CERTIFICATION OF APPROVAL

EFFECT OF PULVERIZED FLY ASH ON COMPACTION EFFORT FOR ASPHALT CONCRETE

by

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Lum Tuck Fai

Acknowledgement

This section is dedicated to express my gratitude towards each and every party that has provided me with knowledge and experience, giving me guidance all the while, and also supporting me throughout this entire study. Without them, this study will not be a success.

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Abstract

Major concern of today's world is on environmentally treatment of wastes. Wastes such as pulverized fly ash (PFA), blast furnace slag, kiln dust, steel slag ash, and etc are increasing rapidly due to the growing production volume in the industry. These waste materials have been recycled and used in construction industry for decades of years. In Malaysia, according to the 8th Malaysia Plan, it is estimated that Malaysia will use up 11.2 million tonnes of coal per annum. This will generate more than 2 million tonnes of PFA annually. Even though there is abundant of PFA in Malaysia, only a small percentage of the PFA is utilized for construction purposes. Main development in this country is focused on the construction of road which consumes a huge amount of materials both raw and processed so if waste products can be used as a substitute to the constituent of asphalt mix design, a more economical asphalt mix can be produce while at the same time solving the problems of disposing waste products. In this study, pulverized fly ash will be replacing the normal filler of quarry dust or Ordinary Portland Cement (OPC) in the asphalt mix. The objectives of this study are to determine the effect of PFA application in asphalt concrete and to obtain an optimum compaction effort for the mix design. Two sets of asphalt specimens with the respective mineral filler of Ordinary Portland Cement (OPC) and the pulverized fly ash were prepared with different compaction effort and tested using Marshall Mix Test. As a conclusion, the results showed that the substitution of OPC with PFA gives a better performing asphaltic concrete in stability, flow, Marshall Stiffness, and air voids at a lower compaction effort.

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1.0 INTRODUCTION

1.1 Background of Study

The development of road construction in Malaysia is very important due to the fact that the most feasible mode of transportation in the country is by land. The size of the country also encourages the means of transportation by land. Out of 14 states, 11 are interconnected by highway. This stresses on the importance of developing a better performing and more economical asphalt pavement.

There are several types of asphalt pavement in Malaysia but the most typical ones are conventional asphalt pavement. The conventional asphalt pavement is made of coarse aggregates, fine aggregates, binder, and mineral filler. Typical coarse aggregates used are granites while the typical fine aggregates used are sandstones. Common binder used is bitumen. As for the mineral filler, Ordinary Portland Cement will be used.

In order to produce a higher performance asphalt pavement, a higher initial cost will incur. However, in the long run, higher performance asphalt pavement requires lower maintenance and repairing costs, hence became more economical. Asphalt pavement construction involves a lot of compaction work which increases the cost of the construction so it will be economy wise if the compaction work can be reduced.

Studies on the mixture content required for asphalt concrete is done in order to come out with a mixture content of asphalt concrete mixture that requires a lower overall compaction effort while maintaining or improving other properties of the asphalt concrete.

Incorporation of new materials into the asphalt mix is regarded as the most suitable solution. The selection of this material depends primarily on availability and cost of the material. For economical cost wise, incorporation of industrial waste, recycled products or by-products is encouraged.

1.2 Problem Statement

Pulverized fly ash is a by-product from electricity production. Pulverized fuel ash or pulverized fly ash is produced when pulverized bituminous, hard coal is burned in power station furnaces. The resulting material is siliceous ash consisting of oxides of silica, aluminium and iron, and containing less than 10% of calcium oxide. Hence, there is a need to dispose or recycle this unwanted waste. Under most circumstances, recycling of this material or incorporation of this material into useful applications to benefit mankind would be a preferable solution.

Because of the composition of this siliceous material, it is potentially suitable to be used for replacing of normal filler in asphalt pavement construction. Previous studies have shown that pulverized fly ash will be able to reduce permanent deformation and increase flexural stiffness. Besides that, the physical properties of pulverized fly ash are also suggesting that it can reduce the compaction effort required by the asphalt pavement.

1.3 Objective

The main objective of this project is to investigate the feasibility of reducing compaction effort in asphalt concrete by introducing pulverized fly ash as mineral filler in asphalt concrete and proposes an optimum compaction effort for a PFA modified pavement will be proposed.

1.4 Scope of Study

The scope of study is to understand the characteristics of pulverized fly ash and performs lab tests to determine the optimum compaction effort for a pulverized fly ash modified pavement.

The scope of study also includes the determination of whether the compaction effort can be reduced by introducing PFA as a substitute for normal filler such as quarry dust or Ordinary Portland Cement (OPC).

Besides that, the scope of study also includes the studies on the properties of the PFA modified asphalt concrete such as the stability, flow, density, porosity and etc.

2.0 LITERATURE REVIEW AND/OR THEORY

2.1 Introduction

By-product of coal combustion, pulverized fly ash, is very much resembles volcanic ashes which are used as hydraulic cement about 2,300 year ago. This cement got the term "pozzolan" from a small Italian town of Pozzuoli where the cement was made. A pozzolan has a siliceous/aluminous composition which forms cementitous compound when mixed with lime and water.

Pulverized fly ash is incorporated into the asphalt pavement as a replacement of normal filler of quarry dust or Ordinary Portland Cement (OPC). This pulverized fly ash can be obtained easily and in a considerable low price due to the fact that it is actually a by-product from coal combustion industry. Using pulverized fly ash as the filler not only help to solve the waste treatment problem but also increase the flexural stiffness and reduce permanent deformation of asphalt pavement.

Road pavement construction requires a lot of compaction work. Most of the cost of road pavement construction comes from the working procedures and not the cost of materials. Hence if replacement of quarry dust and OPC with pulverized fly ash in asphalt pavement can reduce the compaction effort, then the cost of asphalt concrete pavement construction can also be lowered.

Literature reviews related to the topic will be discussed in this chapter. The literature reviews includes Pulverized Fly Ash (PFA) (characteristics and statistics), Sewage Sludge Ash in Asphalt Concrete, and Jordanian Oil Shale Fly Ash on Asphalt Mixes.

2.2 Pulverized Fly Ash (PFA)

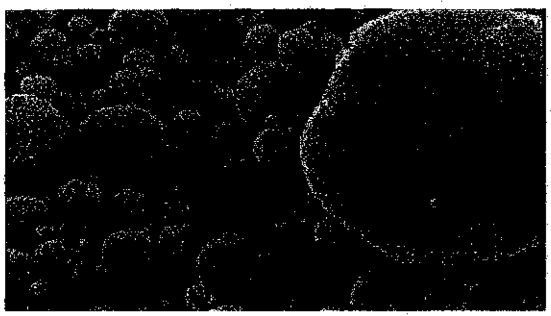

Figure 2.1: Pulverized Fly Ash

(Reproduced from fly ash properties and uses by Kevin Copeland)

PFA constitutes of very fine particles which majority are glassy spheres, scoria, iron rich fractions, crystalline matter, and carbon. PFA have a high surface area to volume ratio due to its size and shape. Besides that, it is a solid material with agglomerated materials on its surface. Basically, the spherical portion of PFA is somewhat immune to dissolution due to its glassy structure. This property is quite similar to glass, both in elemental composition and leaching properties, which is relatively inert. However, there are spheres on the surface that are either easily exchangeable or adsorbed molecules which, when acted with liquid, become dissolved. Some of the very minute spheres may dissolve into solution and become a leachate[6].

2.2.1 Statistics of PFA Application in United States

During 1997, about 817 million metric tons of coal was burned by the electric utilities in United States of America, producing 1.8 million Gigawatt Hours of electricity. From this process, estimated coal combustion products (CCPs) were 95 million metric tons[8].

This coal combustion products (CCPs) comprise of fly ash, bottom ash, boiler slag, and also flue gas desulphurization (FGD). Out of these 95 million metric tons CCPs, more than 26 million metric tons were used in various applications. The leading usage of CCPs is in concrete and cement applications, followed by waste stabilization and solidification, structural fill, roadbase and subbase materials, blasting grit and roofing granule markets, manufacture of wallboard, mining applications, snow and ice control, and others. The remaining unused CCPs will be disposed to landfills. This causes the rise of environmental concern as the CCPs produced is increasing with the increment of coal being combusted for the electricity generation. Hence, various studies and experiments have been carried out to find suitable uses of CCPs in any means[8].

Thanks to the effort by Barry R. Stewart and Rustu S. Kalyoncu, information regarding the statistics of applications of Coal Combustion Products (CCPs) is gathered and tabulated. The tabulated statistic is showed in table 5.

Table 2.1: Applications of Coal Combustion Products (CCPs) in United States

(Reproduced from Materials Flow in the Production and Use of Coal Combustion Products)

Applications	Fly Ash	Bottom Ash	Boiler Slag	FGD Material	Total
Cement and concrete	8.6	0.5	-	0.2	9.3
Waste stabilization & solidification	2.8	0.2	-	-	3.0
Structural fills	2.6	1.3	-	-	3.9
Roadbase and subbase	1.3	1.2	-	-	2.5
Blasting grit / roofing granules	-	0.2	2.1	-	2.3
Mining applications	1.3	0.2	-	0.1	1.6
Wallboard	-	-	-	1.5	1.5
Snow and ice control	-	0.6	-	-	0.6
Others	1.0	0.7	0.3	0.2	2.2
Landfill disposal	37.2	10.7	0.1	20.9	68.9
Total	54.8	15.6	2.5	22.9	95.8

All values are in million metric tons.

2.2.2 PFA Chemical and Physical Properties

The PFA comprises predominantly of inert mineral oxides where approximately 95 percent of the ash is made up of silicon oxide, aluminum oxide, iron oxide, and calcium oxide. The other 5 percent is made up of oxides of magnesium, potassium, sodium, titanium, and sulfur. In a typical fly ash, there will be about 0.1 percent by weight of trace elements. The types and proportion of trace elements in PFA are highly variables. Usual trace elements that can be found in PFA includes Arsenic, Boron, Barium, Beryllium, Cadmium, Cobalt, Chromium, Copper, Gallium, Germanium, Lanthanum, Manganese, Mercury, Nickel, Lead, Scandium, Silver, Tin, Strontium, Vanadium, Yttrium, Ytterbium, Zinc, and Zirconium[6].

Physical properties of PFA include fineness, particle size distribution, density, color, and the presence of oil or ammonia.

The fineness of PFA is usually varies depending on the source of PFA. The particle size varies from below 1 μm to 200 μm or more. Acceptable fineness in United States is 45μm. The finer the particles of fly ash is, the greater the surface area for pozzolanic reactions[9].

Fineness of PFA is better indicated by the particle size distribution. A fly ash might have a distribution based on the mass. The distribution can be as follows; 0.3-2 % below 1 μm, 30-70 % finer than 10 μm, 0.5-7 % above 100 μm and 0-2 % above 200 μm[9]. Due to it unique particle size distribution, PFA can achieve low permeability when compacted[11].

As for density of PFA, it ranges from 2 to 2.8 and this will determine the volume it will occupy for a given mass. Differences in density may indicate a different coal source[9]. Also, by having low particle density, PFA, when compacted has a low density compared to most other fill materials[11].

Color of PFA is usually grey. Although the color may varies from white to black depending on the coal source. The color will affect the color of concrete products but not in asphalt concrete[9].

Oil and ammonia may be present in PFA because sometimes they are added to the pulverized coal boiler at startup. Testing of the presence of oil and ammonia is important because these components will affect the performance of the PFA[9].

Water reducing properties of PFA and the spherical shape of its particles has proven to influence the compactibility of ash-modified lean concrete allowing an easier compaction. Reduction in moisture content results in higher compacted densities being obtained[11].

