CERTIFICATION OF APPROVAL

Use of Pulverized Fly Ash in Asphalt Concrete Mixture

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.

(YEE CHUNG TUCK)

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Abstract

The increasing wastes and by-products from the rapidly developed industries nowadays, has become a major concern globally, whereby, on how to handle these wastes and by-products properly without causing any damages to the society and environment. Among the wastes/by-products from the industries are such as, steel slag ash, kiln dust, blast furnace slag and much more. In this study, the concern will be on Pulverized Fly Ash (PFA), which is a by-product from the coal combustion industry. The highway construction requires lots of raw material from the natural resources. Hence, researches on incorporating industries wastes into asphalt pavement, to reduce consumption and need on virgin aggregates are indeed important. In this study, experiments will be conducted to study on the characteristics of asphalt concrete mixture when PFA is mixed into the mixture rather than using OPC as filler. Marshall Mix Test will be carried out to determine the optimum binder content (OBC) for both mixtures in order to design or determine the material proportions to prepare samples for performance tests. In this study, the samples are prepared by using 55% of coarse aggregates, 40% fine aggregates and 5% filler (both for OPC and PFA mixtures) and the OBC for both OPC and PFA mixtures are 5.58% and 5.45% respectively. Among the performance tests involved in this study are Wheel Tracking Test (deformation/rutting) and Beam Fatigue Test (asphalt concrete mixture deterioration). The obtained results will be analyzed and discussed to determine the advantages or disadvantages of incorporating PFA into asphalt concrete mixture in engineering aspects, such as workability, permanent deformation, fatigue life and flexural stiffness. From the performance tests conducted, PFA mixture has lower permanent deformation, higher flexural stiffness but lower fatigue life as compared to conventional mixture.

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Chapter I

Introduction

1.1 Introduction

The purpose of this study is to research on application of industrial wastes or by-products in asphalt concrete mixtures. The increasing volume of generated wastes and disposal of these wastes had eventually become a global issue to the world. As a result, lots of studies and researches on industrial wastes application in highway industry have been conducted as the efforts of revealing the possible positive results such as, upgrading the current highway system and lower construction and rehabilitation cost. The wastes that have been studied include rice husks ash, steel slag ash; kiln dust, fiber from oil palm and others recycle materials. The selected waste in this study is Pulverized Fly Ash (PFA), a waste generated from coal burning industry.

Sieve analysis as accordance to BS812: Part 103:1985 will be conducted to determine the aggregate gradation, followed by Marshall Mix Test as accordance to BS598: 1985 to determine the optimum binder content (OBC) for designing the bituminous mix. The obtained results will be compared and conform to JKR ACW 20 standard. Upon obtaining the bituminous mix design, samples will be prepared and performance tests, which are Wheel Tracking Test and Beam Fatigue Test, will be conducted. The obtained results from both tests will be analyzed and discussed to determine the improvements achieved in the study.

Lastly, this study will include the recommendations for future works that can be implemented, as the expansion from this study, such as other performance tests to determine the improvements in other aspects.

1.2 Background of Study

In this new millennium, the needs and demands to develop new asphalt concrete mixture with better and higher performance as compared to the conventional one, has become more significant especially highway engineering fields or industries. A better and higher performance asphalt concrete mixture may have higher initial cost, however this cost will be overcome in long term, due to the lower rehabilitation and repairing cost in future work. Hence, economy-wise, it is truly encouraged to develop a better and higher performance asphalt concrete mixture.

The typical type of asphalt pavement used in Malaysia for the moment, is the conventional asphalt pavement, which consists of coarse aggregates, fine aggregates, binder and filler. The commonly used filler is Ordinary Portland Cement (OPC). The critical concerns associated with pavement are the defects and problems regarding pavement performance, such as:

- Permanent deformation/rutting
- Cracking
- Water susceptibility

For this matter, the selection of material to be applied is another concern, due to availability and cost of the material itself, which regards as economy concern. Hence, utilization of industrial wastes and by-products are viewed as a prevailing trend these days. The carried out studies on using these wastes into asphalt concrete mixture showed positive results, in terms of strength, durability, performance and other aspects. Among the wastes used before are steel slags, klin dust, blast furnace slag and other industries' wastes.

1.3 Problem Statement

As the volume of waste and by-product materials generated in our society and the cost of disposal continue to increase, there is increased pressure and incentive to recover and recycle these materials for use in secondary applications. Since the highway construction industry required large volume of raw materials, hence introducing these wastes into highway industry is expected to be a better option. In facts, many highway agencies have become participants in these recycling efforts. In spite of this, by recycling these wastes, it was hope that the consumption of natural resources can be reduced.

1.4 Objective and Scope of Study

The main objective of this study is to determine the suitability of using PFA as a replacement material for filler in asphalt concrete mixture. The commonly used filler in highway industries are quarry dust and OPC. The purpose of the study is to determine the improvement achieved by using PFA as a filler substitute in asphalt concrete mixture.

Jabatan Kerja Raya (JKR) ACW 20 will be the standard guideline to be used throughout this study, in order to achieve optimum binder content from Marshall Mix test before determining the improved performance. The performances to be determined in this study are:

- Permanent deformation/rutting through Wheel Tracking Test
- Flexural Stiffness through Beam Fatigue Test.
- Fatigue life through Beam Fatigue Test.

1.5 Organization of Thesis

This report is divided into a few chapters and each chapter will discuss extensively concerning the findings, outcomes, procedures, discussions, conclusions and last but not least the recommendations for future works of this study. There are 7 chapters in this report, and the content of each report are such as:

Chapter 1

This chapter will brief regarding background of the study, problem statement, objective and scope of study for this research.

Chapter 2

This chapter will brief about the material classifications, which are coarse aggregates, fine aggregates, filler and binder. Besides, PFA production, current management and usage of PFA, physical and chemical properties of PFA, improvements achieved by using other industries wastes and lastly, the excepted or theoretical improvements to be achieved by using PFA in asphalt concrete mixture.

Chapter 3

The main content in this chapter is regarding methodology of the research, which will explain briefly, steps by steps, all the laboratory tests that had been implemented in this study, such as sieve analysis, Marshall Mix test and the 2 performances tests which are Wheel Tracking test and Beam Fatigue test.

Chapter 4

The results obtained from sieve analysis will be used in this chapter to determine the materials proportions to be used in this study, as accordance to JKR ACW 20 specifications. Besides, the outcomes from the Marshall Mix test are included in this chapter to determine the optimum binder content, by taking into consideration Marshall Stability, Bulk Density, Voids and Flow, to be used in preparing samples for performances tests.

Chapter 5

This chapter will brief and display the outcomes or results obtained from the implemented performances tests, which are Wheel Tracking and Beam Fatigue test.

Chapter 6

Discussion on the obtained results from implemented performances tests will be done extensively in this chapter, in order to explain the outcomes obtained in this study. This is done by including all the technical terms and related facts in highway engineering views.

Chapter 7

This last chapter consists of summary or conclusions for this study, and also provides recommendations as the guidelines of frame works from future researches works for this study.

Chapter II

Literature Review and Theory

2.1 Introduction

In this chapter, focused will be given on material classification as been stated in Jabatan Kerja Raya (JKR) manuals, and to give a rough idea on roles of each component in asphalt concrete mixture, that will contribute towards producing a good asphalt concrete mixture, in terms of its performance.

Then, explanation on Pulverized Fly Ash production, current PFA management, PFA in construction industries, PFA physical and chemical properties, examples of successful wastes incorporated in highway industry and lastly, the theoretically improvements achieved in this study.

2.2 Materials Classifications

Material classification is an important procedure in determining and selecting the suitable material to be used in asphalt concrete mixture. This is because in asphalt concrete mixture, a well-graded aggregate is an important factor and criterion to be fulfilled initially. Having a well-gradation of aggregates, these aggregates will eventually filled up the voids and pore spaces in between the aggregates and hence providing higher strength and durability to the mixture itself. The components of asphalt pavement constitutes of:

1) Binder
2) Coarse aggregates
3) Fine Aggregates
4) Filler

The role of each elements in the mixture is important, for instance coarse aggregates provide the mechanical frame, providing strength to the mixture, while fine aggregates and fillers functioned to fill in the voids, due to its smaller particle sizes. Lastly, bitumen which performed as binder will provide stability to the whole structure when it binds together all the elements in the pavement.

2.2.1 Binder

There are varieties of bitumen grade available, ranging from grade 40 to 200. The selection of bitumen grade to be used depends largely on the climate and the designed traffic loading. For instance, a high temperature and traffic loading will require lower penetration bitumen, hence a lower penetration bitumen grade is recommended, such as 40/50, while for a lower temperature and traffic loading will use a higher penetration bitumen grade, such as 180/200. For normal temperature and traffic loading, a bitumen grade of 80/100 is adequate. The function of binder is to bind all the elements together and hold them properly in other to develop the mixture's strength and stability.

2.2.2 Coarse Aggregates

Coarse aggregate shall be screened crushed hard rock, angular in shape and free from dust, clay, vegetative and other organic matter, and other deleterious substances(3). The main function of coarse aggregate is to provide the primary strength to the mixture itself. Thus, good quality coarse aggregates are recommended to be used in the mixture. The quality of the coarse aggregate can be determined by several means or tests, such as, Los Angeles Abrasion test, and Aggregate Compaction Value test. All these tests will provide information regarding the quality of the coarse aggregates.

2.2.3 Fine Aggregates

Fine aggregates shall be clean natural sand, screened quarry fines, or mining sand. It also shall be non-plastic and free from clay, loam, aggregations of material, vegetative and other organic matters, and other deleterious substances[3]. Fine aggregates functioned to enhance the mixture's stability, through interlocking of aggregates and filling the voids. Hence, well-graded fine aggregates, in the range of 2.36 mm to 0.075 mm are important to ensure the mixture's stability.

2.2.4 Filler

Mineral filler shall be finely divided mineral matter such as rock dust, limestone dust, hydrated lime, hydraulic cement or other suitable material[3]. At the time of mixing with bitumen it shall be sufficiently dry to flow freely and shall be essentially free from agglomerations. Not less than 70% by weight shall pass the No.200 sieve (0.075 mm). The smaller size particles (less than 0.075 mm) will eventually fill up the voids in between coarse and fine aggregates. In present study, Pulverized Fly Ash is proposes to be used as the filler in producing better performance pavement instead of conventional pavement that used of OPC.

2.3 Pulverized Fly Ash (PFA)

PFA to be used in Portland Cement Concrete (PCC) must meet the requirements of ASTM C618 [6]. Under this specification, PFA is categorized as:

- Class F fly ash
- Class C fly ash

Fly ash that is produced from the burning of anthracite or bituminous coal is typically pozzolanic, and is referred to as Class F fly ash, if it meets the chemical composition and physical requirements specified in ASTM C618. Meanwhile, fly ash that produced from the burning of lignite or sub-bituminous coal, in addition to having pozzolanic properties, will also have some self-cementing properties (ability to harden and gain strength in the presence of water). If this fly ash meets the chemical composition and physical requirements as been described in ASTM C618, hence it will be referred as Class C fly ash.

Fly ash is stored dry in silos, so that it can be used or disposed of in a dry or wet form. Water can be added for stock-pilling or land-filling in a conditioned form (15% to 30% moisture), or for disposal by sluicing into settling ponds or lagoons in wet form. The main advantage of conditioning fly ash is the reduction of blowing or dusting during transportation and outdoor storage.

2.3.1 Production of PFA

Pulverized Fly Ash, (PFA) is produced from the process of burning pulverized coal in a coal-fired boiler (wastes by-products). PFA is a fine-grained, powdery particulate material that is carried off in the flue gas and usually collected from the flue gas by electrostatic precipitators, bag houses or mechanical collection devices such as cyclones. Currently, there are 3 types of coal-fired boiler furnaces, which are dry-bottom boilers, wet-bottom boilers and cyclone furnaces. The commonly used is dry-bottom furnace.

When pulverized coal is combusted in a dry-ash, dry-bottom boiler, 80% of all the ash leaves the furnace as fly ash, entrained in the flue gas. When pulverized coal is combusted in wet-bottom (slag-tap) furnace, about 50% of the ash is retained in the furnace, with the remaining 50% being entrained in the flue gas. Lastly, in a cyclone furnace, where crushed coal is used as a fuel, 70% - 80% of the ash is retained as boiler slag and only 20% to 30% leaves the furnace as dry ash in the flue gas(1). **Figure 2.1** showed the flow diagram of fly ash production in a dry bottom coal-fired utility boiler operation.

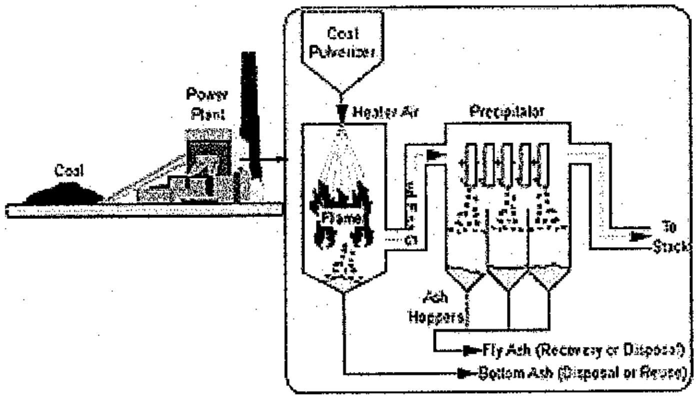


Figure 2.1:

Fly Ash Production in a dry bottom coal-fired utility boiler operation.

In 1996, the most recent year for which fly ash statistics are available, the electrical utility in United States of America, generated approximately 53.5 million metric tons of coal fly ash. Until 1996, the fly ash production annually remained roughly the same since 1977, ranging from 42.9 to 49.7 million metric tons (47.2 to 54.8 million tons) [(2)]. (if possible, include similar statistic in Malaysia)

2.3.2 Current PFA management

2.3.2.1 Recycling

Approximately 14.6 million metric tons (16.2 million tons) of fly ash were used in 1996, and of this total, 11.85 million metric tons (13.3 million tons) or about 22% of the total quantity of fly ash produced, were used in constructions-related applications. **Table 2.1** showed the list of the leading construction application, in which fly ash was used.

In between 1985 to 1995, the usage of fly ash fluctuated in between 8 to 11.9 million metric tons (11.3 million tons) per year, averaging 10.2 million metric tons (11.3 million tons) per year. Fly ash is useful in wide range of applications, since fly ash is a pozzolan, a siliceous or alumini-siliceous material that, when in a finely divided form and in the presence of water, will combine with calcium hydroxide (from lime, Ordinary Portland Cement) to form cementitious compound[4].

Applications	Quantity Used		Percent of Total Used
	Million metric tons	Million tons	
Cement production and/or concrete products	7.2	8.0	60
Structural fills or embankments	1.9	2.2	17
Stabilization of waste materials	1.7	1.9	14
Road base or sub-base materials	0.63	0.7	5
Flow-able fill and grouting mixes	0.27	0.3	2
Mineral filler in asphalt paving	0.15	0.2	2
Approximate Total	*11.85*	*13.3*	*100*

Table 2.1: Leading construction application of PFA

2.3.2.2 Disposal

Although fly ash generated/produced is used in many applications, however about 70% to 75% of the fly ash is still disposed of in landfills or storage lagoons. Fortunately, much of this ash is capable of being recovered and used.

