformation for the wearing course.

iv. On the mixture performance, fly ash incorporated bituminous mixtures has a good performance to be use as mineral filler in bituminous mixtures especially for improving permanent deformation and it has an adequate performance for improving fatigue characteristic. Cement incorporated bituminous mixtures found has a good performance for improving fatigue distress, but has poor resistance to permanent deformation. However, based on the finding quarry dust incorporated bituminous mixture does not have any special advantage for improving performance of bituminous mixture.

v. The bituminous paving mixture using bitumen penetration grade 50-60 exhibits a better resistance on permanent deformation, while mixture using bitumen penetration grade 80-100 has a better resistance to fatigue distress.

5.2 Recomendations

This study used laboratory specimens to evaluate the effect of filler properties and filler proportion on the rutting and fatigue performance of asphalt concrete material. This investigation excludes viscosity test and the effect of water on the pavement material. Therefore, in order to verify the result of this study, viscosity test together with some immersion test are recommended.

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APPENDIX A
T-TEST RESULTS FOR OPTIMUM BITUMEN CONTENT

T-Test: Two-Sample Assuming Unequal Variances

Alpha: 0.05

H_0: $\mu_1 = \mu_2$

H_1: $\mu_1 \neq \mu_2$

If t stat < t critical one-tail → H_0 (the difference is not significant)

If t stat ≥ t critical one-tail → H_1 (the difference is significant)

Summarized OBC of Bitumen Pen Grade 50-60 Mixtures

	Required Bitumen (%)								
Filler Type	Cement			Quarry Dust			Fly Ash		
(F/B)/ (Mixture Properties)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Max Density	6.50	6.5	6.1	6.5	6.3	6.1	6.4	6.3	5.8
Max Stability	6.5	5.75	5.55	6.5	5.85	5.45	6.2	5.45	5.25
VFB (70%)	6.5	6.35	6	6.5	6.25	5.9	6.25	6.1	5.7
Min VMA	6.4	6.1	5.7	6.15	6.05	5.65	5.95	5.75	5.5
Average/ OBC	6.48	6.18	5.84	6.41	6.11	5.78	6.20	5.90	5.56

Summarized OBC of Bitumen Pen Grade 80-100 Mixtures

	Required Bitumen (%)								
Filler Type	Cement			Quarry Dust			Fly Ash		
(F/B)/ (Mixture Properties)	0.75	1	1.25	0.75	1	1.25	0.75	1	1.25
Max Density	6.50	6.5	6.5	6.5	6.5	6.25	6.3	6.15	5.85
Max Stability	6.2	6	5.5	6.1	5.55	5.5	5.85	5.45	5.35
VFB (70%)	6.25	5.95	5.85	6.45	6.15	5.9	6.25	6.05	5.75
Min VMA	6.40	6	5.75	6.05	6	5.7	5.85	5.7	5.55
Average/ OBC	6.34	6.11	5.90	6.28	6.05	5.84	6.06	5.84	5.63

A.1. Comparing F/B Ratio

Bitumen Pen Grade 50-60 Incorporated with Cement

F/B	0.75	1	0.75	1.25	1	1.25
Mean	6.475	6.175	6.475	5.8375	6.175	5.8375
Variance	0.0025	0.1075	0.0025	0.065625	0.1075	0.065625
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	3		3		6	
t Stat	1.809068		4.884914		1.622273	
P(T<=t) one-tail	0.084074		0.008202		0.077936	
t Critical one-tail	2.353363		2.353363		1.94318	
P(T<=t) two-tail	0.168147		0.016405		0.155872	
t Critical two-tail	3.182446		3.182446		2.446912	

Bitumen Pen Grade 50-60 Incorporated with Quarry Dust

F/B	0.75	1	0.75	1.25	1	1.25
Mean	6.4125	6.1125	6.4125	5.775	6.1125	5.775
Variance	0.030625	0.042292	0.030625	0.080833	0.042292	0.080833
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	6		5		5	
t Stat	2.221968		3.819037		1.92367	
P(T<=t) one-tail	0.034007		0.006193		0.056199	
t Critical one-tail	1.94318		2.015048		2.015048	
P(T<=t) two-tail	0.068013		0.012385		0.112399	
t Critical two-tail	2.446912		2.570582		2.570582	