Most PFA possesses self-cementing properties when they are compacted. The result of this hardening, if it occurs, is that settlement within PFA fill is less than with other materials[11].

2.2.3 PFA in Malaysia

The statistical information on the PFA in Malaysia such as the energy resources consumption, PFA composition, and ASTM specification for PFA classification is obtained and tabulated as follows:

The energy resources consumptions in Malaysia from 1995-2005:

Table 2.2: Consumptions of energy resources
(Reproduced from Physical and Chemical Properties of Pulverized Fly Ash in Malaysia)

Year	1995	2000	2005
Fuel (%)	11.0	5.3	3.0
Coal (%)	9.7	7.9	30.3
Gas (%)	67.8	78.7	61.0
Hidro (%)	11.3	8.0	5.4
Others (%)	0.2	0.1	0.1
Total (gw/h)*	41,813	69,371	102,340

*gigawatt/hour

The chemical composition of PFA obtained from local power plant is found to be as such:

Table 2.3: PFA composition
(Reproduced from Physical and Chemical Properties of Pulverized Fly Ash in Malaysia)

Element	Content (% wt)
SiO_2	59.00
Al_2O_3	20.00
Fe_2O_3	3.70
CaO	6.90
MgO	1.40
SO_3	1.00
K_2O	0.90
Loss On Ignition	4.62

It is noticed that PFA comprises of Oxides from Silica, Aluminium, Iron, Calcium, Magnesium, Sulphur, and Potassium. There is also loss due to ignition. Different coal source have different chemical composition due to the nature of the coal source[7].

Table 2.4: ASTM specification for PFA classification
(Reproduced from Physical and Chemical Properties of Pulverized Fly Ash in Malaysia)

Chemical composition	ASTM C 618 Specification
Total $SiO_2 + Al_2O_3 + Fe_2O_3$	50.0 % min – Class C 70.0 % min– Class F
CaO	> 10% - Class C < 10% - Class F
SO_3	5.0 % max.
Na_2O	1.5% max.
Loss on ignition LOI	6.0% max.

Fly ash produced from anthracite or bituminous coal is classified as Class F fly ash, meanwhile fly ash from lignite or sub-bituminous coal is classified as Class C fly ash. This classification depends on the chemical composition and physical requirements as described in ASTM C618[7].

2.2.4 PFA Chemical and Physical Properties from Slag Cement Sdn. Bhd.

The PFA in the laboratory is obtained from Slag Cement Sdn. Bhd. Hence, the chemical and physical properties of this PFA should be known before conducting any laboratory work. The following properties are tested from a dispatched sample dated from 1st January 2006 to 31st January 2006.

Table 2.5: PFA chemical and physical properties

(Reproduced from Slag Cement Sdn. Bhd.)

Test Type	BS EN 450 : 1995	Result
45 μm Sieve Residue (%)	Max 40.0	19.00
Loss on Ignition (LOI) (%)	Max 6.0	1.23
Sulphuric Anhydride (SO_3) (%)	Max 3.0	0.64
Silica (SiO_2) (%)	Min 25.0	39.82
Chloride (Cl) (%)	Max 0.10	<0.01
Free Calcium Oxide (CaO) (%)	Max 1.0	0.19
Activity Index : 28 Days (%)	Min 75	N/A
: 90 Days (%)	Min 85	N/A
*Soundness (mm)	Max 10	N/A
Density (kg/m^3)	-	2620
Magnesium Oxide (MgO) (%)	-	5.48
Iron Oxide (Fe_2O_3) (%)	-	16.65
Aluminium Oxide (Al_2O_3) (%)	-	20.43
Calcium Oxide (CaO) (%)	-	13.56
Potassium Oxide (K_2O) (%)	-	0.75
Sodium Oxide (Na_2O) (%)	-	0.36
Remarks: * Accordance to BS EN 450 : 1995 : Clause 4.2.5 – Soundness Test is required only if Free Calcium Oxide exceeds 1.0% by mass.		

The results from this PFA chemical and physical properties satisfies BS EN 450 : 1995 (Fly Ash for concrete – definitions, requirements , and quality control). Hence, this PFA is to be used in the laboratory tests.

This PFA is classified as class F PFA according to ASTM specification for PFA classification (SiO2 + Al2O3 + Fe2O3 = 76.9% > 70% min, CaO = 0.19 < 10%).

2.2.5 Comparison of Concrete Containing Fly Ash from UK and Malaysia

In this paper by Muhd Fadhil Nuruddin, Nasir Shafiq and Ibrahim Kamaruddin, a comparison between concrete containing fly ash from Drax, UK and also Manjung, Malaysia. The comparison is focused on permeability, porosity, and compressive strength of the concrete[12].

From this paper, it is stated that Malaysia consumes 8 million tons of coal annually. This is only 0.17 per cent from the world annual utilisation of coal which is at 4800 million tons. Malaysia's electricity generation dependency is more on natural gas which is standing on 65 per cent compared to coal which is only 28 per cent. In 2004, Malaysian government has decided to increase the coal dependency to 40 per cent by 2010. From this increase, it is estimated that 2.5 to 3 million tons of fly ash will be produced per annum[12].

Table 2.6: Comparison of PFA properties from UK and Malaysia
(Reproduced from Permeability, Porosity and Compressive Strength of Concrete Containing Fly Ash obtained from UK and Malaysia sources)

PFA from Manjung, Malaysia	PFA from Drax, UK
Contains 11.47% calcium oxide	Contains 2.55% calcium oxide
Silica content at 56%	Silica content at 50%
Coarser	Finer
Not as desirable pozzolanic properties	Better pozzolanic properties
Lower long term strength in concrete	Higher long term strength in concrete

2.3 Effect of Sewage Sludge Ash in Asphalt Concrete

Literature review has been done on this paper on incorporation of sewage sludge ash in asphalt concrete. In this paper, studies have been carried out by using sewage sludge ash as a replacement of either the mineral filler or the fine aggregate in asphalt concrete. When the sewage sludge ash used have a 100% passing through sieve size No.30 (0.60 mm), then it is a substitute for the mineral filler in the asphalt concrete (according to the specification requirements of AASHTO M17-83). Otherwise, it is either used as the substitutes for both mineral filler and fine aggregate, or it will be crushed and/or screened if the sludge ash is too large to remove oversized particles. In this study, 5.5 percent sludge ash by weight is used[4].

The results yielded as compared to the control asphalt concrete mix using normal filler is as below:

Table 2.7: Results of sewage sludge ash modified asphalt concrete mix

(Reproduced from Sewage sludge ash as mineral filler in asphalt concrete)

Properties	Effect of Sewage Sludge Ash
Skid Resistance	No significant effect
Plasticity	Non-plastic (meet AASHTO requirements)
Organic Impurities	Less than 2%
Stability	Increases stability of mix
Mix Density	Decreases the density of mix
Air Voids	Increases air voids in mix
Durability	Slightly improved
Viscosity	Increases the viscosity of the binder

There are unresolved issues regarding the usage of sewage sludge ash in asphalt concrete mix as there is presence of metals in the sludge ash. This remains unresolved because there are no environmental criteria established yet for the acceptable level of trace material content[4].

2.4 Effect of Jordanian Oil Shale Fly Ash in Asphalt Mixes

In order to resolve the problems of having abundant fly ash from the direct combustion of oil shale, various studies are being carried out to exploit the usage of this source in a beneficial way[5].

In this journal, the study is regarding the usage of fly ash from combustion of oil shale as a replacement for mineral filler in asphalt mixes. Fly ash that passes 0.075 mm sieve is prepared as the mineral filler. The test is done by varying the percentage of fly ash (0%, 10%, 50%, and 100%) as replacement filler in the asphalt mixes[5].

The tests used in this study are Marshall Stability, indirect tensile strength, stripping resistance, resilient modulus, dynamic creep, fatigue, and rutting test[5].

In the end, after analyzing the results, it is indicated that by replacing normal mineral filler with shale oil fly ash, there are improvements in both strength and water sensitivity of the asphalt concrete mixes. It is also shown that, the most effective percentage of fly ash in improving the properties of the asphalt concrete mixes is 10%[5].

2.5 Workability of Asphalt Concrete

Workability defines the ease for the pavement construction in the field. It is measured in the laboratory during compaction (gyratory compactor) by comparing the height of the specimens with different gyratory revolutions[17]..

Another way to study the workability of asphalt concrete is by calculating the workability in term of Workability Index (WI). WI is the inverse of mixture's porosity value on revolutions equal zero[17]..

3.0 METHODOLOGY/PROJECT WORK

3.1 Literature Review

Although literature review is a very basic part in the project, it is a very important because proper literature review provides better understanding on the project topic and also clearer vision on the objectives of the project. With better understanding, the project can be executed smoothly and efficiently. Literature review is done by research and review on existing papers, journals, books, reports, news, etc. Literature review is an on-going procedure throughout the entire project duration as further information is constantly being retrieved as the references for the project.

3.2 Discussion and Collaboration

To ensure that the researcher of the project is inline with the objectives and goals of the project, discussion and collaboration with the supervisor is necessary. Participating in meetings with the supervisor also enables discussion regarding the activities conducted and findings to be made. Hence, meeting is arranged to meet the supervisor weekly.

3.3 Material Procurement

The procurement of materials for the project will be handled by the lab technician but the selection of the materials will be specified beforehand. The main materials for this project would be aggregates (coarse and fine), binder, and filler (normal filler for control set and PFA for test specimens).

The aggregates used should be from the same batch of aggregates to ensure the consistency of the performance. Hence, the aggregates should be procured sufficiently from the same batch. As for the binder, the grade of the binder used in all tests should be the same in order to obtain more precise results. For both filler, OPC and PFA, it should be in good condition and not hardened.

3.4 Specimen Preparation

Two set of specimens are required in this project. The first set will serve as control specimens while the second will be the test specimens. The control set is using a fix percentage of OPC as filler. On the other hand, the test set is using the same percentage of filler but instead of OPC, pulverized fly ash (PFA) is used.

The study would be conducted using Marshall Mix test where the number of compaction blows is fixed for OPC as filler and is varied for PFA as filler. For every test of that particular number of blows, three samples are prepared. This is to ensure the consistency of the results by taking the average value from the three results.

The stability and the flow value are recorded for every test. This test is done to both control set and test set so that a comparison can be made between two different fillers.

3.4.1 Aggregates

Two types of aggregates will be used in the asphalt mix design, coarse aggregates and fine aggregates. The coarse aggregates are granite and the fine aggregates are sandstones.

For the coarse aggregates, it is obtained from the stockpile and is washed with water to get rid of the dust and other impurities. The aggregates are then oven dried for one day at a temperature of 105°C to remove the moisture on the aggregates surface.

As for fine aggregates, it does not require washing with water as it contains very fine particles in it that will be washed away by the water. The fine aggregates are obtained from stockpile and are oven dried for one day at a temperature of 105°C to remove the moisture on the aggregates surface.

These aggregates are then sieved through a series of sieve sizes to determine the gradation of the aggregates. From the sieve analysis, the gradation of the aggregates is compared to the Jabatan Kerja Raya (JKR) specification to check whether the gradation of the aggregates is complying with the standards.

Table 3.1: Gradation limits for aggregates

(*Reproduced from JKR Specifications Manual for Asphalt Pavement Construction*)

Sieve Size	Percentage Passing by Weight (%)
28 mm	100
20 mm	76 – 100
14 mm	64 – 89
10 mm	56 – 80
5 mm	46 – 71
3.35 mm	32 – 58
1.18 mm	20 – 42
425 µm	12 – 28
150 µm	6 – 16
75 µm	4 – 8

3.4.2 Mineral Filler

Mineral filler is a main component in asphalt mix design. Mineral filler shall be material of very fine particles such as quarry dust, rock dust, limestone dust, cement, and other similar materials. Agglomerated mineral filler is deemed spoilt and can not be used to produce the asphalt mix. Its main function is to "stabilizes" or increases the apparent viscosity of the bitumen, reducing drainage[14].