2.3.3 Application of PFA in Construction

PFA has been used as additive in concrete and showing positive improvements in the behavior and properties of concrete, while in plastic state and long term hardened concrete. Among the improvements achieved by applying PFA in concrete are :[5]

Concrete in plastic state	*Long term concrete performance*
1. Improved workability 2. Reduced segregation 3. Increased pump-ability 4. Reduces equipment wear	1. Increase concrete strength 2. Reduces drying shrinkage 3. Resistant to sulphate attack 4. Mitigates alkali aggregate 5. Reduces heat of hydration 6. Cost competitive

Table 2.2: Advantages of PFA in concrete

While **Table 2.2** showed the improvements achieved by applying PFA in concrete, below listed down the desired improvement parameter to be achieved in highway construction industries which are:

- Stiffness
- Permanent deformation
- Fatigue life
- Flexibility
- Impermeability
- Durability
- Workability
- Economy

2.3.4 Current usage of PFA

PFA had been used in variety of ways in the construction industries since past decades. Among the PFA applications are [7]:

i. ***Portland Cement Concrete- supplementary cementitious material***

Fly ash has been successful used as admixture in PCC and is the largest use of fly ash. It can be used as a feed material for producing Portland cement and as a component of Portland-pozzolan blended cement. While applying fly ash in this way, fly ash must be in dry form, and the quality shall be monitored closely. The important properties that need to be considered are fineness, loss on ignition and chemical content. The fly ash used must also have sufficient pozzolanic reactivity and must be of consistent quality.

ii. ***Asphalt Concrete – mineral filler***

Mineral filler in asphalt concrete mixture consists of particles, less than 0.075 mm (No 200 sieve) in size, to fill voids in pavements and serve to improve the cohesion of binder and mixture's stability. Fly ash is capable of meeting the gradation requirements and other pertinent physical (non-plastic) and chemical (organic content) requirements of mineral filler specifications. Fly ash must be in dry form, and for certain sources of fly ash having high content of lime (CaO), may be useful as an anti-stripping agent, and commonly applied in hot mix asphalt.

iii. ***Stabilized base (sub-base)***

Sub-base are mixtures of aggregates and binders, which increase strength, bearing capacity and pavement's sub-structure durability. Since fly ash may exhibit pozzolanic properties (self cementing), it can and has been successfully used as part of the binder in stabilized base construction applications. The successfulness depends on the strength's development within the matrix formed by the pozzolanic reaction between fly ash and the activator. The cementitious matrix acts as binder to hold aggregate particles together.

iv. ***Flow-able fill***

This is a slurry mixture consists of sand or other fine aggregate and a cementitious binder (normally used as substitute for compacted earth backfill). Fly ash is used in flow-able fill applications as fine aggregate and supplement to or replacement for cement. When fly ash is added in large quantities, the fly ash will act as both fine aggregates and part of cementitious matrix.

v. ***Embankment and fill material***

As embankment or fill material, fly ash is used as a substitute for natural soils. For this manner, fly ash must be stock-piled and conditioned to its optimum moisture content to ensure the material is not too dry and dusty or too wet and unmanageable. When fly ash, is at or near its optimum moisture content, it can be compacted to its maximum density and will behave as like a well compacted soil.

2.3.5 Physical Properties

Fly ash consists of fine, powdery particles that are predominantly spherical in shape and glassy (amorphous) in nature. The carbonaceous material in fly ash is composed of angular particles, and the particle size distribution is similar to silt (less than 0.075 mm or No 200 sieve). Although sub-bituminous fly ashes are silt-sized, they are slightly coarser than bituminous fly ashes. (2)

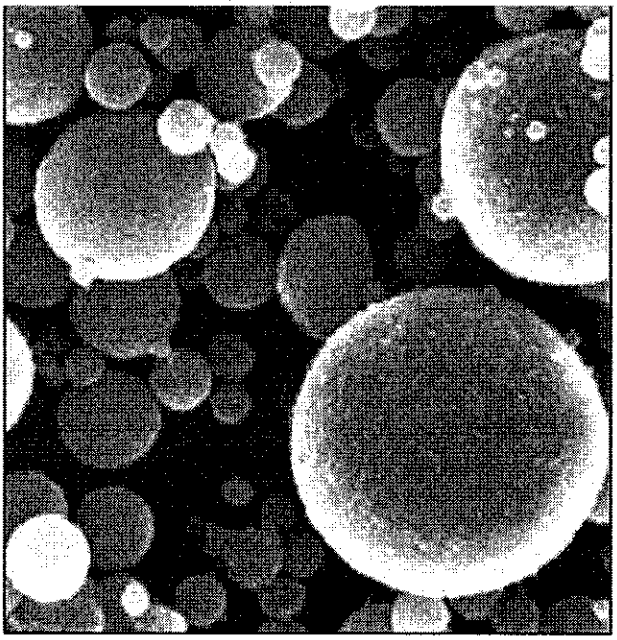


Figure 2.2: PFA particle shape (microscopic)

The specify gravity of fly ashes ranges from 2.1 to 3.0, while its specific surface area (measured by Blaine air permeability method) [8] may range from 170 to 1000 m^2/kg. Fly ash color can vary from tan to gray to black, depending on the amount of unburned carbon. The lighter the color, the lower will be the carbon content.

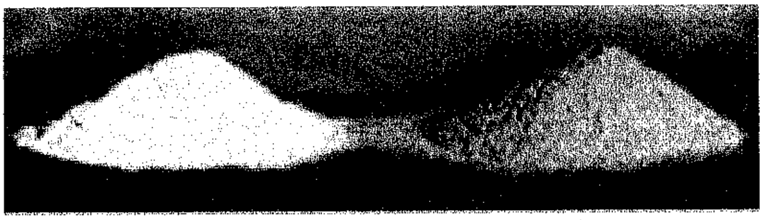


Figure 2.3: Typical fly ash color

2.3.6 Chemical Properties

The main components of bituminous coal fly ash are silica, iron oxide and calcium, with varying amounts of carbon, measured by loss on ignition (LOI). Lignite coal fly ashes are characterized by higher concentrations of calcium and magnesium oxide and reduced percentages of silica and iron oxide, as well as lower carbon content, compared to bituminous coal fly ash[9]. **Table 2.3** compared the normal range of chemical constituents of bituminous coal fly ash with lignite and sub-bituminous coal fly ash.

The main difference between Class C and Class F fly ash is in the amount of calcium, silica, alumina and iron content in the ash[8]. In Class F fly ash, total calcium typically ranges from 1 to 2 percent, mostly in the form of calcium hydroxide, calcium sulfate and glassy components in combination with silica and alumina. In contrast, Class C fly ash may have reported calcium oxide contents as high as 30 to 40 percent [10]. Another difference between Class F and Class C is that the amount of alkalis (combined sodium and potassium) and sulfates (SO_4) are generally higher in the Class C fly ashes than in the Class F fly ashes.

Component	*Bituminous*	*Sub-bituminous*	*Lignite*
SiO_2	20 – 60	40 – 60	15 - 45
Al_2O_3	5 – 35	20 – 30	10 – 25
Fe_2O_3	10 – 40	4 – 10	4 – 15
CaO	1 – 12	5 – 30	15 – 40
MgO	0 – 5	1 – 6	3 – 10
SO_3	0 – 4	0 – 2	0 – 10
Na_2O	0 – 4	0 – 2	0 – 6
K_2O	0 – 3	0 – 4	0 – 4
LOI	0 – 15	0 – 3	0 – 5

Table 2.3: Normal range of chemical composition for fly ash produced from different coal types (expressed as percent by weight)

2.4 Other industries wastes

Despite of using PFA in asphalt concrete mixture, other wastes and by-products from the industries had also been studied and researched concerning its application in highway construction industry. **Table A-1** in the appendix showed the applications of other wastes and by-products from the industry. Among the wastes by-products are:

2.4.1 Steel slag

The improved properties are :(11):

- **Stability**

  A very high stability, 1.5 to 3 times higher than conventional mixes with good flow properties.

- **Stripping resistance/good frictional**

  Resistance to stripping is enhanced due to the presence of free lime.

- **Rutting resistance**

  Resists rutting after cooling but yet still compactable due to good flow properties. This property is advantageous for highways, industrial roads, parking areas subjected to heavy axle loads.

2.4.2 Blast furnace slag

The improved properties are [12]:

- **Stability**

  The angular shape and high friction angle of crushed BFS, contributes to good lateral stability.

- **Frictional property**

  This is due to rough, vesicular surface texture, high angularity and hardness of BFS.

- **Resistance to rutting**

  This is due to good flow properties, resulting in a mix that resists rutting after cooling and yet compactable.

- **Resistance to stripping**

  Due to its hydrophobic nature, BFS has a high affinity for asphalt cement compared to water, resulting in excellent adhesive bond between BFS aggregate particles and asphalt cement, hence excellent in stripping resistance.

2.5 Expected improvement by applying PFA

Theoretically, the expected improvements are:

Reduction in porosity

This is because of the small particles size, mainly less than No 200 sieve (0.075 mm). As a result of this small particle size, PFA particles will fill in the voids in between coarse and fine aggregates.

Resistance to cracking

This is due to the reduction of porosity, since voids may not only contain water alone, but as well as air, the entrapped air will oxidize the binder and hence, the binder will not hold the aggregates properly anymore. As time passed, cracking will be then initiated.

Resistance to rutting

Due to PFA nature properties (hydrophobic to water), PFA particles have lower affinity towards water, and thus when water filled up the void in asphalt concrete mixture, the binder shall still hold the aggregate tightly. Hence, permanent deformation will be significantly reduced.

Improved Workability

Since PFA particles are spherical in shape, thus this will ease the placement of asphalt concrete mixture while still in hot condition.

Economy

Cost savings from reduction of maintenance activities in long term, longer serviceability life and better and higher performance asphalt pavement. Lastly, reduction in disposing cost of the wastes.

2.6 Conclusion

As a summary for this chapter, the materials to be used in asphalt concrete mixture need to be classified conform to the specifications, in order to proceed with the design mix. The specification used in this study is accordance JKR standards.

The improvements achieved by incorporating wastes from industries, highly dependent on physical and chemical properties of the wastes itself. For instance, the shape of the particle, either spherical or angular, will eventually give different characteristics, whereby a spherical shape will improve the workability, while for angular shape particle, will have higher frictional resistance.

CHAPTER III

METHODOLOGY

3.1 Introduction

Studies and research on applying industries' wastes and by-products had been carried out. This is because the results of applying these wastes showed convincing results in improving asphalt pavement performance and properties. Among the wastes and by-products are, blast furnace slag, steel slag and crumb rubber. In this study, Pulverized Fly Ash (PFA) is incorporated into asphalt pavement as filler.

This chapter discusses briefly on the procedures and experiments need to be conducted in this study. All selected materials to be used in this study are required to conform to the JKR specifications and standards. This is because if the materials used are not accordance to the specifications, then the asphalt pavement is subjected to road failure when is introduced to the public use [Dr. Ibrahim Kamaruddin].

Briefly, the first step in the study is to determine the optimum binder content of conventional mixture (controlled unit) where the determined binder content will be used to mix the controlled unit. The same procedures will be done by replacing Ordinary Portland Cement (OPC) with Pulverized Fly Ash (PFA). Then the comparison of performance for both mixtures will be conducted using ***Wheel Tracking Test*** and ***Beam Fatigue Test***. The objectives are to study the improvements by incorporating PFA as filler in asphalt concrete mixture and to study the effects and behaviors of the bituminous mix with the existence of PFA rather than Ordinary Portland Cement.

3.2 Preparation of Materials

3.2.1 Aggregates

The type of aggregate used in this research is granite obtained from the laboratory stockpiles. Even though the aggregates have been graded during the production process in quarry, sieve analysis still has to be conducted to get a better gradation of aggregates. These are the procedures in preparing the aggregates [13]:

- Aggregates are transferred from the stockpiles to the laboratory.
- Aggregates are washed to clean away the dusts and clays.
- Aggregates are incubated in the oven with temperature more than 100°C to evaporate the moist trapped between the aggregates.
- Aggregates are then sieved with a series of sieve sizes according to Jabatan Kerja Raya (JKR) specifications shown in **Table 3.1**.
- Aggregates are then to be weighed according to the amount needed for mix.

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

Table 3.1:

Gradation limits for aggregates according to JKR standard for ACW 20 wearing course.

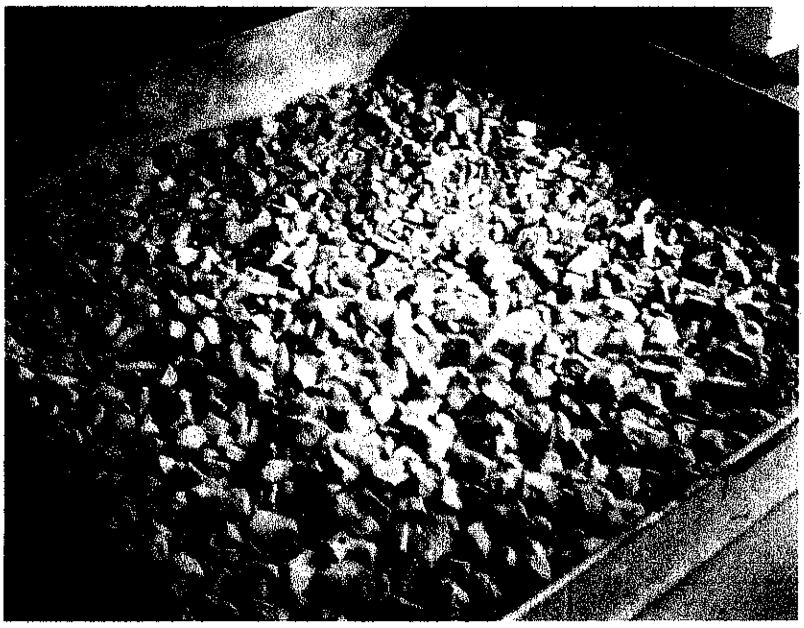


Figure 3.1:
Coarse aggregates

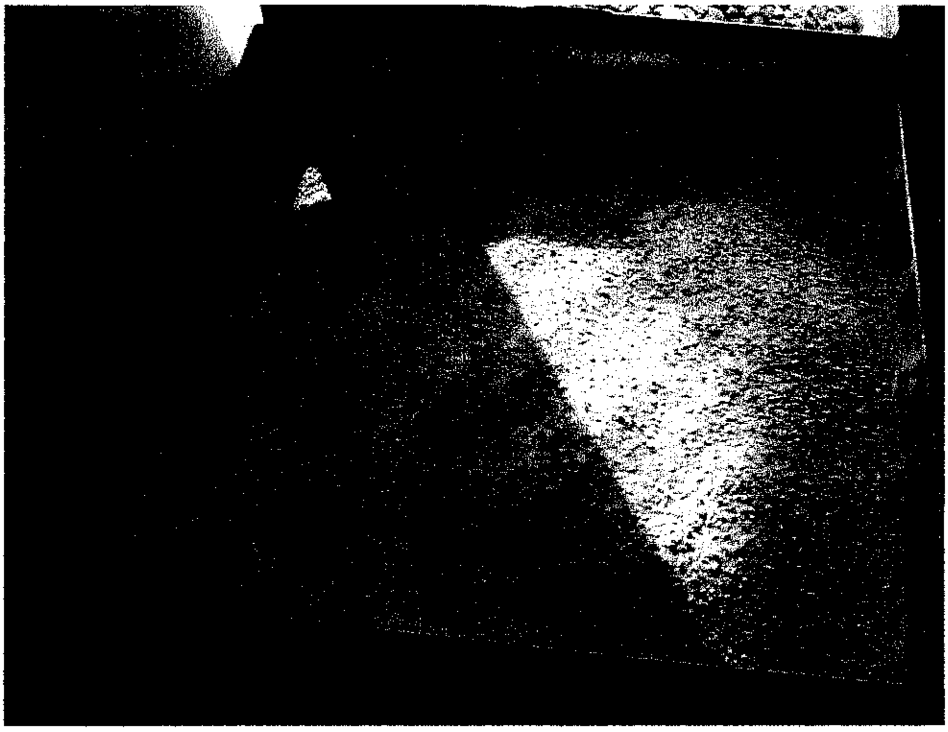


Figure 3.2:
Fine aggregates

3.2.2 Filler

Ordinary Portland Cement (OPC) will be used as filler for this project as the controlled unit, whilst PFA shall be used for comparison of performance and improvement, in terms of deformation and fatigue life. According to the JKR specifications, not less than 70% by weight of filler shall pass the BS 75μm sieve.