Bitumen Pen Grade 50-60 Incorporated with Fly Ash

F/B	0.75	1	0.75	1.25	1	1.25
Mean	6.2	5.9	6.2	5.5625	5.9	5.5625
Variance	0.035	0.141667	0.035	0.058958	0.141667	0.058958
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	4		6		5	
t Stat	1.427493		4.159513		1.506993	
P(T<=t) one-tail	0.113307		0.002974		0.096085	
t Critical one-tail	2.131847		1.94318		2.015048	
P(T<=t) two-tail	0.226614		0.005948		0.19217	
t Critical two-tail	2.776445		2.446912		2.570582	

Bitumen Pen Grade 80-100 Incorporated with Cement

F/B	0.75	1	0.75	1.25	1	1.25
Mean	6.3375	6.1125	6.3375	5.9	6.1125	5.9
Variance	0.018958	0.067292	0.018958	0.181667	0.067292	0.181667
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	5		4		5	
t Stat	1.532262		1.95351		0.851776	
P(T<=t) one-tail	0.093014		0.061231		0.216615	
t Critical one-tail	2.015048		2.131847		2.015048	
P(T<=t) two-tail	0.186029		0.122463		0.43323	
t Critical two-tail	2.570582		2.776445		2.570582	

Bitumen Pen Grade 80-100 Incorporated with Quarry Dust

F/B	0.75	1	0.75	1.25	1	1.25
Mean	6.275	6.05	6.275	5.8375	6.05	5.8375
Variance	0.054167	0.155	0.054167	0.102292	0.155	0.102292
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	5		5		6	
t Stat	0.983935		2.21212		0.837869	
P(T<=t) one-tail	0.185166		0.038948		0.217103	
t Critical one-tail	2.015048		2.015048		1.94318	
P(T<=t) two-tail	0.370333		0.077896		0.434205	
t Critical two-tail	2.570582		2.570582		2.446912	

Bitumen Pen Grade 80-100 Incorporated with Fly Ash

F/B	0.75	1	0.75	1.25	1	1.25
Mean	6.0625	5.8375	6.0625	5.625	5.8375	5.625
Variance	0.060625	0.103958	0.060625	0.049167	0.103958	0.049167
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	6		6		5	
t Stat	1.109225		2.640726		1.08609	
P(T<=t) one-tail	0.154901		0.019252		0.163502	
t Critical one-tail	1.94318		1.94318		2.015048	
P(T<=t) two-tail	0.309802		0.038503		0.327004	
t Critical two-tail	2.446912		2.446912		2.570582	

A.2. Comparing Filler Type

Bitumen Pen Grade 50-60, F/B ratio 0.75

Filler	cmt	qd	cmt	fa	qd	fa
Mean	6.475	6.4125	6.475	6.2	6.4125	6.2
Variance	0.0025	0.030625	0.0025	0.035	0.030625	0.035
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	3		3		6	
t Stat	0.686803		2.840188		1.65903	
P(T<=t) one-tail	0.270767		0.032818		0.07409	
t Critical one-tail	2.353363		2.353363		1.94318	
P(T<=t) two-tail	0.541533		0.065636		0.148181	
t Critical two-tail	3.182446		3.182446		2.446912	

Bitumen Pen Grade 50-60, F/B ratio 1.0

Filler	cmt	qd	cmt	fa	qd	fa
Mean	6.175	6.1125	6.175	5.9	6.1125	5.9
Variance	0.1075	0.042292	0.1075	0.141667	0.042292	0.141667
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	5		6		5	
t Stat	0.322973		1.101838		0.990899	
P(T<=t) one-tail	0.379893		0.156379		0.183617	
t Critical one-tail	2.015048		1.94318		2.015048	
P(T<=t) two-tail	0.759785		0.312757		0.367234	
t Critical two-tail	2.570582		2.446912		2.570582	

Bitumen Pen Grade 50-60, F/B ratio 1.25

Filler	cmt	qd	cmt	fa	qd	fa
Mean	5.8375	5.775	5.8375	5.5625	5.775	5.5625
Variance	0.065625	0.080833	0.065625	0.058958	0.080833	0.058958
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	6		6		6	
t Stat	0.326628		1.558234		1.136706	
P(T<=t) one-tail	0.377521		0.085095		0.149506	
t Critical one-tail	1.94318		1.94318		1.94318	
P(T<=t) two-tail	0.755043		0.170189		0.299013	
t Critical two-tail	2.446912		2.446912		2.446912	