As for this study, Pulverized Fly Ash (PFA) is proposed to be used as the mineral filler in the asphalt mix design substituting the conventional Ordinary Portland Cement (OPC). Both PFA and OPC are sieved through a series of sieves to determine the gradation. According to Jabatan Kerja Raya (JKR) specification, not less than 70% by weight of the mineral filler shall pass the No.200 sieve (0.075 mm). This is to ensure that there will be enough fine particles to fill up the voids in between the coarse and fine aggregates.

3.4.3 Binder

The binder in asphalt mix design will be bitumen. Bitumen is a non-crystalline viscous material, usually black in color, possesses adhesive and water proofing characteristic. It is typically comprise of at least 80% carbon and 15% hydrogen, with the remaining being oxygen, sulfur, nitrogen, and traces of various metals.

The main function of bitumen in asphalt mix design is to bind all the aggregates and filler together to develop the strength and stability of the asphalt mix. There are many types of bitumen which is differentiated by their grades. The grade of bitumen to be used depends on the climate, design traffic loading, types of aggregates used, and also the type of construction methods applied. Most of the time, the selection of bitumen grade will depends on the climate factor and the design traffic loading. In this study, the grade of bitumen used is 80 pen bitumen.

3.5 Sieve Analysis

Sieve analysis is a method of making a mechanical grain-size analysis of aggregates regardless of whether it is coarse or fine to determine the gradation of the aggregates. This analysis is done to study the particle size distribution of aggregates that will be used in the Marshall Mix Design later on.

The gradation and the particle size distribution are determined by shaking or vibrating the sample sieve shaker through a successive set of sieves. The coarser sieves (5 mm aperture and above) are made of perforated-plate and the finer sieves are made of woven-wire.

The successive set of sieves used depends on the types of aggregates that are to be sieved. In this study, for coarse aggregates, a set of sieves of the following sizes are used; 20 mm, 14 mm, 10 mm, 6.3 mm, 5 mm, 3.35 mm, and 2.36 mm. As for fine aggregates sieve analysis, the following set of sieve sizes are used; 5 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm. To determine the particle size distribution of the filler (OPC and PFA), the following sieve sizes are used; 0.6 mm, 0.3 mm, 0.15 mm, 0.075 mm, and 0.063 mm. Last but not least, for mixed materials of the asphalt mix design, the following sieve sizes are used; 28 mm, 20 mm, 14 mm, 10 mm, 5 mm, 1.18 mm, 0.3 mm, 0.15 mm, and 0.075 mm.

The results of this analysis are normally reported as the cumulative percentage by mass passing each test sieve and are plotted on appropriate graph paper to determine the cumulative grading curve. As for single-sized aggregates, it is however more usual to report the percentage retained between successive sieves.

Overloading of sieves can cost a serious error in the results; hence the sample masses to be sieved must be kept within the maximum sample masses allowed.

3.6 Marshall Mix Design

Marshall Mix Design is one of the laboratory designs for hot-mix asphalt concrete mix. The objective of Marshall Mix Design is to determine the economical mixture of bitumen content, the cement content (filler), and the gradation of aggregates. This test is also used to yield a mix that is sufficient in cement content (filler) to ensure a durable surface layer, sufficient mix stability so that no extra distortion or displacement will occur, sufficient voids for further compaction due to traffic loading without flushing, bleeding and loss of stability, and also sufficient workability to prevent segregation.

There are two parts in this Marshall Mix Design, the preparation of asphalt specimens and the testing of the asphalt specimens. First of all, the optimum binder content (OBC) must be determined before preparing the control and the test specimens. The OBC is determined by preparing specimens using a range of bitumen content (3%-7%) for both OPC and PFA. The specimens are then tested for their stability and flow. Heights, diameter, weight in air, and weight in water of the specimens are also noted. From all the information gathered, graphs of stability, flow, density, air voids, and Marshall Stiffness versus bitumen content are plotted. The OBC is obtained from interpretation of all the graphs plotted.

After that, 3 control specimens using the OBC are prepared with a compaction effort of 75 blows using the Marshall Compactor. As for the test specimens, 3 specimens using OBC for every of the following compaction effort using the Marshall Compactor is prepared: 75 blows, 60 blows, 45, and 30 blows. The results are gathered and interpreted.

The Marshall stability-flow test measures the maximum load resistance and corresponding deformation (or flow) of a standard test specimen at 60°C (140°F) when subjected to a constant rate of deformation, 51 mm (2in.)/min, until failure occurs. The total number of Newtons (lb) required to produce failure is recorded as the Marshall stability value. The deformation (or flow) at maximum load is recorded and expressed in units of 1/100 in[14].

3.7 Results and Analysis

Tables and graphs would be plotted during the entire period of the project. These tables and graphs will be analyzed thoroughly and the findings will be noted. During analysis, literature review will be done to compare or verify findings in order to prove the truthfulness and reliability of the results.

3.8 Conclusion and Recommendation

In this part, the findings will be concluded to know whether or not it has achieved all the objectives that have been set earlier on. Recommendation regarding on how to further improve this final year project is also included in this section.

4.0 RESULTS & DISCUSSIONS

4.1 Sieve Analysis Results

The followings are the tabulated results for the sieving analysis done in the laboratory. The sieve analysis is done for coarse aggregates, fine aggregates, Ordinary Portland Cement (OPC), and Pulverized Fly Ash (PFA).

4.1.1 Coarse Aggregates

A 2kg sample of coarse aggregate (granite) is sieved through a series of sieves as shown in Table 4.1. The results showed that 98.6% is passing the 20mm sieve and only 0.65% passing the 5mm sieve. The analysis is repeated once to further verify the consistency of the results. The results of the second analysis are shown in Table 4.2. This time, 98.1% passing the 20mm sieve and 0.35% passing the 5mm sieve. Since the designed specimens to be produced will be based on dense graded (passing 20mm sieve and retained on 5mm sieve), this source of coarse aggregate is considered suitable.

Table 4.1: Sieve analysis for coarse aggregates (1st analysis)

BS Sieve Size (mm)	Weight of empty sieve (g)	Weight after sieve (g)	Weight Retained (g)	Percentage Retained (%)	Total Passing (%)
20	1599	1627	28	1.4	98.6
14	1281	2025	744	37.2	61.4
10	1311	2187	876	43.8	17.6
6.3	1289	1619	330	16.5	1.1
5	1320	1336	16	0.8	0.3
3.35	1168	1170	2	0.1	0.2
2.36	1138	1139	1	0.05	0.15
pan	823	826	3	0.15	0

Table 4.2: Sieve analysis for coarse aggregates (2nd analysis)

BS Sieve Size (mm)	Weight of empty sieve (g)	Weight after sieve (g)	Weight Retained (g)	Percentage Retained (%)	Total Passing (%)
20	1599	1637	38	1.9	98.1
14	1281	2192	911	45.55	52.55
10	1311	2033	722	36.1	16.45
6.3	1289	1604	315	15.75	0.7
5	1320	1331	11	0.55	0.15
3.35	1168	1169	1	0.05	0.1
2.36	1138	1138	0	0	0.1
pan	823	825	2	0.1	0

4.1.2 Fine Aggregates

A 1kg sample of fine aggregate (river sand) is sieved through a series of sieve as shown in Table 4.3. It is observed that 97.1% is passing the 5mm sieve and only 1.5% is passing the 0.075mm sieve. Further analysis (Table 4.4) showed that 97.2% is passing the 5mm sieve and 2.1% passing the 0.075mm sieve. For dense graded, fine aggregate used must be of passing 5mm sieve and retained on 0.075mm sieve. Hence, this river sand is suitable to be used.

Table 4.3: Sieve analysis for fine aggregates (1st analysis)

BS Sieve Size (mm)	Weight of empty sieve (g)	Weight after sieve (g)	Weight Retained (g)	Percentage Retained (%)	Total Passing (%)
5	514	543	29	2.9	97.1
1.18	433	755	322	32.2	64.9
0.6	393	585	192	19.2	45.7
0.3	359	564	205	20.5	25.2
0.15	336	506	170	17.0	8.2
0.075	327	391	64	6.4	1.8
pan	393	411	18	1.8	0

Table 4.4: Sieve analysis for fine aggregrates (2nd analysis)

BS Sieve Size	Weight of empty sieve (g)	Weight after sieve (g)	Weight Retained (g)	Percentage Retained (%)	Total Passing (%)
5	514	542	28	2.8	97.2
1.18	433	734	301	30.1	67.1
0.6	393	574	181	18.1	49
0.3	359	563	204	20.4	28.6
0.15	336	523	187	18.7	9.9
0.075	327	405	78	7.8	2.1
pan	393	414	21	2.1	0

4.1.3 Mineral Filler

There are 2 types of mineral filler used in this study. The first mineral filler is the Ordinary Portland Cement (OPC) which is used to produce the control specimens. The second mineral filler is Pulverized Fly Ash (PFA) which is used in the test specimens. The sieve analysis of both the mineral fillers is done by sieving a sample of 50g with a sieving duration of 10 minutes. The results of the sieve analysis for both mineral fillers are shown in Table 4.5 and Table 4.6.

According to JKR standards, mineral filler to be used must have a percentage passing of 0.075mm sieve of at least 70%. From the results of analysis for OPC, it showed that OPC has 76% passing of 0.075mm sieve. As for the results of analysis for PFA, it showed a slightly higher percentage passing of 0.075mm sieve at 78% compared to OPC. Both mineral fillers satisfied the JKR standards and is suitable to be used in the study.

Table 4.5: Sieve analysis for OPC

BS Sieve Size (µm)	Weight of empty sieve (g)	Weight after sieve (g)	Weight Retained (g)	Percentage Retained (%)	Total Passing (%)
600	330	330	0	0	100
150	269	280	11	22	78
75	254	255	1	2	76
63	311	334	23	46	30
pan	245	260	15	30	0

Table 4.6: Sieve analysis for PFA

BS Sieve Size (µm)	Weight of empty sieve (g)	Weight after sieve (g)	Weight Retained (g)	Percentage Retained (%)	Total Passing (%)
600	339	340	1	2	98
150	269	272	3	6	92
75	255	262	7	14	78
63	328	351	23	46	32
pan	247	263	16	32	0

4.2 Design of Optimum Aggregate Gradation

To produce the asphalt concrete using Marshall Mix Design, the optimum aggregate gradation to be used must be obtained. Different source of materials have different aggregate gradation, hence for the optimum aggregate gradation to be achieved in the lab, the aggregate gradation must be adjusted in order to comply with the JKR's envelope of upper and lower boundary.

The method used to determine the optimum aggregate gradation is a "try and error" method where a trial aggregate gradation (50% coarse aggregate, 45% fine aggregate, 5% mineral filler) is being proposed and is calculated as shown in Table 4.7. The values for the percentage retained are taken from the sieve analysis results for the coarse aggregate, fine aggregate and mineral filler. The values are the multiplied by the proposed proportion percentage before obtaining the theoretical total percentage passing.