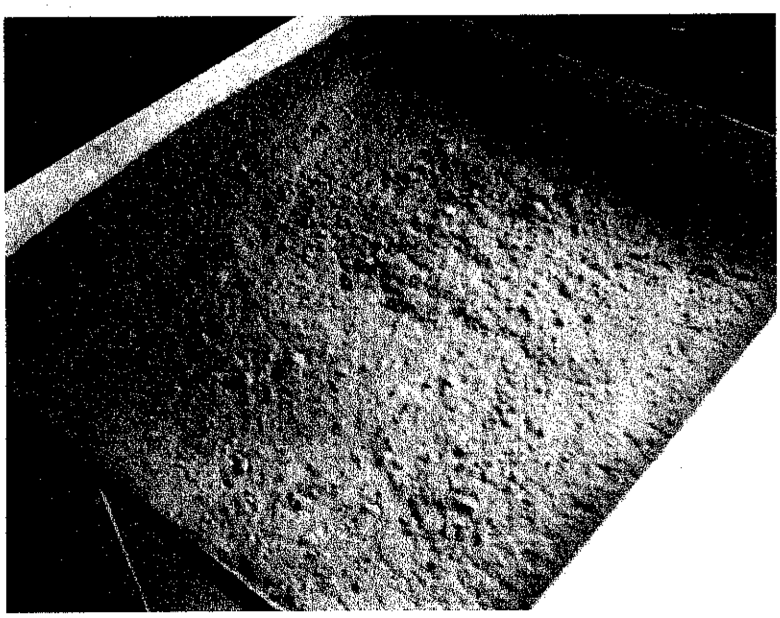


Figure 3.3: Ordinary Portland Cement (OPC)

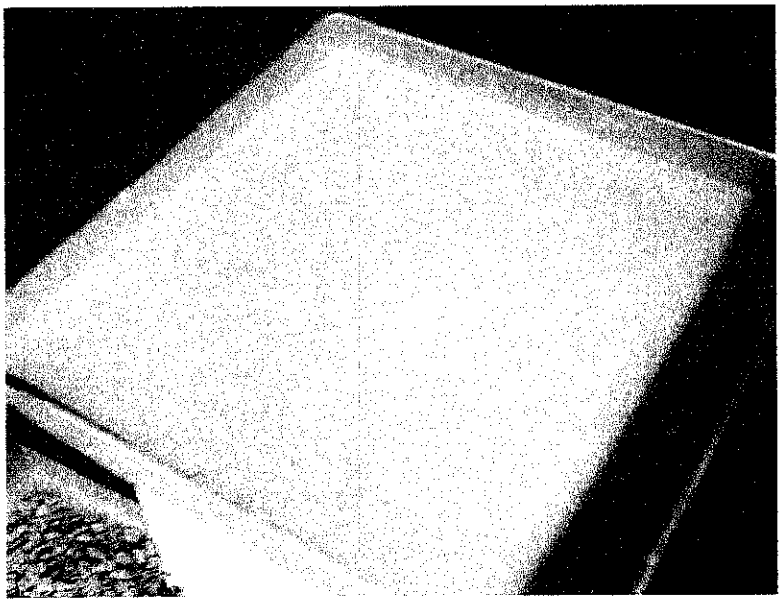


Figure 3.4: Pulverized Fly Ash (PFA)

3.2.3 Binder

Binder grade used for the project is bitumen with penetration 80/100. The bitumen came in drum and directly can be applied for preparing the samples.

3.3 Marshall Mix Test

3.3.1 Introduction

Marshall Mix test is a compression test where a cylindrical shape specimen with a diameter of 100 mm and 63 mm height was loaded radially at a constant rate of strain of 50.8 mm/min [13]. The maximum load in kN that the specimen could withstand is the stability value of the specimen and meanwhile the total amount of deformation in units of mm that occurs up to the point the loads start decreasing is recorded as flow value.

3.3.2 Equipments

a) Equipments used for sample preparation are: spatula, oven, pan, Marshall Mould, gyratory compactor machine and electronic balance.

b) Equipments used to conduct the Marshall Test are electronic balance, buoyancy balance, Vernier scale and Marshall Testing Machine.

3.3.3 Preparation of Asphalt Specimens

1. All materials are batched and kept in an oven at 150°C for 24 hours. The mixer is also heated to the same level of temperature; therefore great care should be exercised when handling hot materials and equipment.
2. The batched granular materials (plus filler) are mixed in the mixer and mixed dryly for about 1 minute, and then the appropriate amount of bitumen is added to the aggregates. Mixing is continued until all particles are coated with bitumen.

3. The materials are compacted in the Marshall Mould (which is also kept at 150°C). After filling the mould with appropriate amount of materials, materials are then evenly distributed in the mould by tamping the materials (using steel rod) 15 times around the edges and 5 times in the centre. At this stage, the sample is ready for compaction using the Gyratory Compactor Machine, which is set to the following standard conditions:

Axial load	=	0.7 MPa
Angle of gyration	=	1°
Number of gyrations	=	150

4. When the specimens have cooled down to room temperature, they are extruded from the moulds. The weight of each specimen in air and water and its height are taken for density calculation.

Figure 3.5: Gyratory Compactor

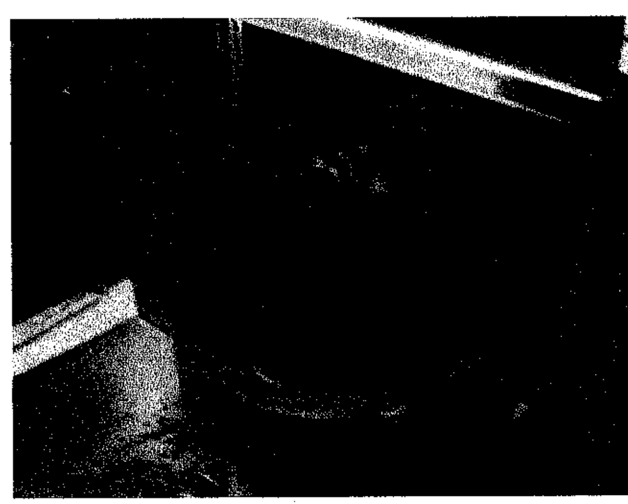


Figure 3.6: Sample extruded from gyratory compactor

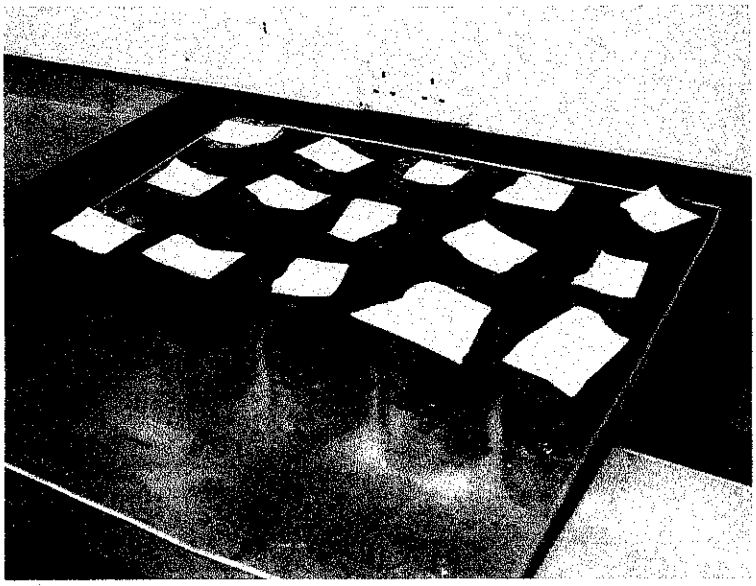


Figure 3.7: Conventional samples (15 samples)

Figure 3.8: PFA samples (15 samples)

3.3.4 Testing Asphalt Specimens

1) The specimens are heated in water bath with temperature of 60°C for 30 minutes.
2) The specimens are then placed in the Marshall testing rig. The breaking head of Marshall testing apparatus is also conditioned to 60°C.

3) The specimens are loaded radially at a constant rate of strain of 50.8 mm/min. The Marshall testing rig is set to stop when the stability exceeded 25 kN or the flow exceeded 10 mm.

4) The stability and flow of each specimen is determined as the maximum load that the specimen can withstand.

5) The stability value obtained above is corrected by coefficient factor (refer Table 3.2) in order to take into account the dimensions of the sample.

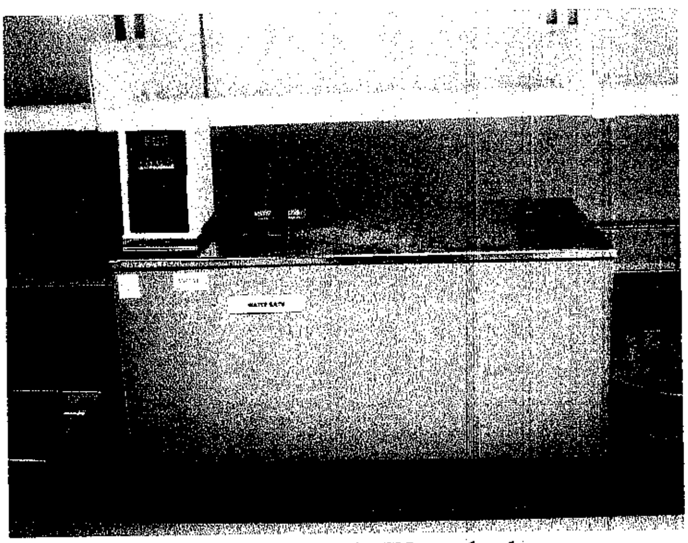


Figure 3.9: Water bath

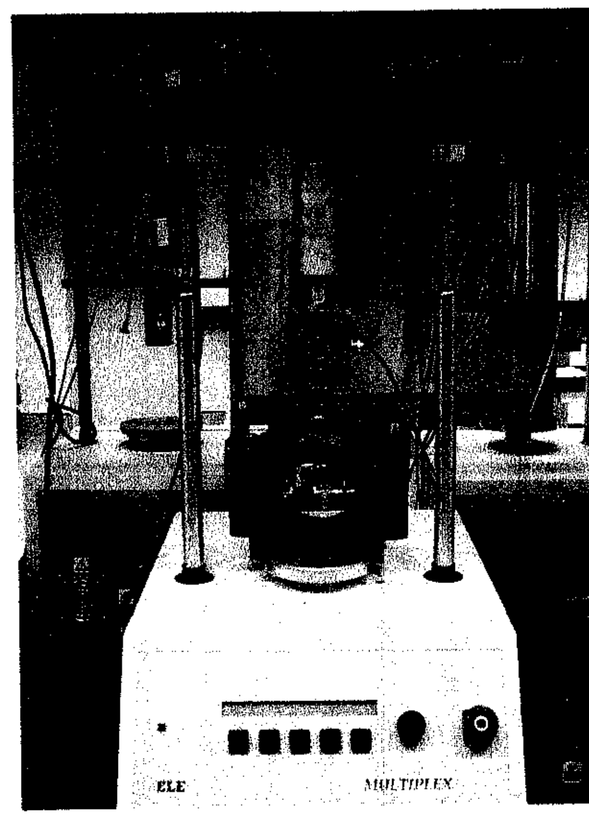


Figure 3.10:
Marshall Testing Rig

Volume of Specimen (cm^3)	Approximate Thickness of Specimen (cm)	Coefficient Factor
200 – 213	2.54	5.56
214 – 225	2.70	5.00
226 – 237	2.86	4.55
238 – 250	3.02	4.17
251 – 264	3.18	3.85
265 – 276	3.34	3.57
277 – 289	3.49	3.33
290 – 301	3.65	3.03
302 – 316	3.81	2.78
317 – 328	3.97	2.50
329 – 340	4.13	2.27
341 – 353	4.29	2.08
354 – 367	4.45	1.92
368 – 379	4.60	1.79
380 – 392	4.76	1.67
393 – 405	4.92	1.56
406 – 420	5.08	1.47
421 – 431	5.24	1.39
432 – 443	5.40	1.32
444 – 456	5.56	1.25
457 – 470	5.72	1.19
471 – 482	5.88	1.14
483 – 495	6.03	1.09
496 – 508	6.19	1.04
509 – 522	6.35	1.00
523 – 535	6.51	0.96
536 – 546	6.67	0.93
547 – 559	6.83	0.89
560 – 573	6.99	0.86
574 – 585	7.14	0.83
586 – 598	7.30	0.81
599 – 610	7.46	0.78
611 – 625	7.62	0.76

Table 3.2: Coefficient factor (CF) for adjusting stability values

3.4 *Wheel Tracking Test*

3.4.1 Introduction

Wheel Tracking Test is used to determine the plastic deformation of asphalt based road surface wearing courses under temperature (normally is 45°C) and pressures similar to those experienced under road use.(14) Such test can be carried out during road construction and also in laboratory. This test will prevent road surfaces being laid, which rut in hot weather and need to be re-laid. The performance of the material is assessed by measure the resultant rut depth after a given number of passes. (15)

3.4.2 Equipments

- Wessex Dry Wheel Tracker
- Specimen slab mould
- Hand compactor
- Oven
- Grease
- Brush
- Asphalt concrete mixer
- Spatula

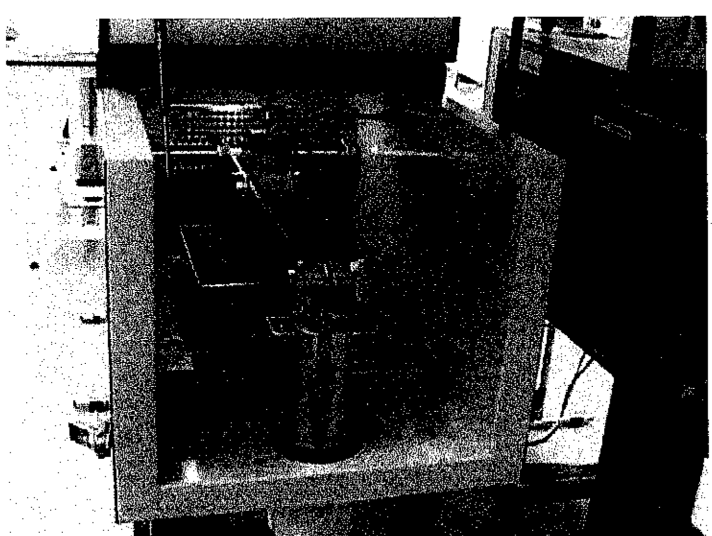


Figure 3.11: Wheel Tracking Test Equipment

3.4.3 Procedures of sample preparation and testing

1. The materials mixing procedure is similar to the Marshall Mix test but the current total mass is approximately 10 kg instead of 1.2 kg for Marshall Mix. The optimum binder content determined earlier in Marshall Stability Test will be used for preparation of conventional mix and PFA sample.
2. Either brown paper square or grease will be applied onto the internal base of the mould for the ease of dismantling of the mould later.
3. The mixed material is evenly spread into the mould and tamped to ensure an even distribution before compacting with the hand compactor.
4. The mixed materials (10kg) need to be compacted layer by layer in three layers.
5. The mixed materials need to be spread until it is about 5mm above the top of the mould if 30kg roller with 310mm face width is used for compaction. Compaction will be carried out until the flat face level with the top of the mould.
6. Sample is allowed to cool in room temperature before being removed from the mould.
7. The slab needs to be cured in an oven of 45°C before it is readily to be tested in the wheel tracking machine with same temperature.
8. The test will run for 1946 cycles with two passes, forth and back [(16)] in one cycle for 45 minutes and the total rut depth is observed from the computer connected to the wheel tracking machine.