Bitumen Pen Grade 80-100, F/B 0.75

Filler	cmt	qd	cmt	fa	qd	fa
Mean	6.3375	6.275	6.3375	6.0625	6.275	6.0625
Variance	0.018958	0.054167	0.018958	0.060625	0.054167	0.060625
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	5		5		6	
t Stat	0.46225		1.949627		1.254393	
P(T<=t) one-tail	0.33166		0.054361		0.128176	
t Critical one-tail	2.015048		2.015048		1.94318	
P(T<=t) two-tail	0.663319		0.108722		0.256352	
t Critical two-tail	2.570582		2.570582		2.446912	

Bitumen Pen Grade 80-100, F/B 1.0

Filler	cmt	qd	cmt	fa	qd	fa
Mean	6.1125	6.05	6.1125	5.8375	6.05	5.8375
Variance	0.067292	0.155	0.067292	0.103958	0.155	0.103958
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	5		6		6	
t Stat	0.265124		1.329069		0.835168	
P(T<=t) one-tail	0.400749		0.116065		0.217805	
t Critical one-tail	2.015048		1.94318		1.94318	
P(T<=t) two-tail	0.801497		0.232129		0.43561	
t Critical two-tail	2.570582		2.446912		2.446912	

Bitumen Pen Grade 80-100, F/B 1.25

Filler	cmt	qd	cmt	fa	qd	fa
Mean	5.9	5.8375	5.9	5.625	5.8375	5.625
Variance	0.181667	0.102292	0.181667	0.049167	0.102292	0.049167
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	6		5		5	
t Stat	0.234576		1.144757		1.09205	
P(T<=t) one-tail	0.411169		0.152067		0.162307	
t Critical one-tail	1.94318		2.015048		2.015048	
P(T<=t) two-tail	0.822338		0.304133		0.324615	
t Critical two-tail	2.446912		2.570582		2.570582	

A.3 Comparing Bitumen Type

Cement

F/B	0.75		1.0		1.25	
Bitumen	50-60	80-100	50-60	80-100	50-60	80-100
Mean	6.475	6.3375	6.175	6.1125	5.8375	5.9
Variance	0.0025	0.018958	0.1075	0.067292	0.065625	0.181667
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	4		6		5	
t Stat	1.877304		0.298985		-0.25137	
P(T<=t) one-tail	0.066849		0.387518		0.405768	
t Critical one-tail	2.131847		1.94318		2.015048	
P(T<=t) two-tail	0.133697		0.775037		0.811536	
t Critical two-tail	2.776445		2.446912		2.570582	

Quarry Dust

F/B	0.75		1.0		1.25	
Bitumen	50-60	80-100	50-60	80-100	50-60	80-100
Mean	6.4125	6.275	6.1125	6.05	5.775	5.8375
Variance	0.030625	0.054167	0.042292	0.155	0.080833	0.102292
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	6		5		6	
t Stat	0.9444		0.28142		-0.2921	
P(T<=t) one-tail	0.190712		0.394831		0.390022	
t Critical one-tail	1.94318		2.015048		1.94318	
P(T<=t) two-tail	0.381424		0.789663		0.780045	
t Critical two-tail	2.446912		2.570582		2.446912	

Fly Ash

F/B	0.75		1.0		1.25	
Bitumen	50-60	80-100	50-60	80-100	50-60	80-100
Mean	6.2	6.0625	5.9	5.8375	5.5625	5.625
Variance	0.035	0.060625	0.141667	0.103958	0.058958	0.049167
Observations	4	4	4	4	4	4
Hypothesized Mean Difference	0		0		0	
df	6		6		6	
t Stat	0.889297		0.252217		-0.38014	
P(T<=t) one-tail	0.20404		0.404646		0.358466	
t Critical one-tail	1.94318		1.94318		1.94318	
P(T<=t) two-tail	0.408081		0.809291		0.716932	
t Critical two-tail	2.446912		2.446912		2.446912	