Table 4.7: Calculation for optimum aggregate gradation (Try and error method)

SIEVE SIZE (MM)	TRIAL % OF MATERIALS X PERCENTAGE RETAINED			TOTAL PERCENTAGE RETAINED	TOTAL PERCENTAGE PASSING
	Coarse Aggregate	Fine Aggregate	Mineral Filler		
20	0.5 x 1.4			0.7	99.3
14	0.5 x 37.2			18.6	80.7
10	0.5 x 43.8			21.9	58.8
6.3	0.5 x 16.5			8.25	50.55
5	0.5 x 0.8	0.45 x 2.9		1.705	48.845
3.35	0.5 x 0.1			0.05	48.795
2.36	0.5 x 0.05			0.025	48.77
1.18	0.5 x 0.15	0.45 x 32.2		14.565	34.205
0.6		0.45 x 19.2		8.64	25.565
0.3		0.45 x 20.5		9.225	16.34
0.15		0.45 x 17.0	0.05 x 22	8.75	7.59
0.075		0.45 x 6.4	0.05 x 2	2.98	4.61
0.063		0.45 x 1.8	0.05 x 46	3.11	1.5
pan			0.05 x 30	1.5	0

The results from Table 4.7 is selectively chosen according to the sieve sized shown in Table 4.8 and is tabulated into Table 4.8 as the calculated percentage passing. The upper and lower columns are the upper and lower percentage passing values set by JKR standards. The values in Table 4.8 are then used to plot a line graph (Figure 4.1) to show that the aggregate gradation is within the limits set by JKR.

Table 4.8: Values of Percentage Passing (JKR standards and calculated)

SIEVE SIZE	LOWER	UPPER	CALCULATED
28	100	100	100
20	76	100	99.3
14	64	89	80.7
10	56	80	58.8
5	46	71	48.845
1.18	20	42	34.205
0.3	12	28	16.34
0.15	6	16	7.59
0.075	4	8	4.61

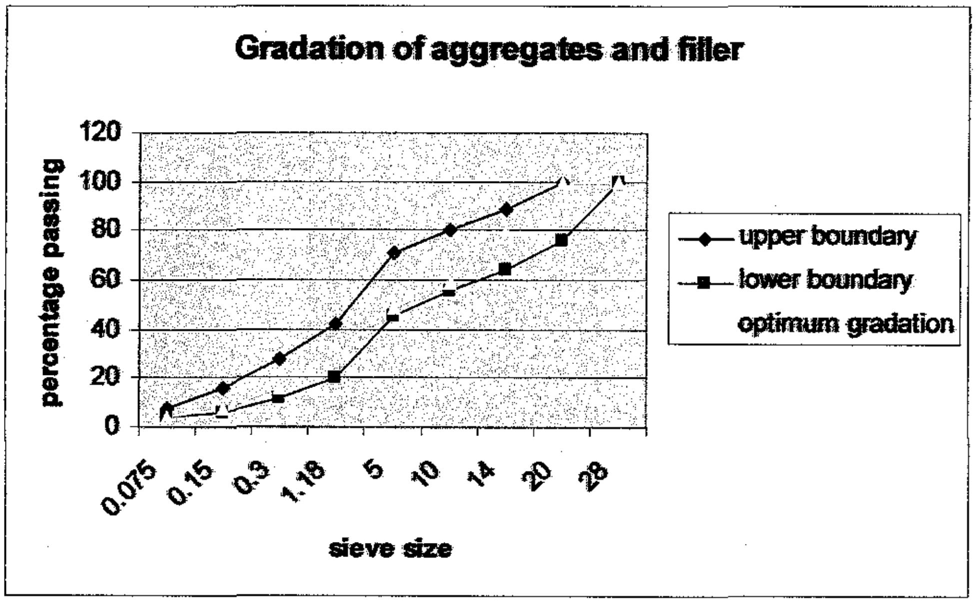

Figure 4.1: Optimum gradation of materials

4.3 Verifying the Designed Optimum Aggregate Gradation

To further verify the reliability of the calculated optimum aggregate gradation designed, sieve analysis using the proposed aggregate gradation for both OPC as filler and PFA as filler is done. A sample of 1kg in total weight (500g coarse aggregate, 450g fine aggregate, and 50g mineral filler) is being sieved through a series of sieve size of 28mm, 20mm, 14mm, 10mm, 5mm, 1.18mm, 0.6mm, 0.15mm, and 0.075mm. The results of the sieve analysis are as shown in Table 4.9 and Table 4.10.

The aggregate gradation curve is then plotted against the upper and lower boundary set by JKR to show whether the actual sieve analysis will show a results that is within the limitation by JKR standards. The optimum aggregate gradation curves for both OPC and PFA are shown in Figure 4.2 and Figure 4.3. Both the aggregate gradation curves are within the boundary and hence, this gradation is proven to be satisfying the JKR standards and will be used in the Marshall Mix Design.

Table 4.9: Sieve analysis for materials (OPC)

Sieve Size	Weight of empty sieve (g)	Weight after Sieve (g)	Weight Retained (g)	Percentage Retained (%)	Percentage Passing (%)
28	1708	1708	0	0	100
20	1586	1601	13	0.65	99.35
14	1324	1669	345	17.25	82.1
10	1105	1526	421	21.05	61.05
5	1148	1423	275	13.75	47.3
1.18	997	1322	325	16.25	31.05
0.6	895	1055	160	8	23.05
0.15	847	1141	294	14.7	8.35
0.075	854	955	101	5.05	3.3
pan	791	857	66	3.3	0

Table 4.10: Sieve analysis for materials (PFA)

Sieve Size	Weight of empty sieve (g)	Weight after Sieve (g)	Weight Retained (g)	Percentage Retained (%)	Percentage Passing (%)
28	1708	1708	0	0	100
20	1586	1586	0	0	100
14	1324	1694	370	18.5	81.5
10	1105	1577	472	23.6	57.9
5	1148	1366	218	10.9	47
1.18	997	1320	323	16.15	30.85
0.6	895	1053	158	7.9	22.95
0.15	847	1142	295	14.75	8.2
0.075	854	931	77	3.85	4.35
pan	791	878	87	4.35	0

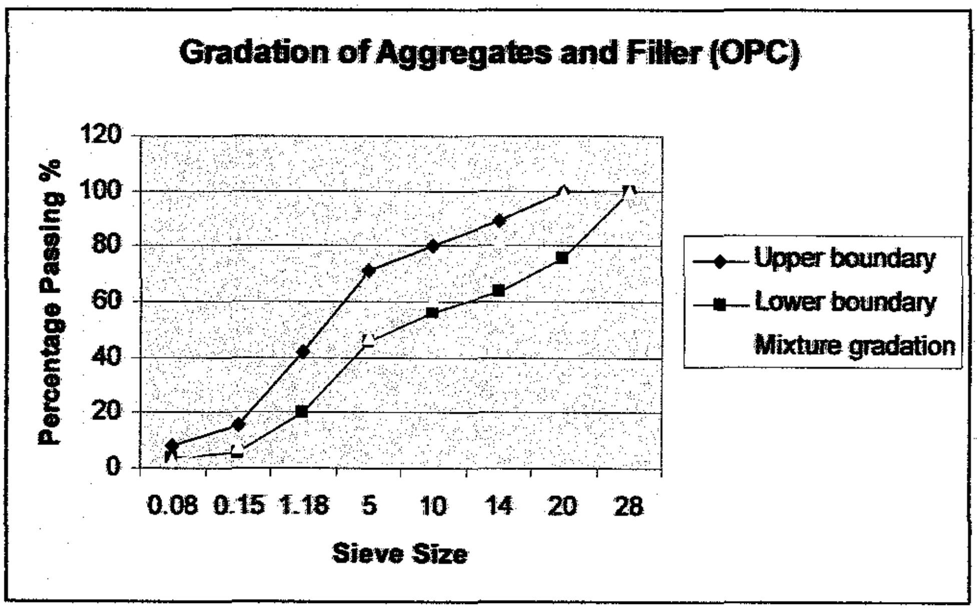

Figure 4.2: Optimum gradation of materials (OPC)

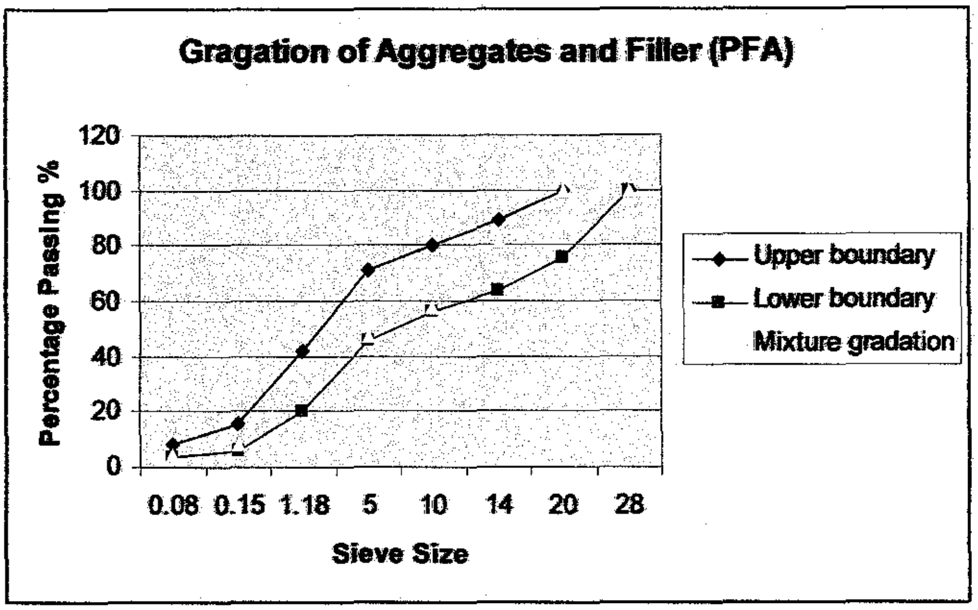

Figure 4.3: Optimum gradation of materials (PFA)

4.4 Design of Optimum Binder Content

In determining the optimum binder content (OBC), specimens are prepared using the optimum aggregate gradation proposed in the earlier stages. The specimens are prepared using 3%, 4%, 5%, 6%, and 7% of bitumen content. The weight of bitumen to be used is calculated based on the bitumen content percentage. For each bitumen content, 3 specimens will be prepared so that a more consistent and reliable result can be obtained. The specimens' preparation is done for both OPC and PFA, hence requiring a total of 30 specimens.

4.4.1 Ordinary Portland Cement (OPC)

The results of specimens prepared using OPC is tabulated in Table 4.11, Table 4.12, Table 4.13. The tabulated data includes height and diameter of specimens, weight of specimens in air and water, stability and flow of specimens, density, bulk specific gravity of mixture, air voids, and Marshall Stiffness.

The density, bulk specific gravity of aggregate, bulk specific gravity of mixture, air voids, and Marshall Stiffness is calculated based on the formulas. Refer Appendix for the formulas.

There are 5 line graphs being plotted using the tabulated data, namely: stability versus bitumen content (Figure 4.4); flow versus bitumen content (Figure 4.5); density versus bitumen content (Figure 4.6); air voids versus bitumen content (Figure 4.7); and Marshall Stiffness versus bitumen content (Figure 4.8). From the 5 graphs, optimum curves are fitted into the plotted data in order to attain the optimum value of bitumen content for each graph. The optimum binder content (OBC) is determined by taking the average values of optimum bitumen content from stability versus bitumen content graph, density versus bitumen content graph, and Marshall Stiffness versus bitumen content graph which gives a value of 5.6% of bitumen content.

At 5.6% of bitumen content, the value of stability, flow and air voids is checked whether it's complying with the JKR standards for test and parameters for asphaltic concrete. It is found that the values of stability, flow and air voids are all within the specified JKR standards.