3.5 Beam Fatigue Test

3.5.1 Introduction

Road pavements are subjected to continuous cyclic deformations under the influence of moving traffic during their lifetime. These deformations are of dynamic character and cause pavement cracking and other types of damage. The processes of asphalt concrete deterioration under the cyclic loadings are determined by the fatigue properties of the material. Deformation of the asphalt concrete in road pavements is of combined character from compressive, tensile and bending caused by traffic and temperature actions (17). Fatigue tests are carried out by applying a load to a specimen in the form of control stress or control strain mode and determining the number of load applications required to induce "failure" of the specimen (3). In control strain mode, failure is defined at the point where the stiffness of the specimen decreases to 50% of the initial stiffness (17).

3.5.2 Equipments

- UTM Machine
- Beam Fatigue Test mould
- Asphalt concrete mixer
- Oven
- Grease
- Brush

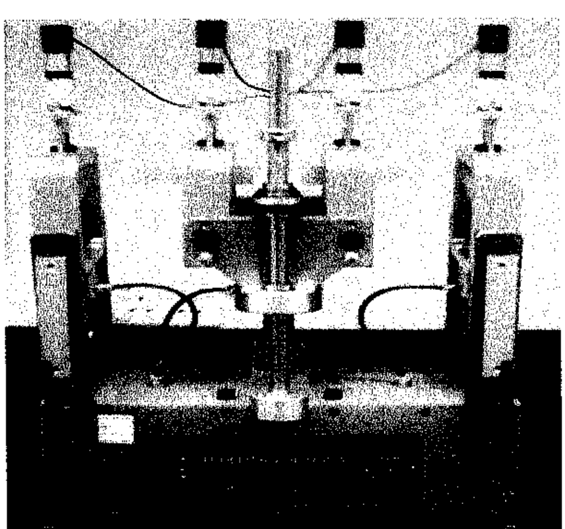


Figure 3.12:
Beam Fatigue Test equipment

3.5.3 Procedures of sample preparation and testing

1. The required beam sample size to be prepared is 63.5mm x 50mm x 400mm with density of 2.23. The mass of mix materials to be prepared will be calculated based on the size and the density. .
2. The mix materials were then compacted in the mould by using the special mould's lid designed for compaction purposes.
3. Beams were then cured in room temperature before tested with the beam fatigue test equipment in UTM machine.
4. The test will be conducted in control sinusoidal strain mode of loading.
5. The test here will be tested in middle strain level which is about 400 to 500 micro strain. Beam fatigue also can be tested using high strain level (600 to 800 micro strain) and low strain level (200 to 300 micro strain).

3.6 Results Analysis

This is the final step of the project where all the test results obtained will be gathered and analyzed. The analysis is based on the comparison of performance and properties between conventional mix and rubber modified mix. All the findings will then be discussed to understand the theory behind the behaviors of PFA modified mix observed in this project.

CHAPTER IV

Mix Design

4.1 Introduction

This chapter will discuss briefly on the results obtained from sieve analysis and Marshall Mix test. The outcomes from sieve analysis will be the material proportions to be used for sample preparation in Marshall Mix design. The determined material proportions will be compared to JKR ACW 20 standard and will conform to this standard. This is shown in aggregate gradation graphs plotted in **Figure 4.1** and **4.2**.

While sieve analysis determines the composition of material proportions, the purpose of implementing Marshall Mix test is to determine the optimum binder content (OBC) of the mixture, by taking into consideration Marshall Stability, Bulk Density and Porosity. The OBC is determined through the plotted graphs of these three aspects, and the value shall be the average value obtained from these 3 aspects. Lastly, the obtained value will be used to determine the flow and shall be counter-checked with standard specified by JKR, to determine the conformance of the mix before preparing samples for performance tests.

4.2 Sieve Analysis

Initially, sieve analysis is conducted to determine the aggregate size gradation of the available aggregates in stockpile. The gradation of coarse aggregates, fine aggregates and Ordinary Portland Cement (OPC) and coarse aggregates, fine aggregates and Pulverized Fly Ash (PFA) are then plotted in a semi-log graph (Refer to **Table 4.1, Table 4.2, Table 4.3, Table 4.4).**

From the results obtained, the proportions of materials to be used are then determined as been shown in **Table 4.5** and **Table 4.6,** and are compared to the ACW 20 envelope, as been shown in **Figure 4.1** and **Figure 4.2**. It is found that the percentage of each material has fall within the envelope and the weight of each component is calculated based on the total weight of 1200 grams. Eventually, the mass of coarse aggregates, fine aggregates and filler to be used for Marshall Mix are 660 grams, 480 grams and 60 grams respectively.

4.2.1 Sieve analysis results

Coarse aggregate

Weight = 6 kg

Sieve size	Weight before sieve	Weight after sieve	Mass retained	Percentage retained	Total passing
20 mm	1600	1726	126	2.10	97.90
14 mm	1297	4077	2780	46.33	51.57
10 mm	1253	2902	1649	27.48	24.08
5 mm	1326	2736	1410	23.50	0.58
1.18 mm	1126	1161	35	0.58	0.00
receiver	793	793	0	0.00	0.00

Table 4.1: Sieve analysis for coarse aggregate

Fine aggregate

Weight = 1 kg

Sieve size	Weight before sieve	Weight after sieve	Mass retained	Percentage retained	Total passing
5 mm	513	525	12	1.2	98.8
1.18 mm	436	926	490	49	51
600 μm	390	559	169	16.9	34.1
300 μm	358	468	110	11	23.1
150 μm	336	445	109	10.9	12.2
75 μm	327	435	108	10.8	1.4
Receiver	246	248	2	0.2	0

Table 4.2: Sieve analysis for fine aggregate

Ordinary Portland cement (OPC)

Weight = 100g

Sieve size	Weight before sieve	Weight after sieve	Mass retained	Percentage retained	Total passing
600 μm	390	390	0	0	100
300 μm	359	363	4	4	96
150 μm	337	347	10	10	86
75 μm	327	342	15	15	71
63 μm	327	367	40	40	31
receiver	246	277	31	31	0

Table 4.3: Sieve analysis for OPC

Pulverized Fly Ash (PFA)

Weight = 100 g

Sieve size	Weight before sieve	Weight after sieve	Mass retained	Percentage retained	Total passing
600 μm	390	390	0	0	100
300 μm	358	360	2	2	98
150 μm	337	343	6	6	92
75 μm	327	341	14	14	78
63 μm	327	347	20	20	58
Receiver	246	304	58	58	0

Table 4.4: Sieve analysis for PFA

Proportions of material (Conventional)

Sieve size	Percent by weight			Percentage Passing by weight (%)	JKR std
	Coarse (55%)	Fine (40%)	Filler (5%)		
28 mm	100.00	100	100	100	100
20 mm	97.90	100	100	98.85	76 – 100
14 mm	51.57	100	100	73.36	64 – 89
10 mm	24.08	100	100	58.25	56 – 80
5 mm	23.50	98.8	100	57.45	46 – 71
1.18 mm	0.58	51	100	25.72	20 – 42
600 μm	0.00	34.1	100	18.64	-
300 μm	0.00	23.1	96	14.04	12 – 28
150μm	0.00	12.2	86	9.18	6 – 16
75μm	0.00	1.4	71	4.11	4 - 8
63 μm	0.00	0	31	1.55	-

Table 4.5: Materials proportion for conventional mixture

Proportions of material (PFA)

Sieve size	Percent by weight			Percentage Passing by weight (%)	JKR std
	Coarse (55%)	Fine (40%)	Filler (5%)		
28 mm	100.00	100	100	100.00	100
20 mm	97.90	100	100	98.85	76 – 100
14 mm	51.57	100	100	73.36	64 – 89
10 mm	24.08	100	100	58.25	56 – 80
5 mm	23.50	98.8	100	57.45	46 – 71
1.18 mm	0.58	51	100	25.72	20 – 42
600 μm	0.00	34.1	100	18.64	-
300 μm	0.00	23.1	98	14.14	12 – 28
150μm	0.00	12.2	92	9.48	6 – 16
75μm	0.00	1.4	78	4.67	4 - 8
63 μm	0.00	0	58	2.90	-

Table 4.6: Material proportion for PFA mixture

From the obtained **Table 4.5** and **Table 4.6,** aggregate gradation graphs for both mixtures are plotted to determine the gradation of aggregate conformances as accordance to JKR ACW 20 specification as been shown in **Figure 4.1** and **Figure 4.2.**

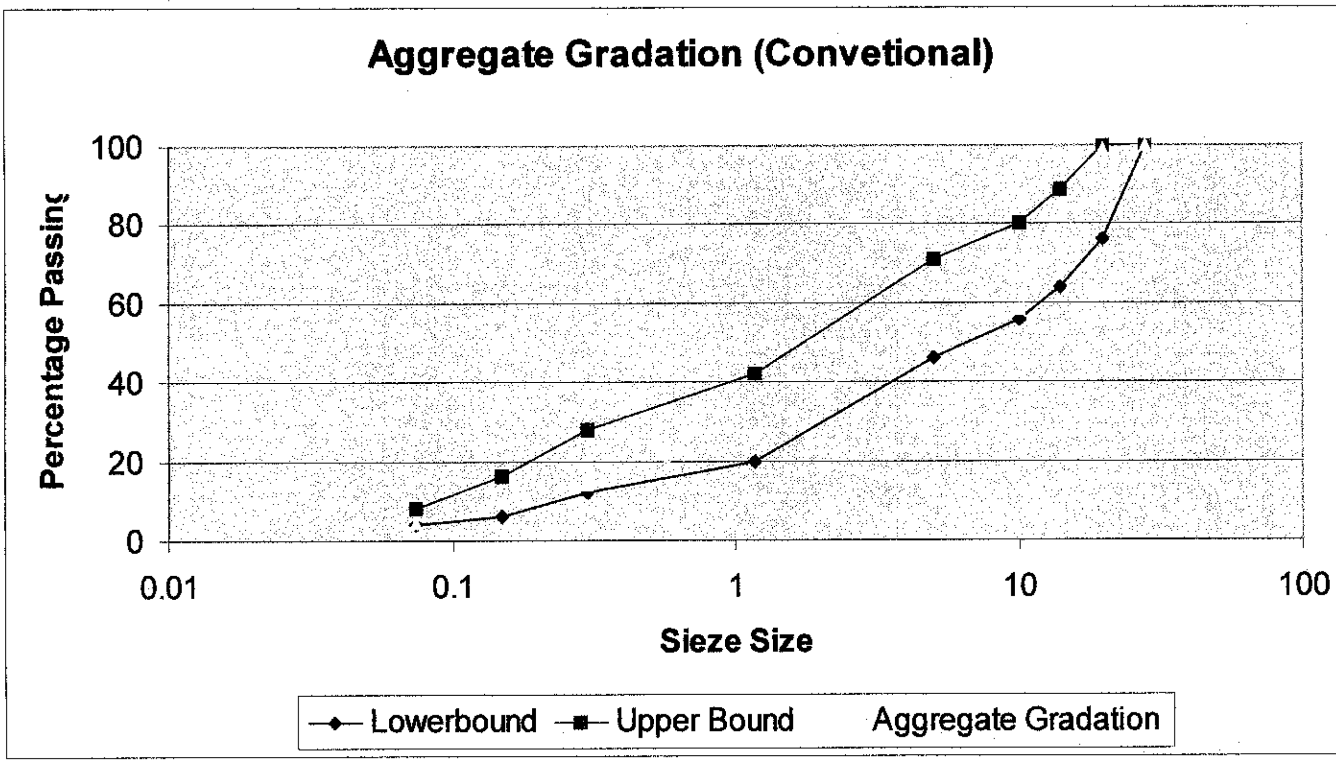


Figure 4.1: Aggregate gradation for conventional mixture

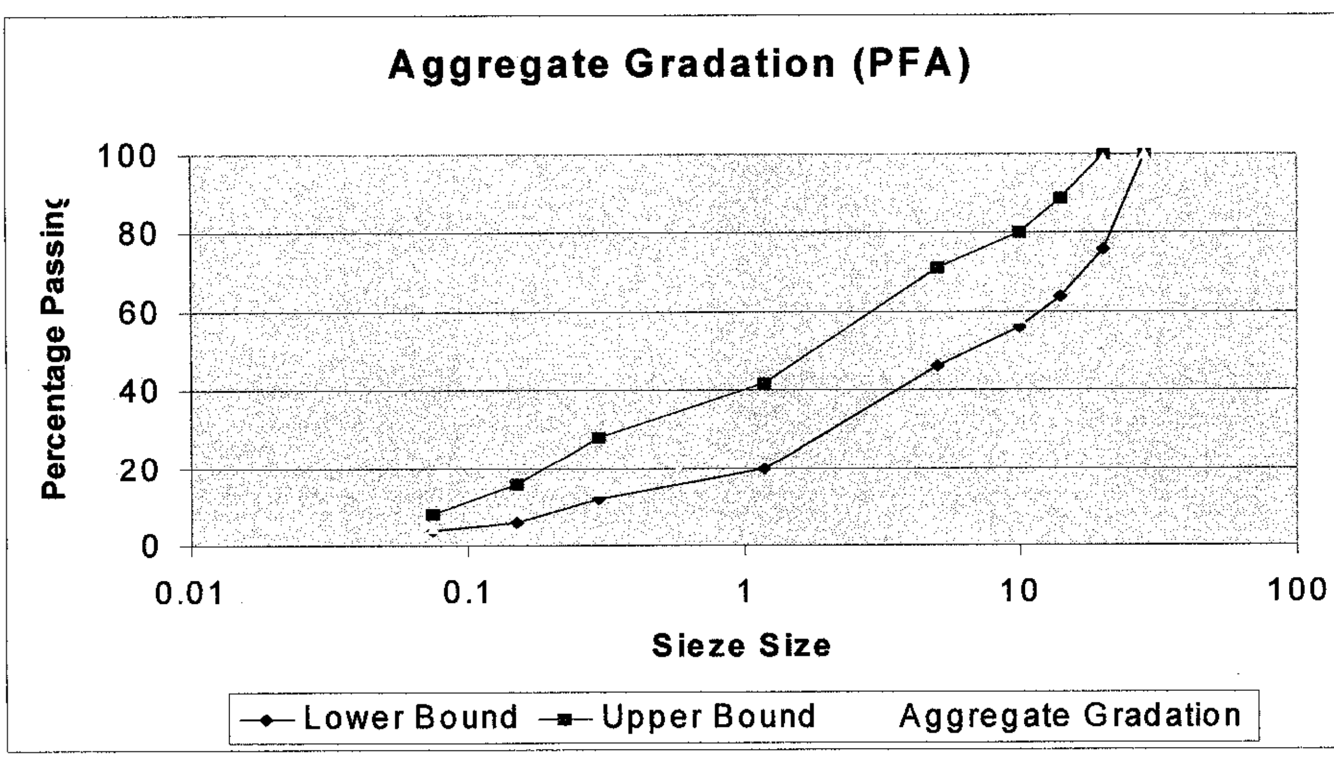


Figure 4.2: Aggregate gradation for PFA mixture

4.3 Marshall Mix Test

Based on the results obtained and calculation done for the Marshall Mix Test (**Table 4.8** and **Table 4.9**), the following graphs are plotted.

1. Marshall Stability vs bitumen content (**Figure 4.3** and **Figure 4.7**)
2. Bulk Density vs bitumen content (**Figure 4.4** and **Figure 4.8**)
3. Porosity vs bitumen content (**Figure 4.5** and **Figure 4.9**)
4. Flow vs bitumen content (**Figure 4.6** and **Figure 4.10**)

The optimum binder content (OBC) will be an average of bitumen contents that yields the maximum stability, bulk density at 4.0% porosity(3). According to **Figure 4.3, Figure 4.4** and **Figure 4.5,** the OBC for conventional mixture is determined as shown:

Optimum Binder Content (conventional)

- **Conventional mixture** = (5.54 + 4.88 + 6.32)/3

  = ***5.58%***

Meanwhile the OBC for PFA mixture is determined by taking the average value obtained from **Figure 4.7, Figure 4.8** and **Figure 4.9.**

Optimum Binder Content (PFA)

- **PFA mixture** = (4.85 + 5.65 + 5.85)/3

  = ***5.45 %***

:onventional
'ype of mix : ACW 20
\VG SG AGG BLEND : 2.58
;G BIT : 1.02 PEN GRD BIT: 80/100

% Bitumen by weight of mix	Specific height	Weight (gm)		Bulk Volume	Specific gravity		Volume (% total)			Voids - %			Correction factor	Stability		Flow (mm)	Stiffness
		in air	in water		Bulk	Theory	Bitumen	Aggregate	Voids	Aggregate	Filled (Bit)	Total Mix		MEAS	CORR		
	70.27	1249	681.1	567.9	2.199331								0.86	18.68	16.06	2.96	
4.5	70.36	1243.3	677.8	565.5	2.198585								0.86	22.46	19.31	3.42	
	69.36	1252.7	698.3	554.4	2.25956								0.89	18.22	16.21	2.75	
					2.219159	2.39	9.790406	82.14328	8.066317	17.85672	54.82756	7.148172			17.19	3.04	5.563
	67.7	1247.8	695.6	552.2	2.259689								0.89	24.97	22.22	3.83	
5	67.49	1253.3	702.1	551.2	2.273766								0.89	23.8	21.18	3.54	
	66.86	1250.2	695.1	555.1	2.252207								0.93	22.48	20.90	4.3	
					2.261887	2.38	11.08768	83.28654	5.625773	16.71346	66.33986	4.962722			21.43	3.89	5.509
	67.29	1245	683.5	561.5	2.217275								0.86	20.19	17.3634	6.44	
5.5	67.77	1261	702.2	558.8	2.256621								0.89	19.47	17.3283	6.21	
	67.04	1246	700.6	545.4	2.284562								0.93	17.33	16.1169	5.73	
					2.252819	2.36	12.14756	82.51606	5.336384	17.48394	69.47837	4.54155			16.93	6.12	2.766
	66.57	1256.9	700.6	556.3	2.259392								0.89	16.15	14.37	7.18	
6	70.2	1259.6	690.7	568.9	2.214097								0.86	14.9	12.8	9.85	
	67.84	1250.3	695.6	554.7	2.254011								0.89	15.22	13.54	8.16	
					2.2425	2.35	13.19118	81.7035	5.105321	18.2965	72.09673	4.574454			13.57	8.39	1.617
	68.3	1254.3	705.6	548.7	2.285949								0.89	15.01	13.35	10	
6.5	70.99	1269.3	695.6	573.7	2.21248								0.83	13.66	11.33	10	
	68.49	1256.7	689.8	566.9	2.216793								0.86	14.69	12.63	10	
					2.238407	2.33	14.26436	81.12058	4.615063	18.87942	75.55507	3.931015			12.44	10	1.244

Table 4.8: Results of Marshall Mix Test for conventional mixture

'FA
'ype of mix : ACW 20
VG SG AGG BLEND: 2.53
;G BIT : 1.02 PEN GRD BIT: 80/100

% Bitumen by weight of mix	Specific height	Weight (gm)		Bulk Volume	Specific gravity		Volume (% total)			Voids - %			Correction factor	Stability		Flow (mm)	Stiffnes
		in air	in water		Bulk	Theory	Bitumen	Aggregate	Voids	Aggregate	Filled (Bit)	Total Mix		MEAS	CORR		
	70.08	1267.8	680.8	587	2.159796								0.86	23.84	20.50	1.51	
4.5	68.93	1269.7	695.3	574.4	2.210481								0.83	23.97	19.89	2.01	
	68.83	1252.9	695.3	557.6	2.246951								0.89	23.81	21.19	1.53	
					2.205742	2.35	9.731217	83.26024	7.008545	16.73976	58.13235	6.13862			20.52	1.68	12.1957
	68.95	1267.1	693.7	573.4	2.209801								0.89	25	22.25	4.6	
5	67.7	1247.2	689.6	557.6	2.236729								0.89	20.86	18.56	5.39	
	68.38	1255.9	680.8	575.1	2.183794								0.89	23.58	20.98	6.42	
					2.210108	2.33	10.83386	82.98825	6.17789	17.01175	63.68458	5.145577			20.60	5.47	3.76609
	68.08	1236.6	684.8	551.8	2.241029								0.93	22.68	21.09	5.46	
5.5	68.22	1255	683.2	571.8	2.194823								0.89	22.73	20.22	6.33	
	68.74	1253.1	694.1	559	2.241682								0.89	22.08	19.65	5.76	
					2.225845	2.31	12.0021	83.13926	4.858635	16.86074	71.18374	3.643084			20.32	5.85	3.47426
	68.6	1255.3	690.6	564.7	2.22295								0.89	16.14	14.36	5.79	
6	68.53	1254	691.6	562.4	2.22973								0.89	18.21	16.20	4.84	
	69.32	1265.1	692.1	573	2.207853								0.86	17.91	15.40	4.47	
					2.220178	2.3	13.05987	82.48882	4.451312	17.51118	74.58017	3.470531			15.32	5.03	3.04464
	71.77	1270.9	689.5	581.4	2.185931								0.83	13.73	11.39	5.83	
6.5	69.92	1265.9	698.8	567.1	2.232234								0.86	14.92	12.83	4.07	
	70.47	1275.4	703.2	572.2	2.228941								0.86	11.96	10.28	5.53	
					2.215702	2.28	14.11967	81.88463	3.995697	18.11537	77.94305	2.820093			11.50	5.14	2.23672

Table 4.9: Results of Marshall Mix Test for PFA mixture

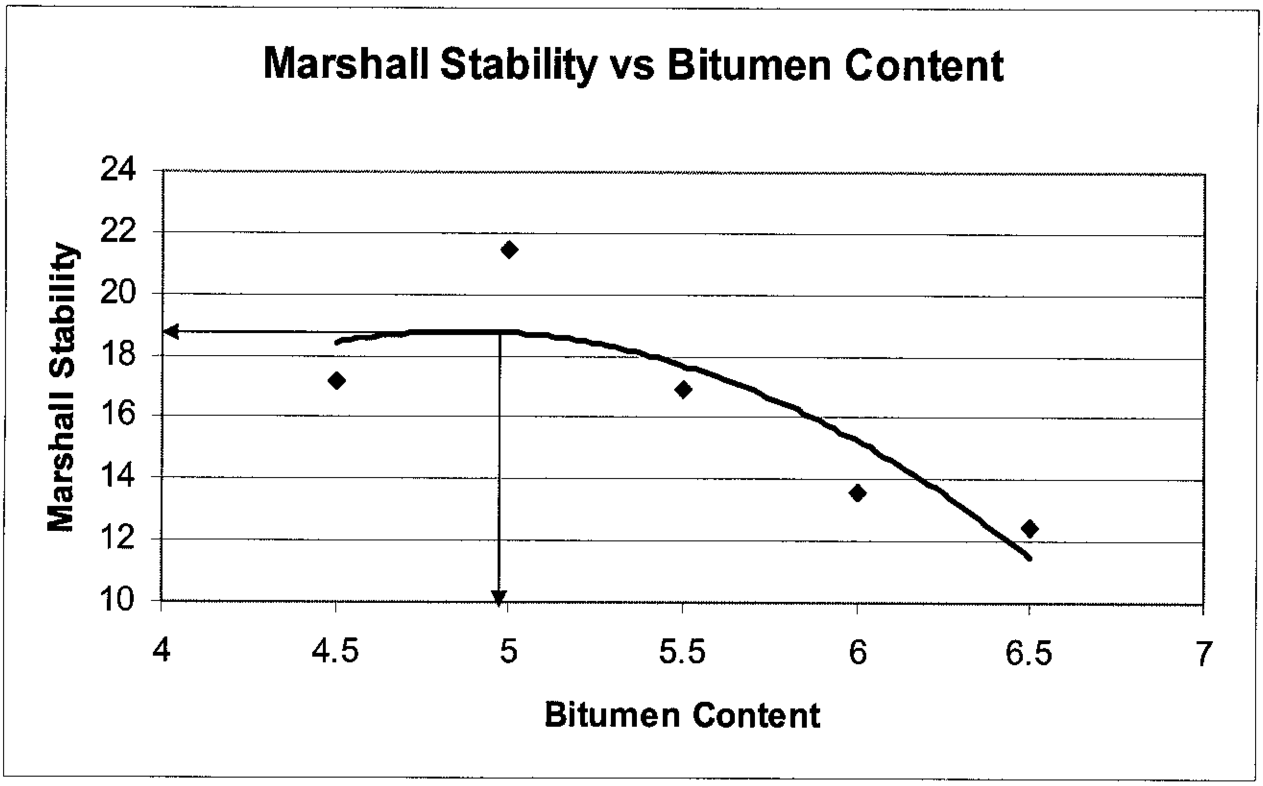


Figure 4.3: Marshall Stability vs Bitumen Content (conventional)

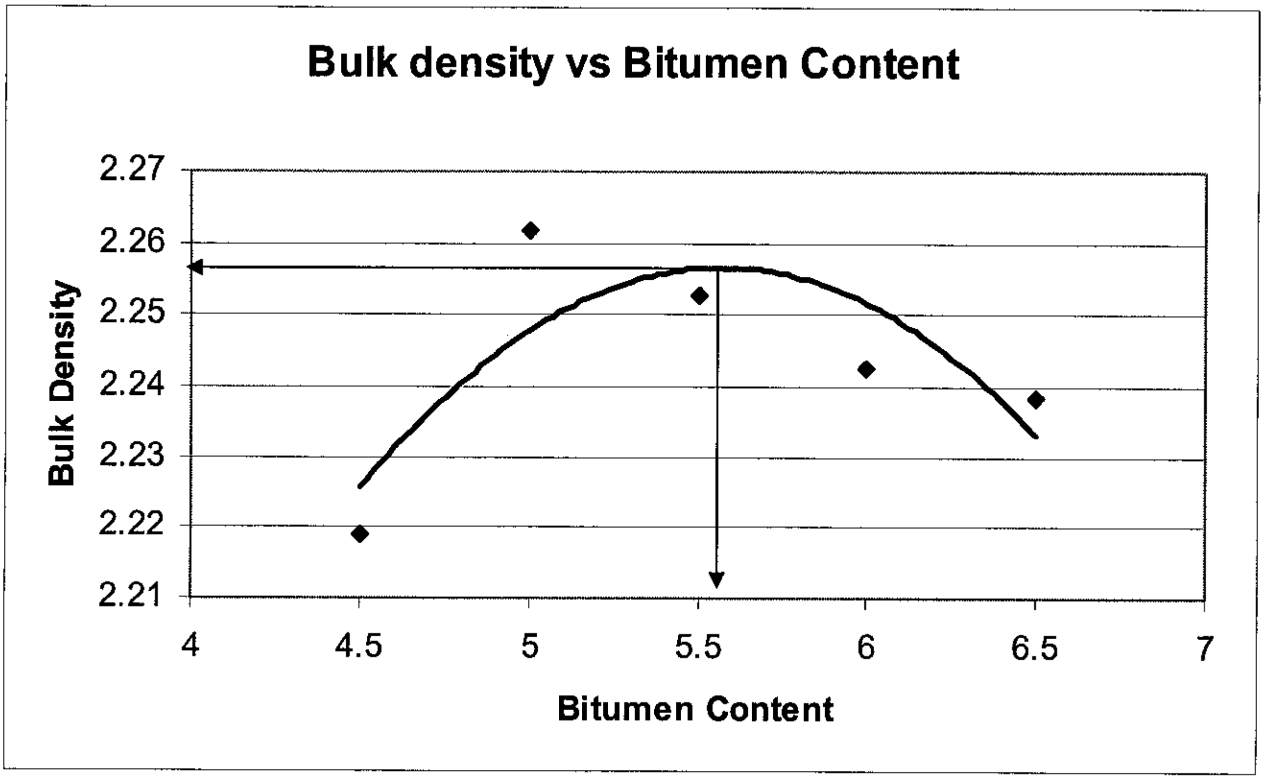


Figure 4.4: Bulk Density vs Bitumen Content (conventional)

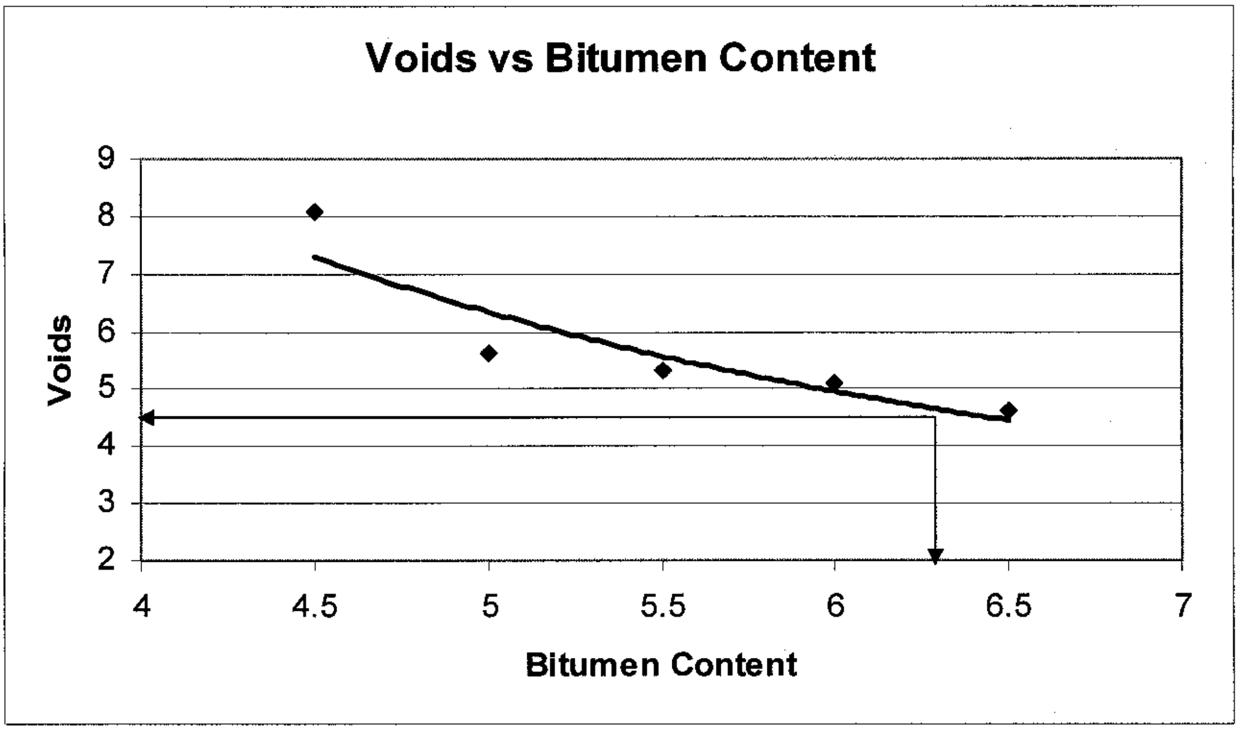


Figure 4.5: Voids vs Bitumen Content (conventional)