Table 4.11: Measurements of specimens

Bitumen Content	Height	Diameter	Weight in air	Weight in water
3%	70.20	102.59	1217.33	683.17
4%	67.74	103.89	1219.33	687.67
5%	68.00	102.77	1228.33	695.50
6%	67.90	102.76	1242.17	704.33
7%	68.59	102.76	1280.00	723.67

Table 4.12: Stability and Flow of specimens

Bitumen Content	Stability	Correction Factor	Corrected Stability	Flow
3%	10.28	0.83	8.53	2.68
4%	8.11	0.83	6.73	5.65
5%	10.38	0.86	8.93	2.83
6%	10.71	0.86	9.21	3.53
7%	7.28	0.86	6.26	3.56

SG Aggregates = 2.648

Table 4.13: Density, SG mixture, Air Voids, and Marshall Stiffness of specimens

Bitumen Content	Density	SG mixture	Air Voids	Marshall Stiffness
3%	2.28	2.529	9.89	3.84
4%	2.29	2.491	7.93	1.44
5%	2.31	2.455	6.10	3.67
6%	2.31	2.42	4.56	3.03
7%	2.30	2.386	3.57	2.04

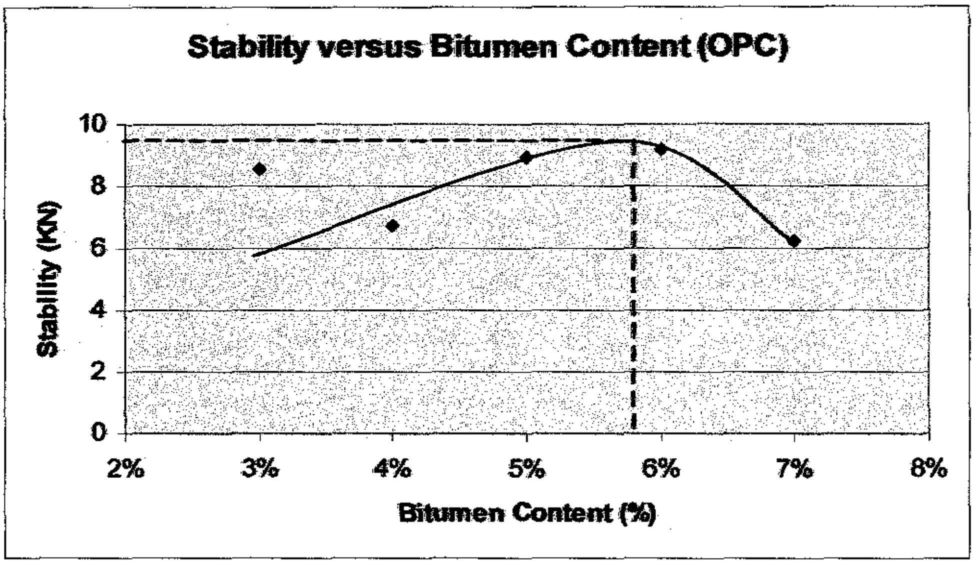

Figure 4.4: Stability versus Bitumen Content

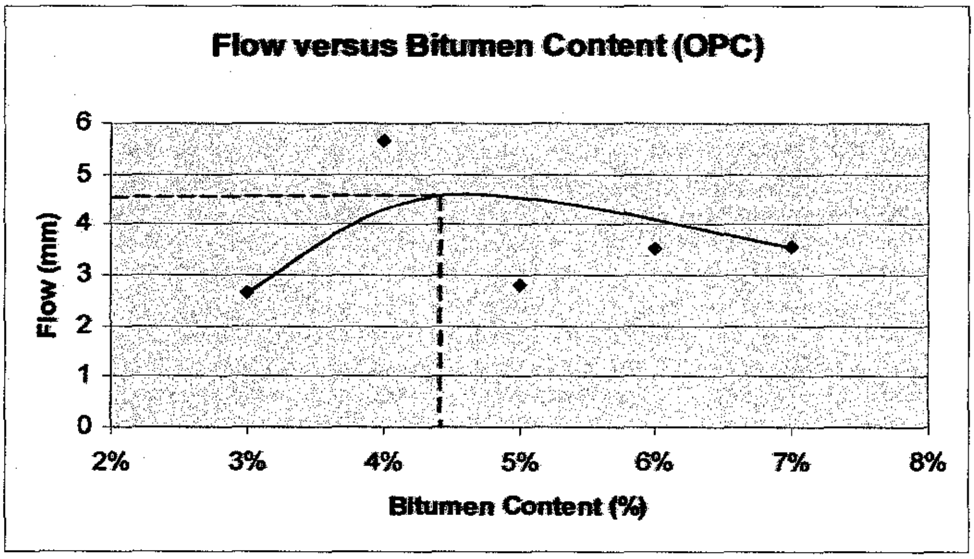

Figure 4.5: Flow versus Bitumen Content

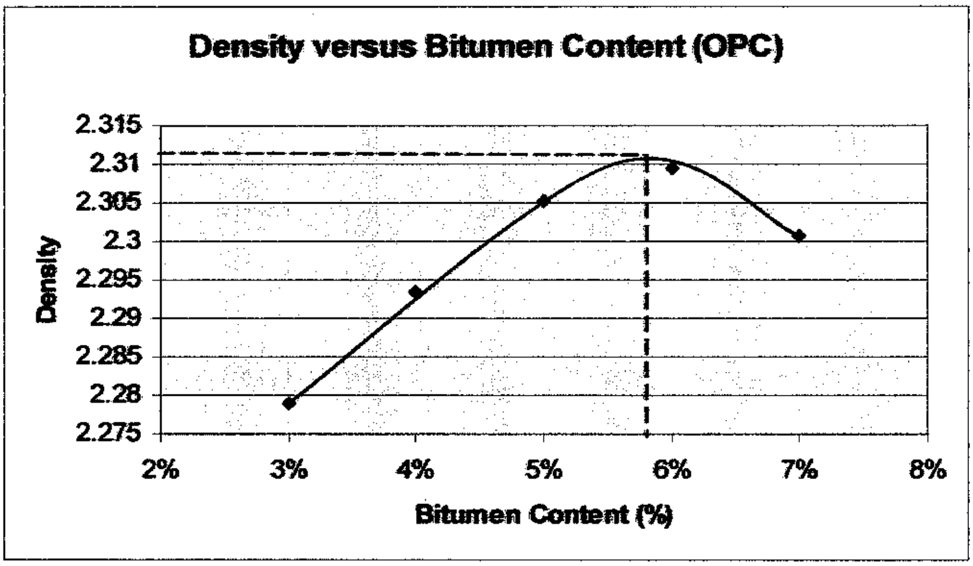

Figure 4.6: Density versus Bitumen Content

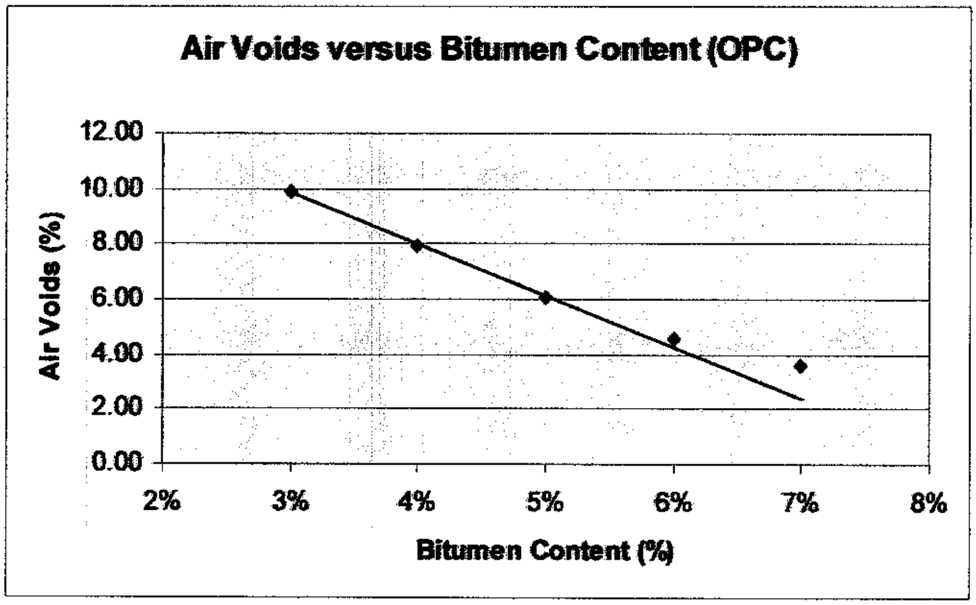

Figure 4.7: Air Voids versus Bitumen Content

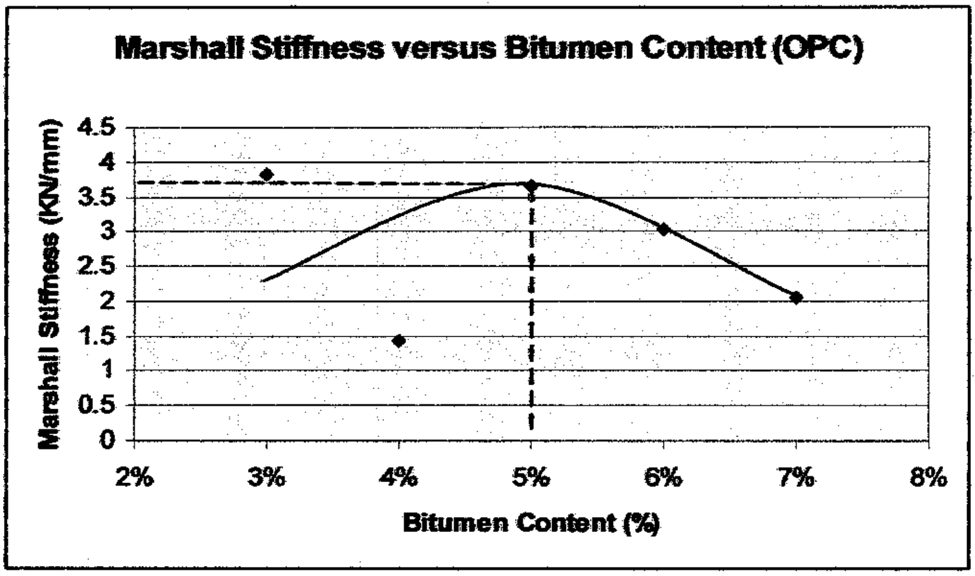

Figure 4.8: Marshall Stiffness versus Bitumen Content

4.4.2 Pulverized Fly Ash (PFA)

As for OBC determination using PFA, the aggregate gradation and percentage of bitumen content used is as of the ones used in OBC determination using OPC. The results are tabulated in Table 4.14, Table 4.15, and Table 4.16. Similarly, 5 sets of line graphs are plotted as shown in Figure 4.9, Figure 4.10, Figure 4.11, Figure 4.12, and Figure 4.13. Optimum curves are also included into each graph to assist in obtaining the optimum value of bitumen content.

The optimum binder content is determined by averaging the optimum values of bitumen content from the graphs of stability versus bitumen content, density versus bitumen content, and Marshall Stiffness versus bitumen content. The OBC for PFA specimens is found to be at 5.7%.

The stability, flow, and air voids at 5.7% bitumen content are checked with JKR standards for test and parameters for asphaltic concrete and are found that the values are within the specified range.