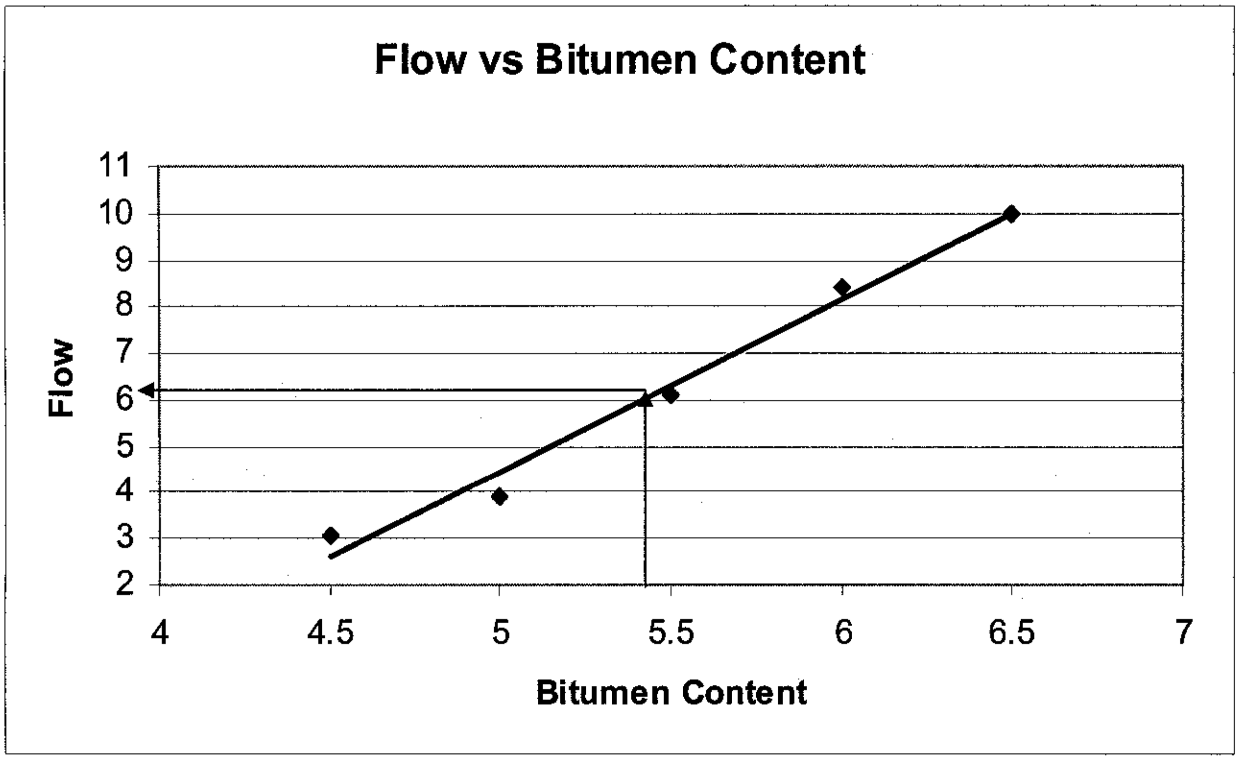


Figure 4.6: Flow vs Bitumen Content (conventional)

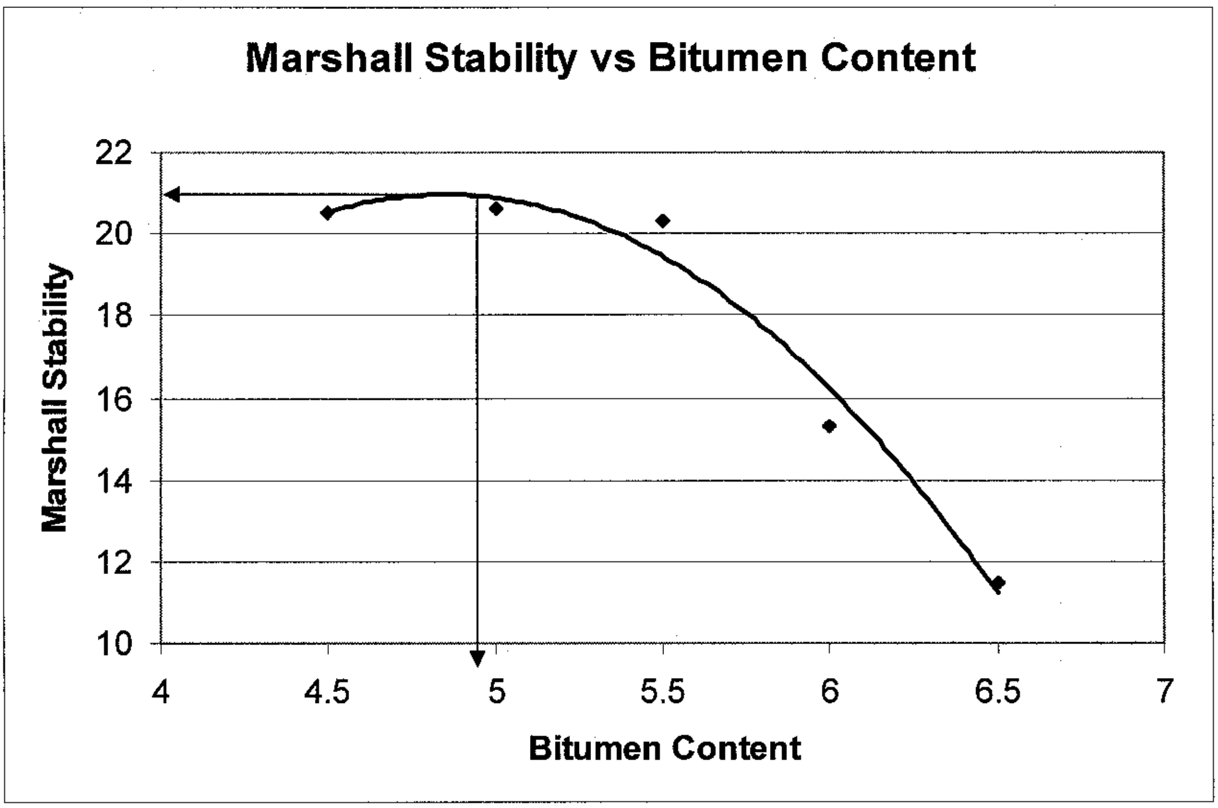


Figure 4.7: Marshall Stability vs Bitumen Content (PFA)

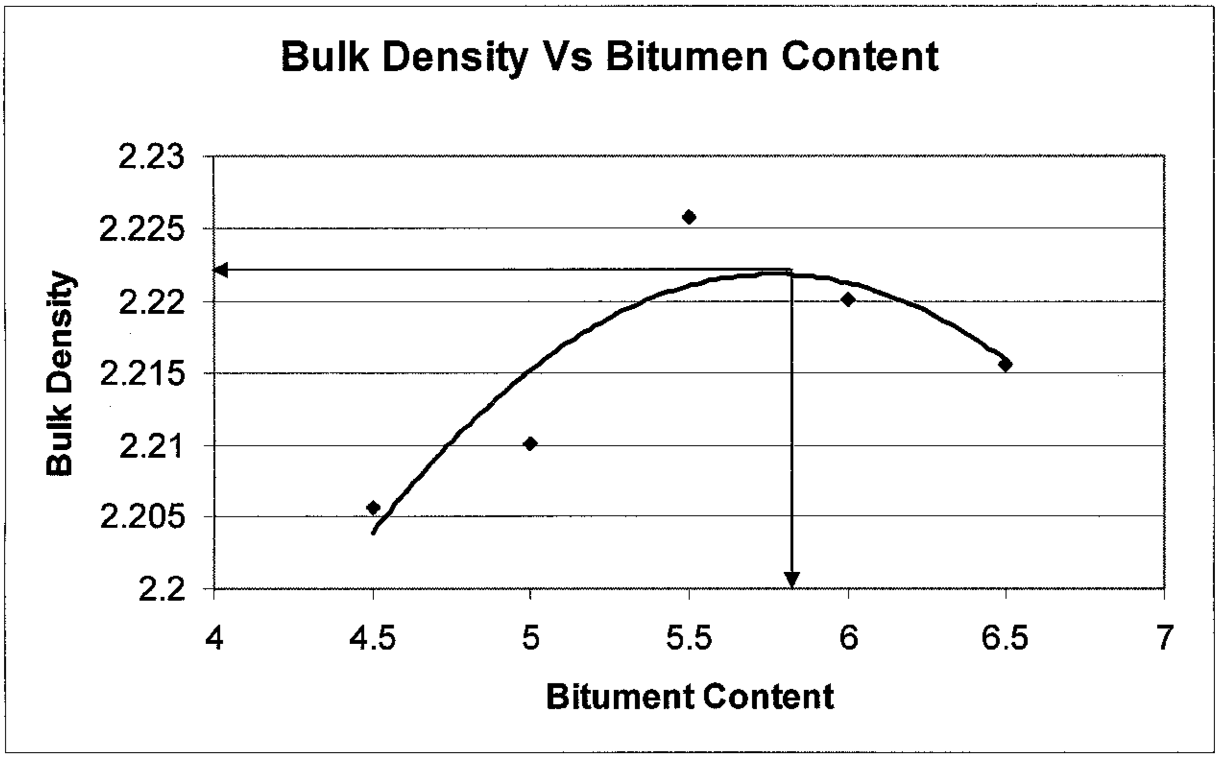


Figure 4.8: Bulk Density vs Bitumen Content (PFA)

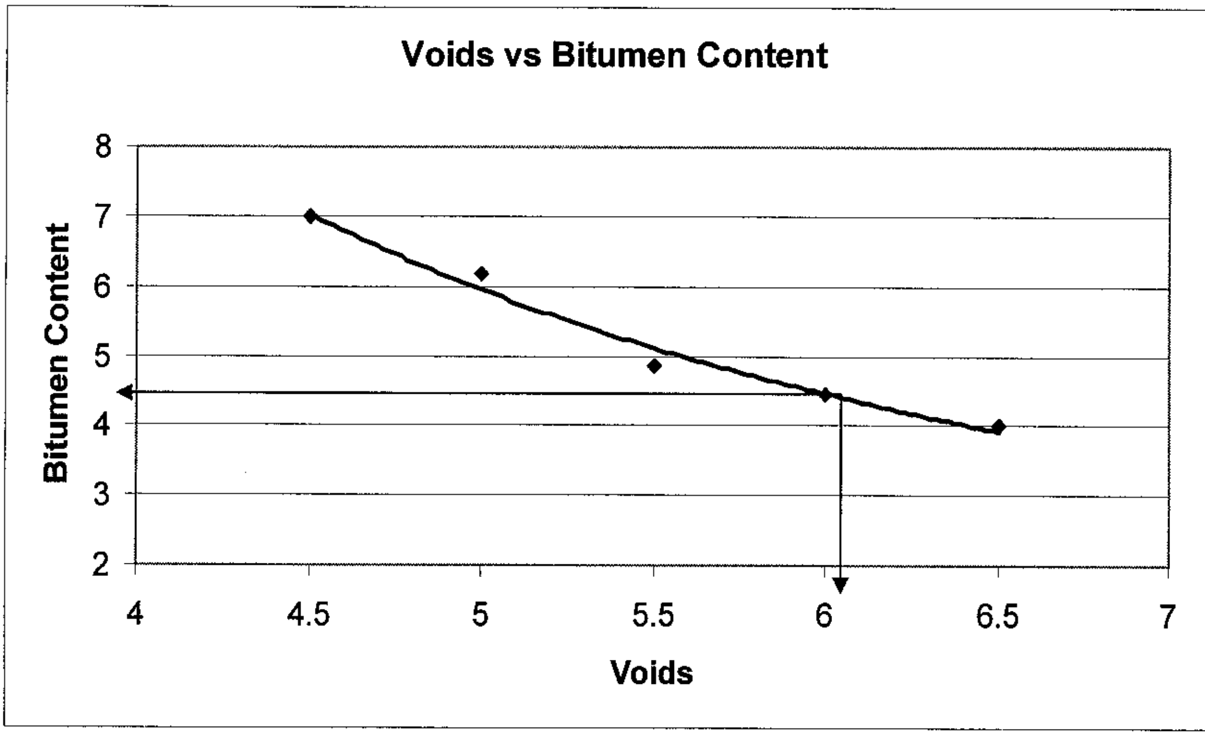


Figure 4.9: Voids vs Bitumen Content (PFA)

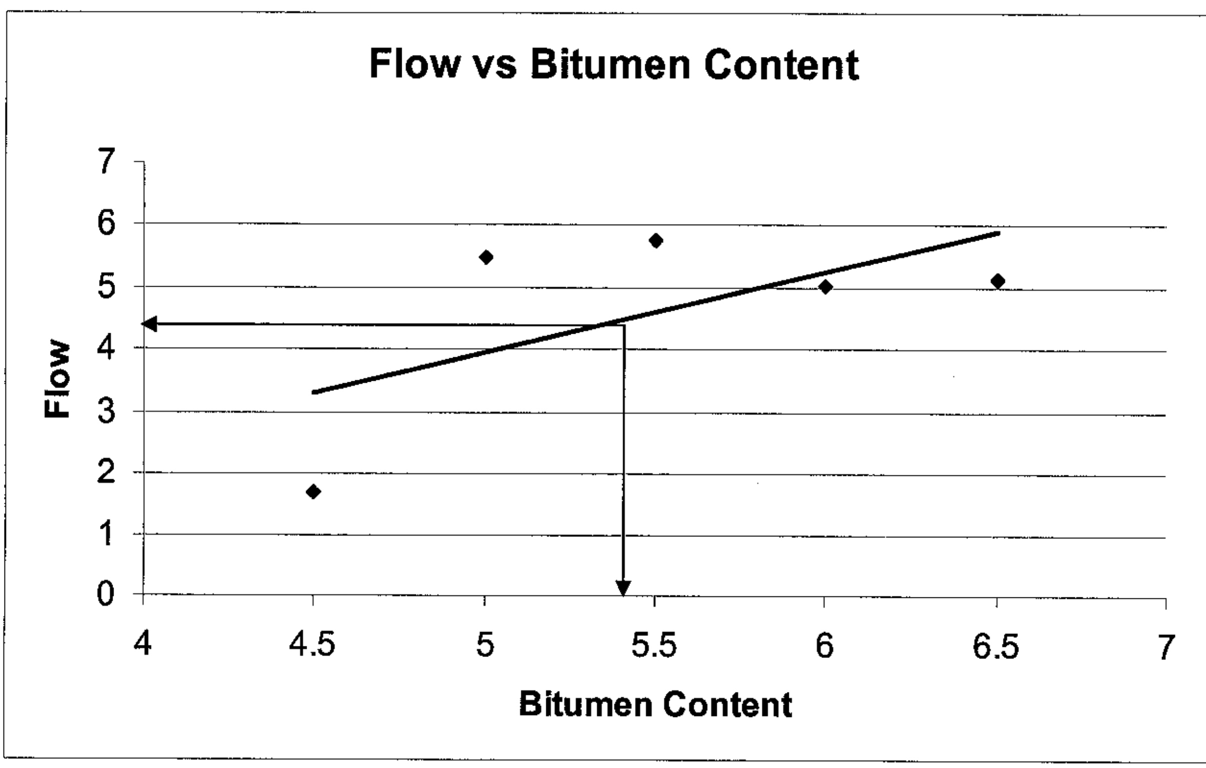


Figure 4.10: Flow vs Bitumen Content (PFA)

Chapter V

Performances Tests

5.1 Introduction

This chapter will focus on the performances tests implemented, which are Wheel Tracking Test and Beam Fatigue Test, to determine permanent deformation and fatigue life of the mixtures respectively. The obtained results for both tests are analyzed and the improvements achieved are determined by comparison between PFA and conventional mixture.