Table 4.14: Measurements of specimens

Bitumen Content	Height	Diameter	Weight in air	Weight in water
3%	69.99	102.74	1230.67	687.33
4%	68.22	103.84	1237.83	694.00
5%	68.78	102.79	1250.33	705.33
6%	68.55	102.84	1261.83	713.33
7%	67.36	102.77	1262.67	712.83

Table 4.15: Stability and Flow of specimens

Bitumen Content	Stability	Correction Factor	Corrected Stability	Flow
3%	6.14	0.83	5.10	2.57
4%	4.48	0.83	3.72	4.09
5%	5.86	0.86	5.04	8.61
6%	5.52	0.86	4.75	3.44
7%	5.41	0.86	4.65	3.08

SG Aggregates = 2.626

Table 4.16: Density, SG mixture, Air Voids, Marshall Stiffness of specimens

Bitumen Content	Density	SG mixture	Air Voids	Marshall Stiffness
3%	2.27	2.509	9.72	2.39
4%	2.28	2.473	7.96	1.10
5%	2.29	2.437	5.86	0.68
6%	2.30	2.403	4.26	1.60
7%	2.30	2.369	3.06	1.76

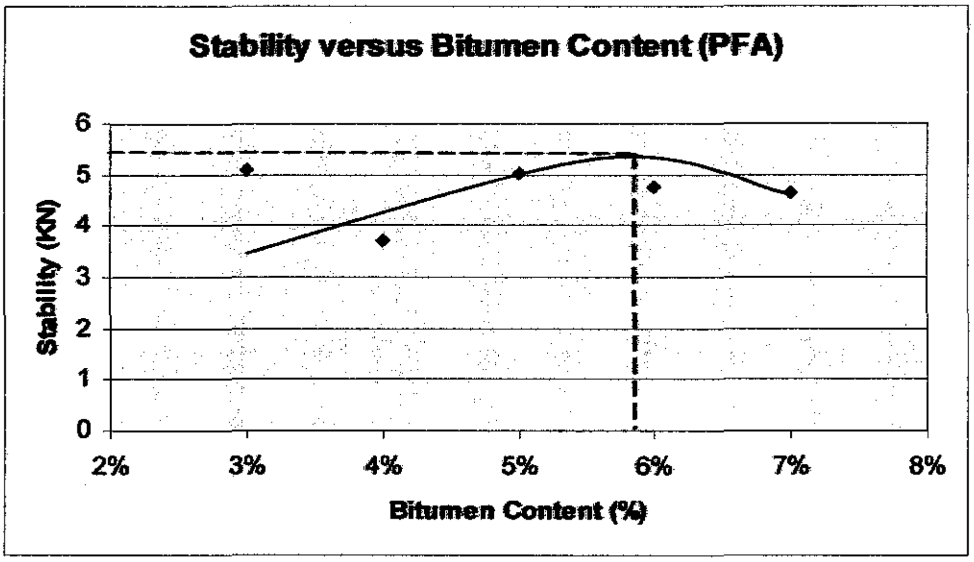

Figure 4.9: Stability versus Bitumen Content

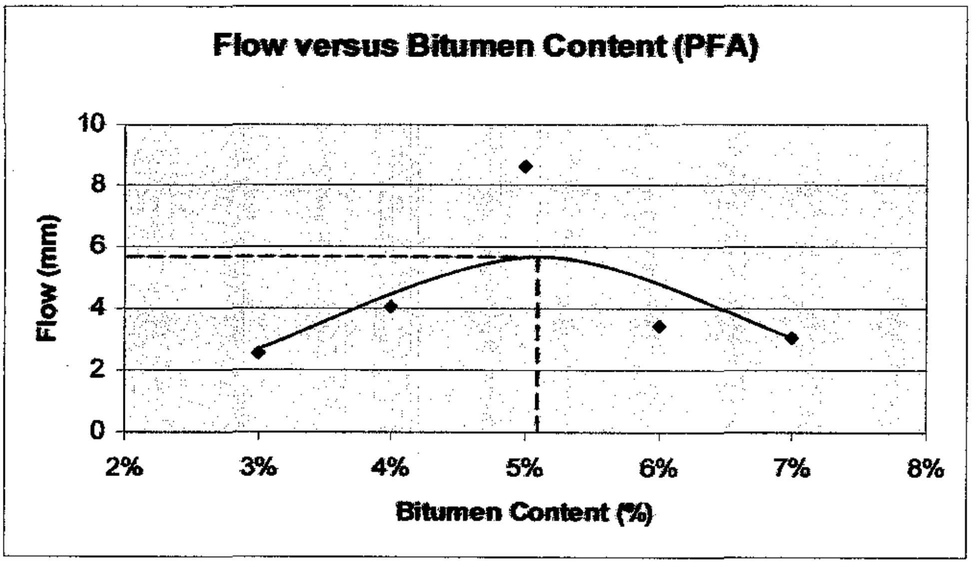

Figure 4.10: Flow versus Bitumen Content

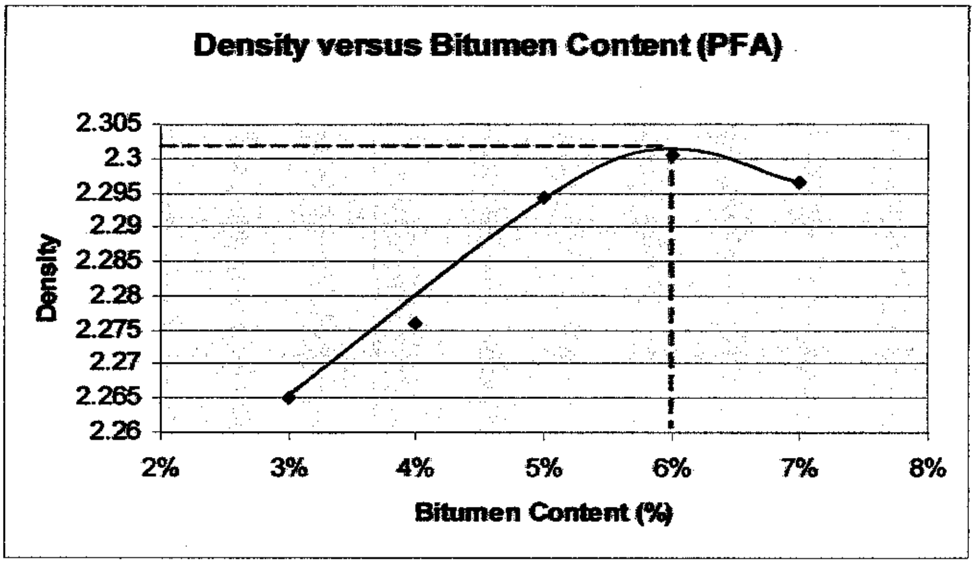

Figure 4.11: Density versus Bitumen Content

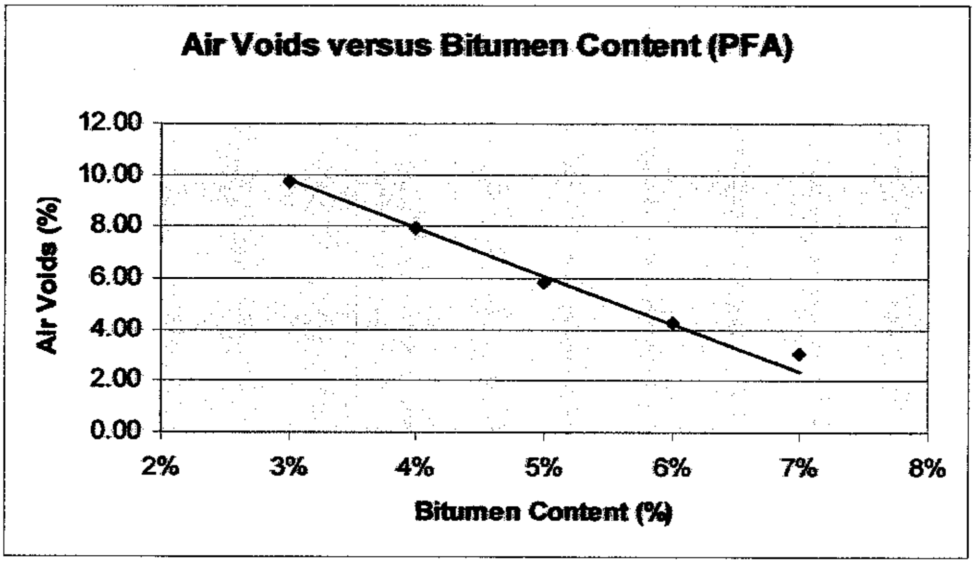

Figure 4.12: Air Voids versus Bitumen Content

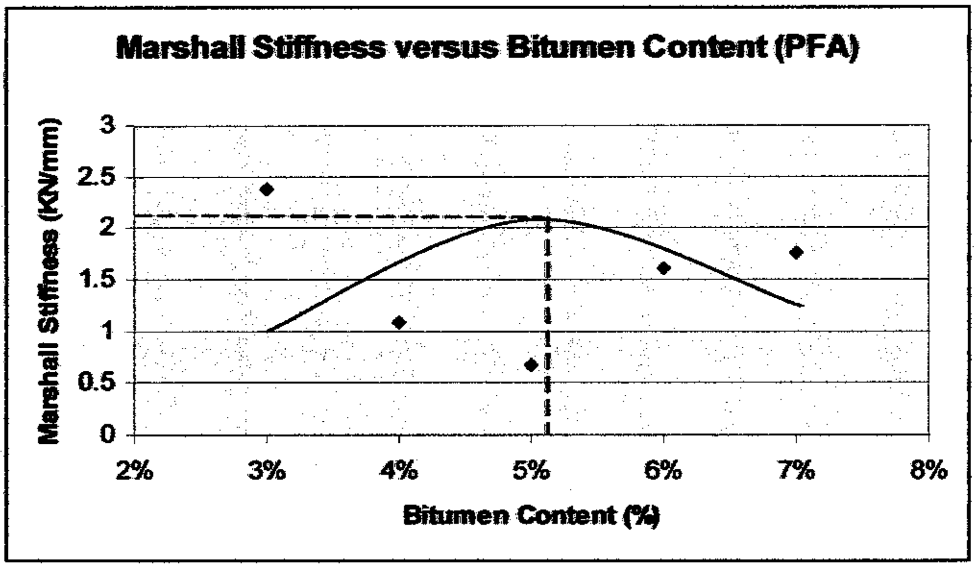

Figure 4.13: Marshall Stiffness versus Bitumen Content

4.4.3 Selection of Optimum Binder Content (OBC)

There are 2 sets of OBC being determined, 5.6% and 5.7% respectively. Since both of the OBC are almost the same, choosing either one of the OBC to be used in the Marshall Mix Design will not cause a significant effect in results difference. The OBC to be used in the Marshall Mix Design is chosen to be 5.7% because at this bitumen content, the specimens will have lower air voids compared to the one with 5.6% bitumen content.

4.5 Testing Results for control specimens (OPC)

Control specimens are prepared using the proposed optimum aggregate gradation of 50% coarse aggregate, 45% fine aggregate, 5% mineral filler and 5.7% bitumen content. For control samples, 3 specimens are prepared using OPC as mineral filler and is compacted to 75 numbers of blows using the Universal Compactor. The results are tabulated in Table 4.17, Table 4.18, and Table 4.19.

Table 4.17: Measurements of specimens

Specimen	Height	Diameter	Weight in air	Weight in water
OPC 75	66.03	103.67	1263.33	725.67

Table 4.18: Stability and Flow of specimens

Stability						
	S1	S2	S3	Average	Correction Factor	Corrected Stability
OPC 75	3.64	4.65	5.06	4.45	0.89	3.96

Flow				
	F1	F2	F3	Average
OPC 75	5.16	0.91	5.1	3.72

SG Aggregates = 2.648

Table 4.19: Density, SG mixture, Air Voids, Marshall Stiffness of specimens

	Density	SG mixture	Air Voids	Marshall Stiffness
OPC 75	2.35	2.43	3.29	1.06

4.6 Testing Results for test specimens (PFA)

Test specimens are prepared using the same optimum aggregate gradation and OBC as control specimens but instead of using OPC as mineral filler, test specimens are prepared using PFA as mineral filler. Instead of preparing for only specimens compacted to 75 numbers of blows using the Universal Compactor, test specimens are also prepared for compaction effort of 60 numbers of blows, 45 numbers of blows, and 30 numbers of blows. This is done in order to see the effect of the reduction in compaction effort to the stability, flow, density, Marshall Stiffness and most importantly, the air voids. The results obtained are tabulated into Table 4.20, Table 4.21, and Table 4.22.

Table 4.20: Measurements of specimens

Specimen	Height	Diameter	Weight in air	Weight in water
PFA 75	66.13	103.8	1259.50	722.67
PFA 60	67.2	101.5	1263.00	721.67
PFA 45	68.4	102.73	1262.33	716.17
PFA 30	67.43	103.87	1260.50	714.17

Table 4.21: Stability and Flow of specimens

Specimen	Stability	Correction Factor	Corrected Stability	Flow
PFA 75	6.21	0.89	5.53	4.30
PFA 60	6.05	0.89	5.38	3.70
PFA 45	5.86	0.86	5.04	3.30
PFA 30	3.69	0.86	3.17	4.39

SG Aggregates = 2.626

Table 4.22: Density, SG mixture, Air Voids, Marshall Stiffness of specimens

	Density	SG mixture	Air Voids	Marshall Stiffness
PFA 75	2.35	2.41	2.49	1.29
PFA 60	2.33	2.41	3.19	1.45
PFA 45	2.31	2.41	4.15	1.53
PFA 30	2.31	2.41	4.15	0.72

4.7 Comparison of Results

It is observed that for compaction effort of 75 numbers of blows using Universal Compactor, specimens using PFA as mineral filler has a higher stability, flow, and Marshall Stiffness compared to specimens using OPC (as shown in Figure 4.14, 4.15, 4.16). Besides that, PFA specimens compacted to 75 numbers of blows also show a lower air voids in the compacted mixture compared to OPC specimens of the same compaction effort (2.49% for PFA 75 compared to 3.29% for OPC 75). Even the air voids of PFA specimens compacted to 60 numbers of blows showed a lower air voids in the compacted mixture than the OPC specimens compacted to 75 numbers of blows (3.19% for PFA 60 compared to 3.29% for OPC 75). This showed that by substituting OPC as mineral filler with PFA, the air voids in the compacted mixture can be improved and the compaction effort can be reduced.

Table 4.23: Test results for control and test specimens

Specimen	Height (mm)	Diameter (mm)	Weight in Air (g)	Weight in Water (g)	Corrected Stability (KN)	Flow (mm)	Air Voids (%)	Marshall Stiffness (KN/mm)
OPC 75	66.03	103.67	1263.33	725.67	3.96	3.72	3.29	1.06
PFA 75	66.13	103.8	1259.50	722.67	5.53	4.30	2.49	1.29
PFA 60	67.2	101.5	1263.00	721.67	5.38	3.70	3.19	1.45
PFA 45	68.4	102.73	1262.33	716.17	5.04	3.30	4.15	1.53
PFA 30	67.43	103.87	1260.50	714.17	3.17	4.39	4.15	0.72

When the numbers of blows are reduced in the PFA specimens, it is noticed that the stability and density of the specimens decreases (shown in Figure 4.17 and Figure 4.19). The flow of the PFA specimens showed a decreasing trend from 75 numbers of blows to 45 numbers of blows before increasing back at 30 numbers of blows (Figure 4.18). As for the Marshall Stiffness of the PFA specimens, it increases from 75 numbers of blows to 45 numbers of blows before decreasing back at 30 numbers of blows (Figure 4.21). This is due to the increment of flow at 30 numbers of blows. On the other hand, air voids showed consistent increment as the numbers of blows are reduced until it reaches equilibrium at 45 numbers of blows and 30 numbers of blows (Figure 4.20).

Observation showed that the optimum numbers of blows for PFA modified specimens are to be at 45 numbers of blows. At this numbers of blows, the PFA modified specimens possess higher stability and Marshall Stiffness, similar flow and density, but having a higher air voids content as compared to OPC specimens compacted to 75 numbers of blows as shown in Table 4.23. Although the air voids percentage is higher, the difference is only about 1% so it is considered negligible. It is checked with JKR standards that the flow and air voids of PFA specimens compacted to 45 numbers of blows meet the minimum requirement for wearing course.

The main factors that contribute to the reduction of compaction effort required to produce a PFA modified asphalt concrete with the similar characteristics as an OPC asphalt concrete will be the shape and the size of the mineral filler particles. PFA consists of finer and more spherical particles as compared to OPC. Due to the finer and more spherical particles, it is easier for the particles of PFA to fill up the air voids in the asphalt concrete. Hence giving a lower air voids content. This can also be the factor why the flow is increased as finer and more spherical particles tend to flow easier.