5.2 Wheel Tracking Test

5.2.1 Calculation for sample mixing

Three samples for each asphalt concrete mixture (conventional and PFA) slabs are mixed and undergone Wheel Tracking Test, to determine the improvement in rutting or deformation. **Table 5.1** and **Table 5.2** showed the calculation to determine the required mass or amount of coarse aggregated, fine aggregated, filler and binder content required for each proportion for conventional and PFA mixture respectively:

Material	*Percentage (%)*	*Percentage (%)*	*Mass (g)*
Coarse aggregate	55	49.42	4942
Fine aggregate	40	40	4000
Filler (OPC)	5	5	500
Binder content	-	5.58	558
Total mass	-	100	10000

Table 5.1: Conventional mix for wheel tracking test slab

Material	*Percentage (%)*	*Percentage (%)*	*Mass (g)*
Coarse aggregate	55	49.55	4945
Fine aggregate	40	40	4000
Filler (OPC)	5	5	500
Binder content	-	5.45	545
Total mass	-	100	10000

Table 5.2: PFA mix for wheel tracking test slab

5.2.2 Results from Wheel Tracking Test (Conventional Mixture)

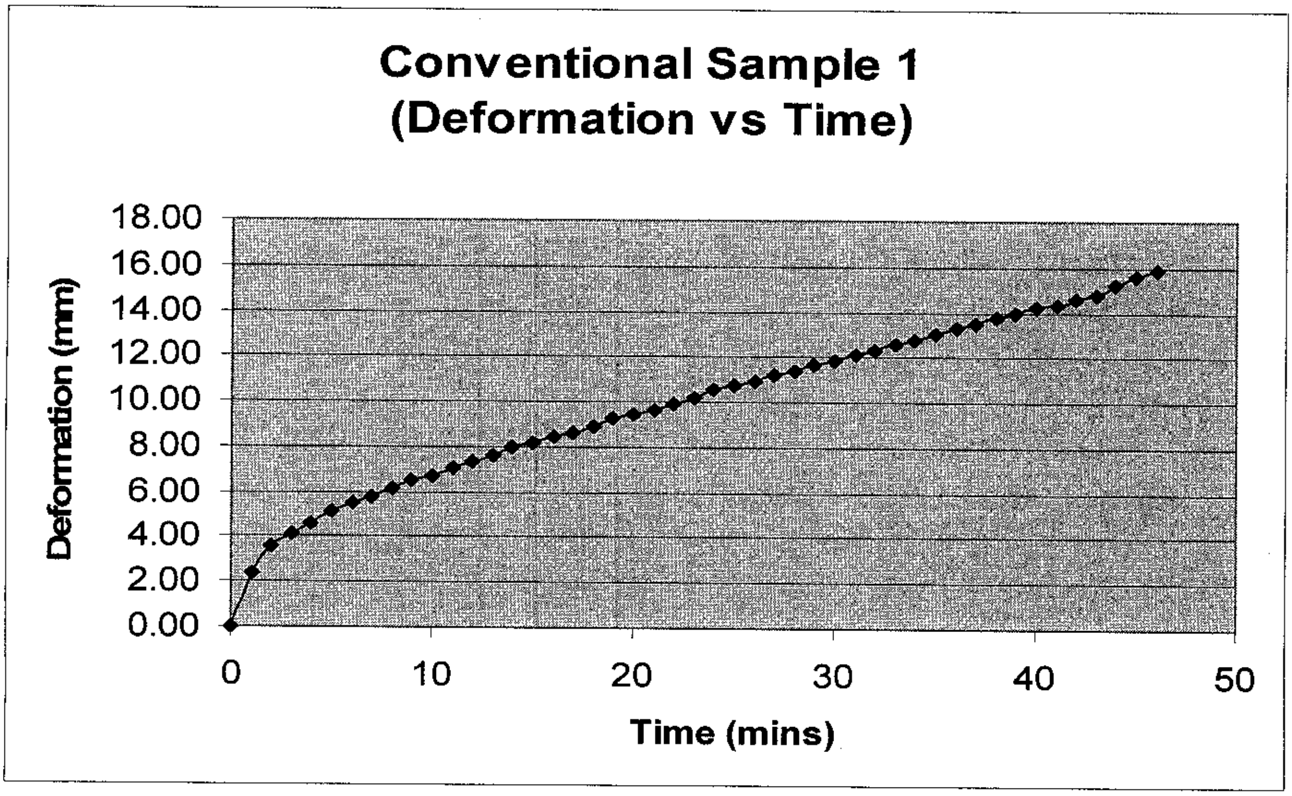


Figure 5.1: Deformation vs Testing Duration of Sample 1

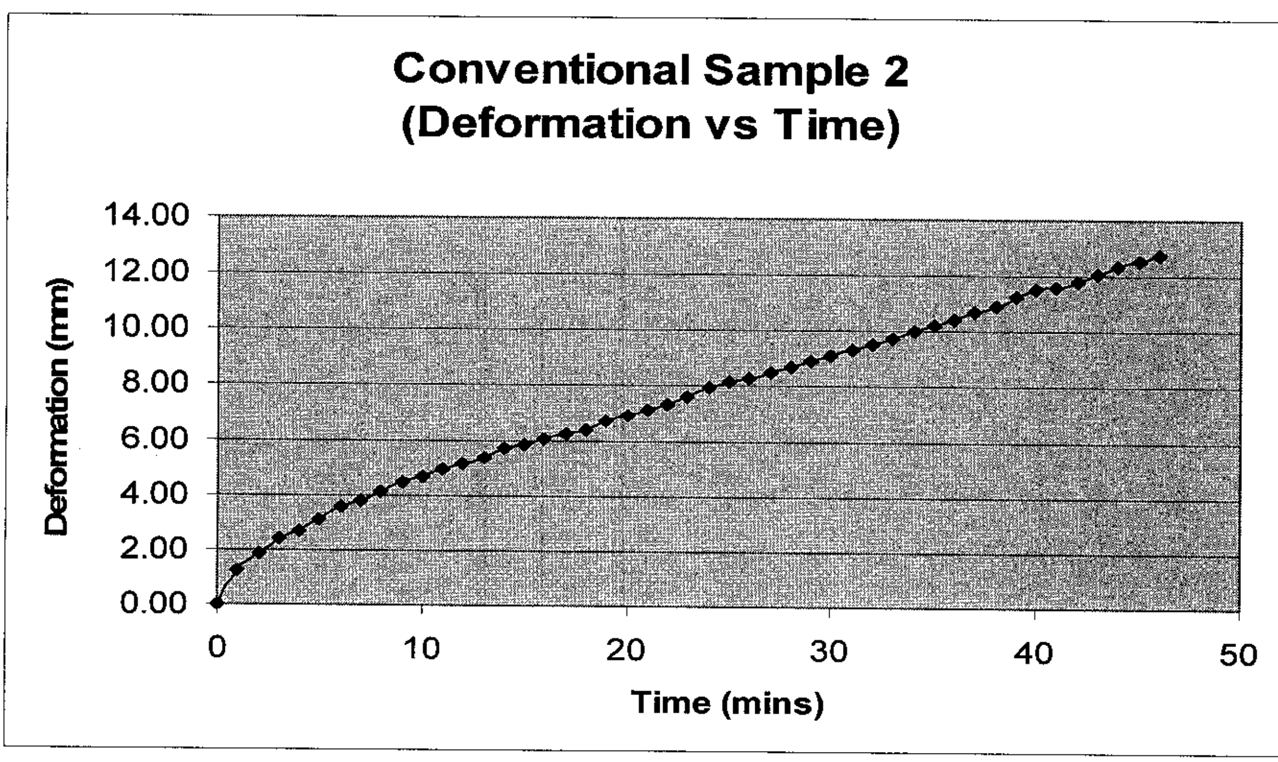


Figure 5.2: Deformation vs Testing Duration of Sample 2

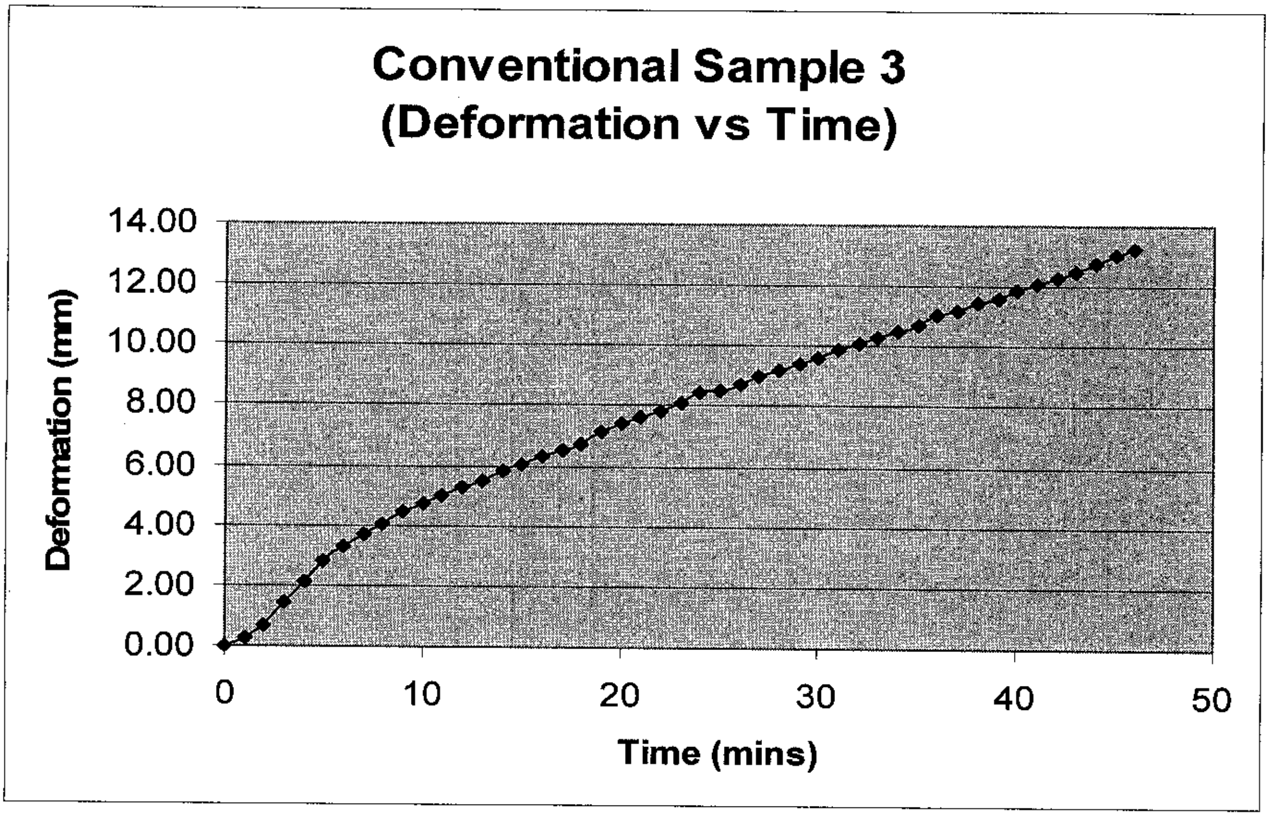


Figure 5.3: Deformation vs Testing Duration of Sample 3

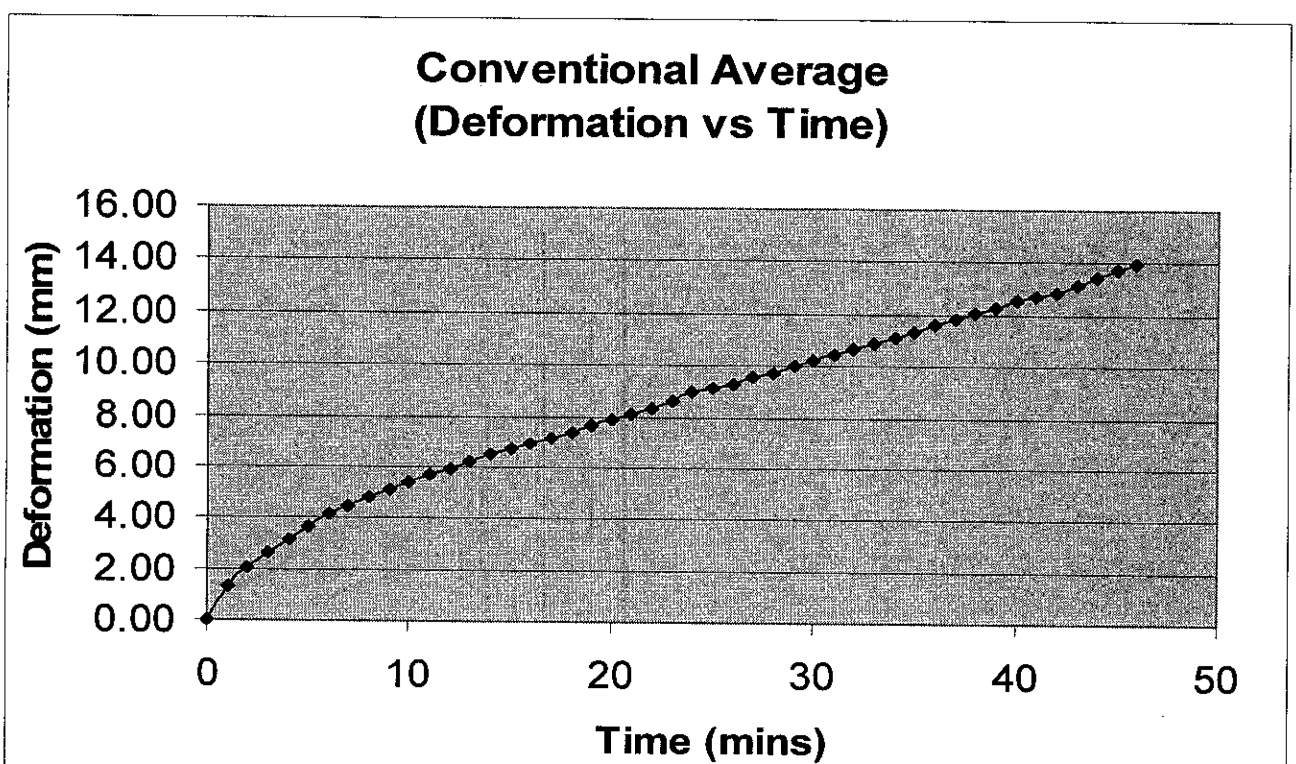


Figure 5.4: Average results for samples 1, 2 and 3

5.2.3 Results from Wheel Tracking Test (PFA Mixture)

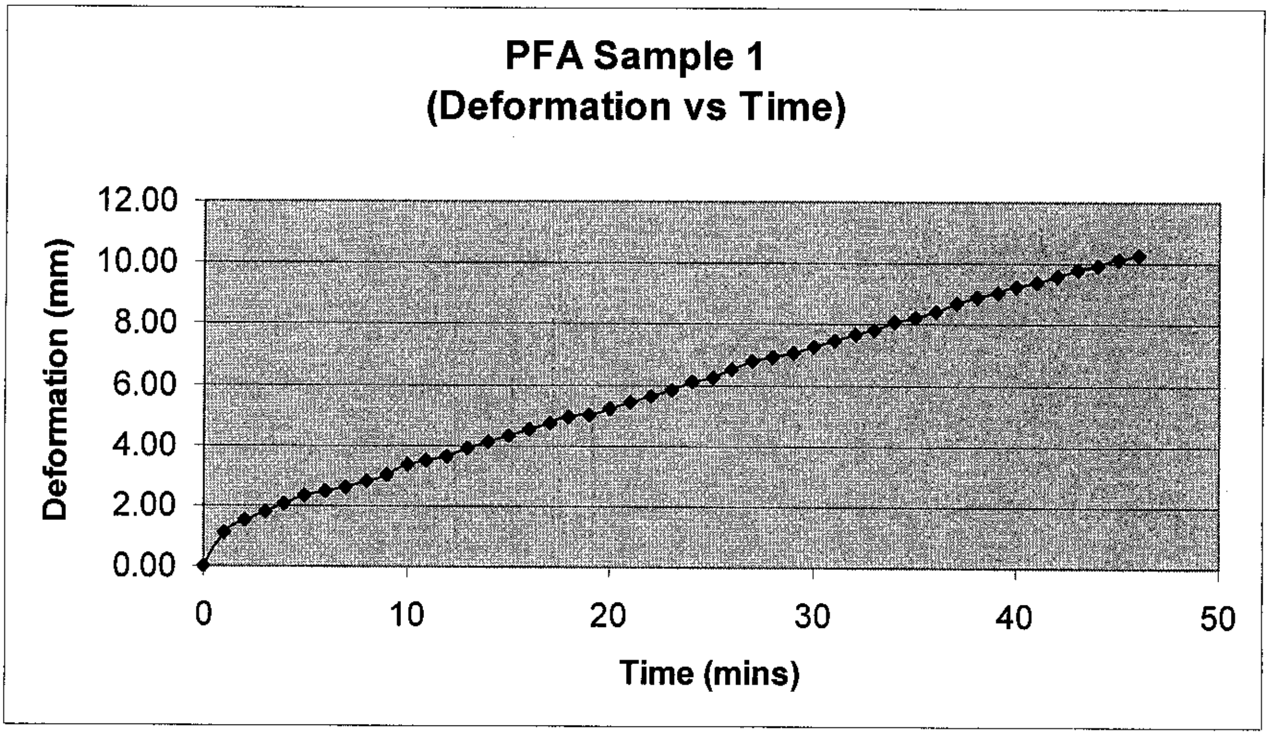


Figure 5.5: Deformation vs Testing Duration of Sample 1

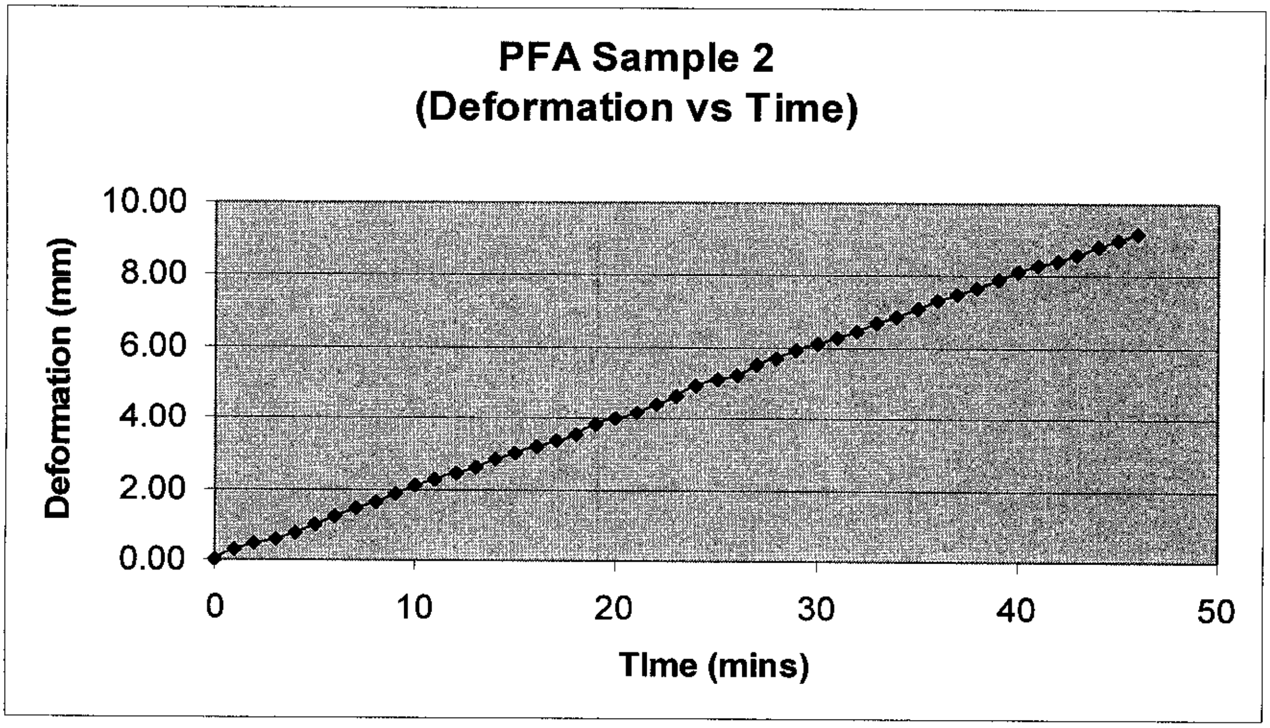


Figure 5.6: Deformation vs Testing Duration of Sample 2

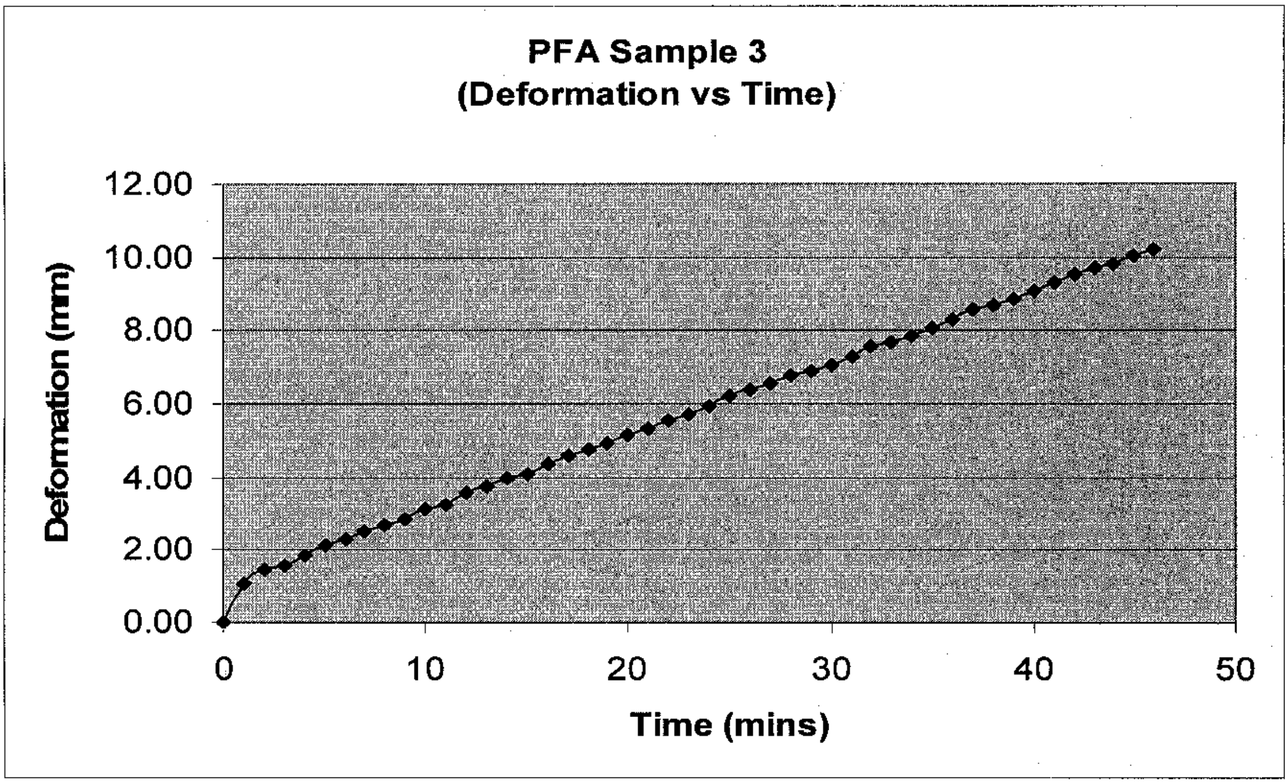


Figure 5.7: Deformation vs Testing Duration of Sample 3