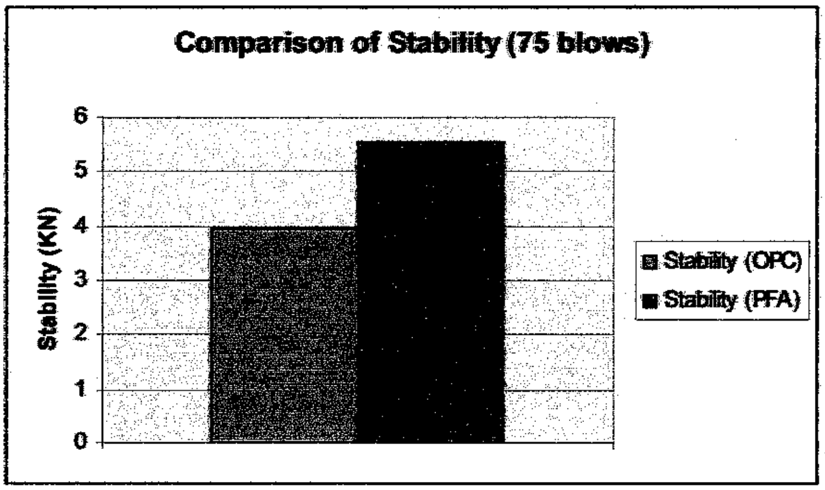

Figure 4.14: Comparison of Stability

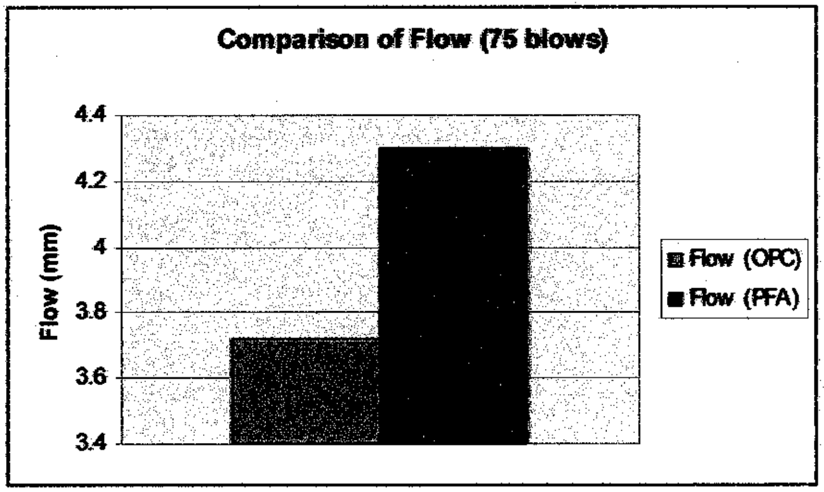

Figure 4.15: Comparison of Flow

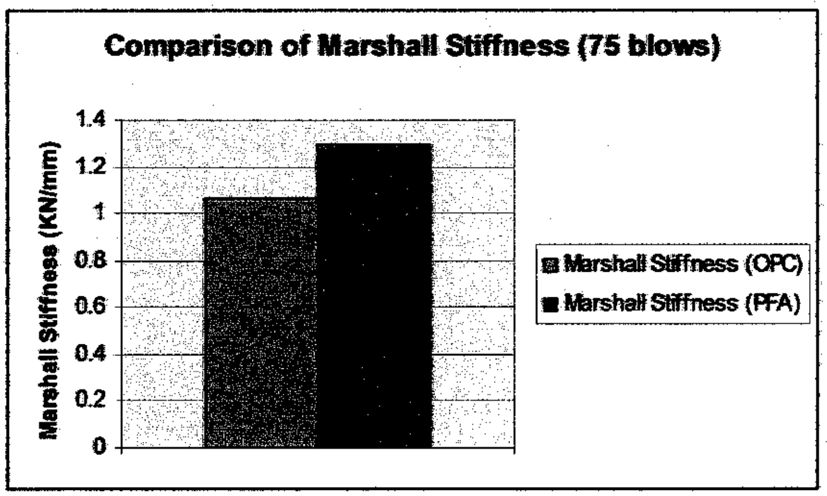

Figure 4.16: Comparison of Marshall Stiffness

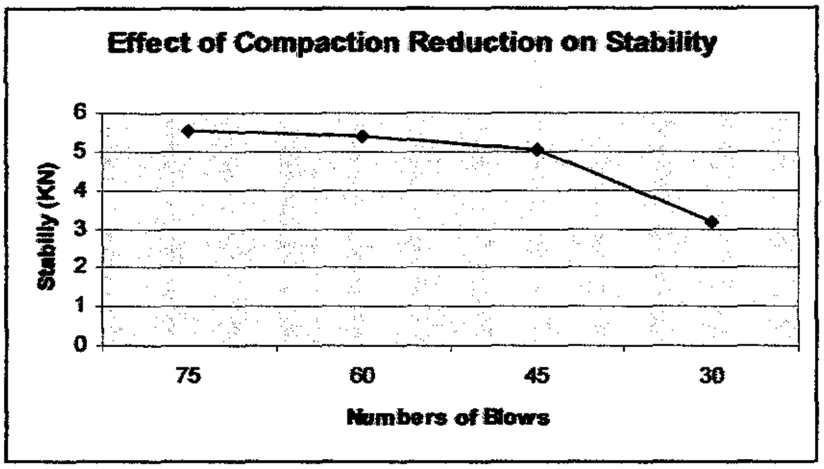

Figure 4.17: Stability versus Compaction Effort

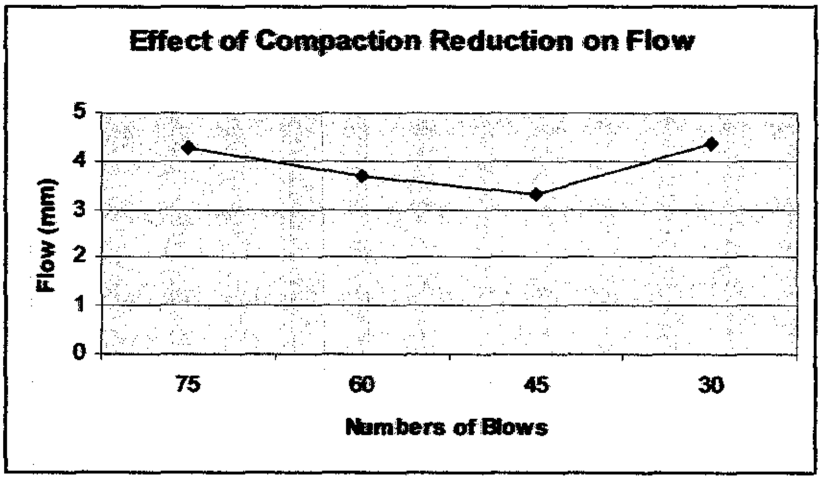

Figure 4.18: Flow versus Compaction Effort

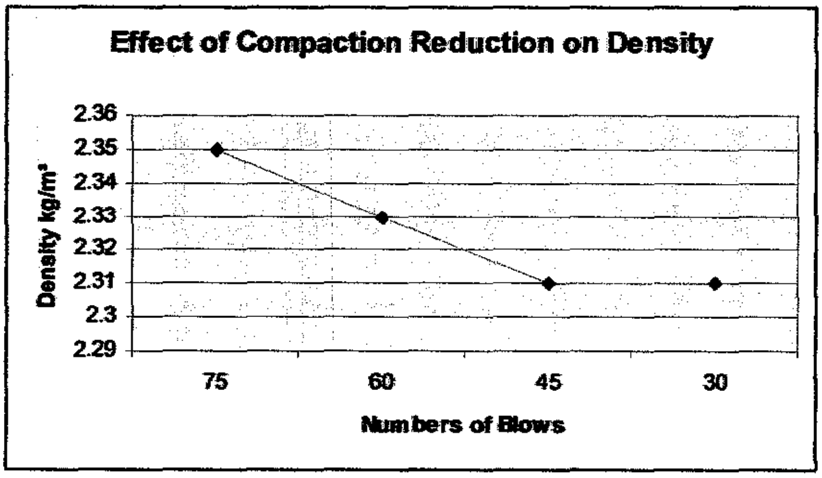

Figure 4.19: Density versus Compaction Effort

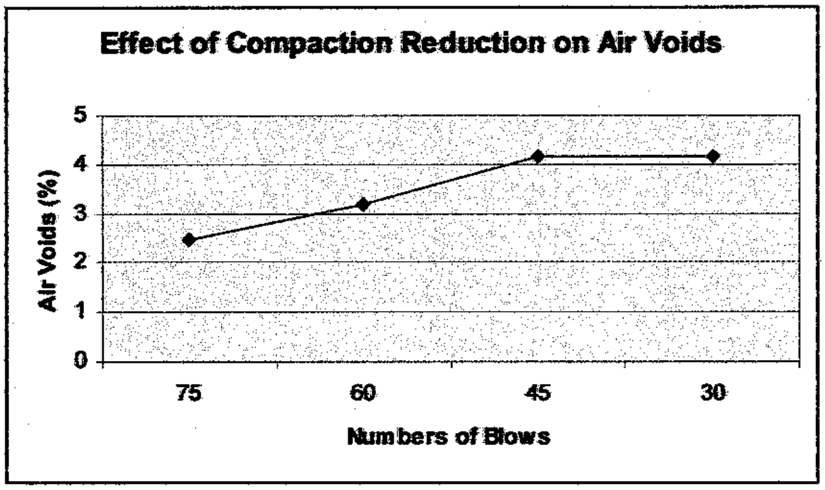

Figure 4.20: Air Voids versus Compaction Effort

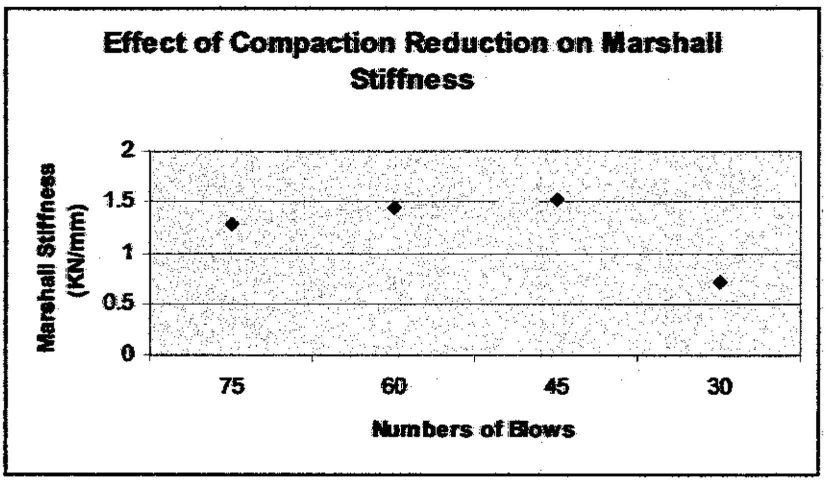

Figure 4.21: Marshall Stiffness versus Compaction Effort

4.8 Summary

PFA specimens have higher stability, flow, and Marshall Stiffness compared to OPC specimens of the same compaction effort (75 numbers of blows). PFA specimens compacted to 75 numbers of blows and 60 numbers of blows also showed a better air voids in the mixture (lower percentage) compared to OPC specimens compacted to 75 numbers of blows. Meanwhile both the OPC and PFA specimens compacted to 75 numbers of blows have the same value of density.

As compaction effort is reduced in the PFA specimens, density, stability, and flow decreases. Air voids and Marshall Stiffness increases as the compaction effort are reduced. At a compaction effort of 30 numbers of blows, flow increases and Marshall Stiffness decreases.

The optimum compaction effort for PFA modified pavement is chosen to be at 45 numbers of blows based on the results that showed that the parameters of the specimens are meeting the JKR standards for wearing course asphalt concrete.

5.0 CONCLUSION & RECOMMENDATION

There is a need to develop an energy saving asphalt concrete in Malaysia due to the importance of land as the dominant mode of transportation. Studies should be done to come out with a new mix design where a more economical, practical, and better performance asphalt pavement can be produced.

The application of pulverized fly ash in asphalt concrete pavement construction have yet to be commercialized and are still being researched and tested on its suitability to replace normal filler in asphalt concrete pavement. Hence, this study on the effect of PFA on compaction effort for asphalt concrete should be carried out.

It is seen that the air voids in asphalt concrete specimens containing PFA as filler (compacted to 75 and 60 numbers of blows) is lower compared to asphalt concrete specimens containing OPC as filler (compacted to 75 numbers of blows). The stability, flow, and Marshall Stiffness of the PFA specimens is of higher values compared to OPC specimens. This proved that by substituting OPC with PFA, the compaction effort can be reduced while maintaining and/or improving the performance of the asphaltic concrete.

The optimum compaction effort for the PFA modified asphalt concrete is selected to be 45 numbers of blows. The reason why it is selected is because, even at this low compaction effort, the results showed that the parameters meet the JKR standards minimum requirement for wearing course asphalt concrete.

To further improve this study in order to achieve a more reliable result, it is recommended that this study to be expanded where the control specimens are also prepared at a compaction effort of 60 numbers of blows, 45 numbers of blows, and 30 numbers of blows. The results from these specimens can then be compared to the PFA specimens at the same compaction effort. This comparison can further enlighten us on the behaviour of asphalt concrete as the compaction effort is being reduced.

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APPENDICES

Formula used:

1. **Determination of Optimum Binder Content (OBC)**

To find weight of bitumen to be used based on the percentage of bitumen

$$\% \text{ Bitumen} = \frac{B}{(B+1200)}$$

where, % Bitumen = percentage of bitumen in fraction
B = weight of bitumen in grams

2. **Bulk Specific Gravity of Aggregate (SG Aggregate)**

$$\text{SG Aggregate} = \frac{\%\text{CA} + \%\text{FA} + \%\text{Filler}}{\frac{\%\text{CA}}{\text{SG CA}} + \frac{\%\text{FA}}{\text{SG FA}} + \frac{\%\text{Filler}}{\text{SG Filler}}}$$

Where, % CA = percentage of coarse aggregate
% FA = percentage of fine aggregate
% Filler = percentage of filler
SG CA = Specific Gravity of coarse aggregate
SG FA = Specific Gravity of fine aggregate
SG Filler = Specific Gravity of filler

3. **Specific Gravity of Mixture (SG Mixture)**

$$\text{SG Mixture} = \frac{100}{\frac{\%\text{Agg}}{\text{SG Aggregate}} + \frac{\%\text{Bitumen}}{\text{SG Bitumen}}}$$

Where, % Agg = percentage of aggregate
% Bitumen = percentage of bitumen
SG Bitumen = Specific Gravity if bitumen

4. **Bulk Specific Gravity of Mixture (Density)**

$$\text{Density} = \frac{Wa}{Wa - Ww}$$

Where, Wa = weight in air
Ww = weight in water

5. **<u>Porosity (Air Voids)</u>**

$$\text{Air Voids} = (1 - \frac{\text{Density}}{\text{SG Mixture}}) \times 100\%$$

6. **<u>Marshall Stiffness</u>**

$$\text{Marshall Stiffness} = \frac{Stability}{Flow}$$

Results for OBC determination (OPC)

Height of Specimens			
Bitumen content	H1	H2	H3
3%	69.78	71.2	69.61
4%	69.65	67.9	65.66
5%	67.03	70.49	66.49
6%	68.28	69.53	65.9
7%	70.46	65.84	69.47

Diameter of Specimens			
Bitumen content	D1	D2	D3
3%	101.35	101.49	104.92
4%	101.79	105	104.89
5%	101.82	101.63	104.86
6%	101.67	101.81	104.79
7%	101.6	104.97	101.7

Bitumen content	Weight in Air		
	W1	W2	W3
3%	1235.5	1224.5	1192
4%	1198.5	1236	1223.5
5%	1205	1250.5	1229.5
6%	1241.5	1263.5	1221.5
7%	1286.5	1265.5	1288

Bitumen content	Weight in Water		
	W1	W2	W3
3%	684	669	696.5
4%	677	693	693
5%	706	695.5	685
6%	703	694.5	715.5
7%	734	720	717

Results for OBC determination (PFA)

Height of Specimens			
Bitumen Content	H1	H2	H3
3%	70.46	70.76	68.75
4%	69.73	67.68	67.25
5%	67.54	69.67	69.14
6%	66.12	69.23	70.31
7%	69.55	65.66	66.86

Diameter of Specimens			
Bitumen Content	D1	D2	D3
3%	101.7	101.62	104.9
4%	101.74	105.23	104.54
5%	104.97	101.75	101.65
6%	105.22	101.63	101.67
7%	101.79	104.82	101.71

Bitumen Content	Weight in Air		
	W1	W2	W3
3%	1232	1226	1234
4%	1238.5	1238	1237
5%	1243	1249	1259
6%	1250	1268.5	1267
7%	1274.5	1264	1249.5

Bitumen Content	Weight in Water		
	W1	W2	W3
3%	689	684	689
4%	695	697.5	689.5
5%	715.5	702	698.5
6%	714.5	722	703.5
7%	707.5	716.5	714.5

Results for Control Specimens (OPC compacted to 75 numbers of blows)

Height of Specimens		
H1	H2	H3
65.7	67.7	64.7

Diameter of Specimens		
D1	D2	D3
104.8	101.6	104.6

Weight in Air		
W1	W2	W3
1261	1267	1262

Weight in Water		
W1	W2	W3
722	730.5	724.5

Results for Test Specimens (PFA)

Numbers of blows	Height of Specimens		
	H1	H2	H3
75	66.8	67.3	64.3
60	67.2	66.8	67.6
45	69.1	67.5	68.6
30	66	69.7	66.6

Numbers of blows	Diameter of Specimens		
	D1	D2	D3
75	104.7	101.6	105.1
60	101.8	101.3	101.3
45	101.8	104.8	101.6
30	105.1	101.6	104.9

Numbers of blows	Weight in Air		
	W1	W2	W3
75	1256.5	1266.5	1255.5
60	1260	1266	1263
45	1266	1269	1252
30	1255.5	1260	1266

Numbers of blows	Weight in Water		
	W1	W2	W3
75	717	729.5	721.5
60	722	718	725
45	720.5	716.5	711.5
30	713.5	714	715

Numbers of blows	Stability		
	S1	S2	S3
75	4.33	3.93	10.38
60	6.89	4.99	6.27
45	7.1	6.45	4.02
30	3.29	5.06	2.71

Numbers of blows	Flow		
	F1	F2	F3
75	4.25	5.22	3.43
60	3.13	3.69	4.28
45	1.64	1.81	6.46
30	5.29	2.66	5.21