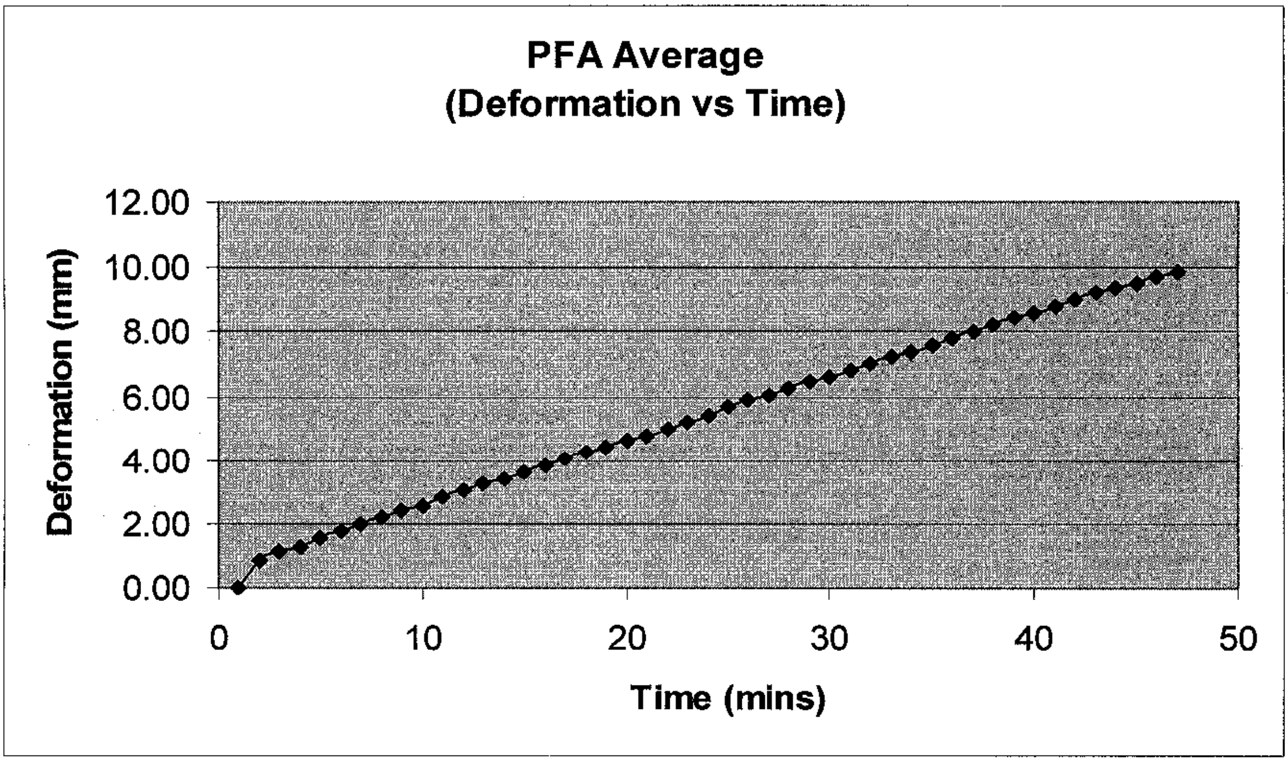


Figure 5.8: Average results for samples 1, 2 and 3

5.2.4 Results discussion (Wheel Tracking Test)

Tables 5.3 and **5.4** summarized the obtained results from **Wheel Tracking Test,** for both conventional and PFA mixtures, as been shown from **Figure 5.1** to **Figure 5.8.**

Sample	Initial rut depth	Final rut depth	Duration	Slope/gradient
1	0.00	15.86	45 mins	0.3524
2	0.00	12.75	45 mins	0.2833
3	0.00	13.22	45 mins	0.2938
Average	0.00	13.94	45 mins	0.3098

Table 5.3: Wheel tracking results of conventional mixture

Sample	Initial rut depth	Final rut depth	Duration	Slope/gradient
1	0.00	10.30	45 mins	0.2289
2	0.00	9.18	45 mins	0.2040
3	0.00	10.22	45 mins	0.2271
Average	0.00	9.90	45 mins	0.2200

Table 5.4: Wheel tracking results of PFA mixture

Based on both tables, it can be noticed that the rutting or deformation had been greatly improved upon applying PFA into the mixture instead of OPC. As been shown, the rut depth after 45 minutes (approximately 2000 cycles) of test, under the same condition, the final rut depth for conventional sample 1, 2 and 3 are 15.86 mm, 12.75 mm and 13.22 mm respectively, giving the average rut depth for all 3 samples as 13.94 mm.

Meanwhile for PFA mixture, rut depth of 10.30 mm, 9.18 mm and 10.22 mm are obtained for sample 1, 2 and 3 respectively with an average of 9.90 mm. These obtained results will be further discussed in the later chapter.

5.3 Beam Fatigue Test

5.3.1 Results from Beam Fatigue Test

Figures 5.9 and **5.10** below showed the results obtained from conventional and PFA mixtures respectively in beam fatigue test.

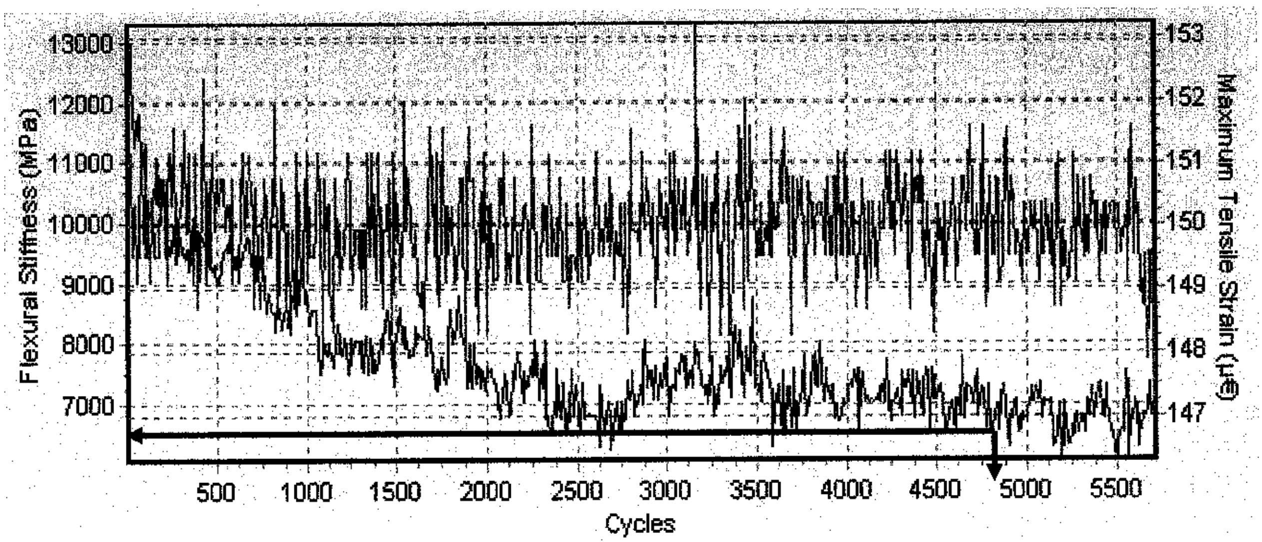


Figure 5.9: Flexural stiffness vs Cycles for conventional mixture

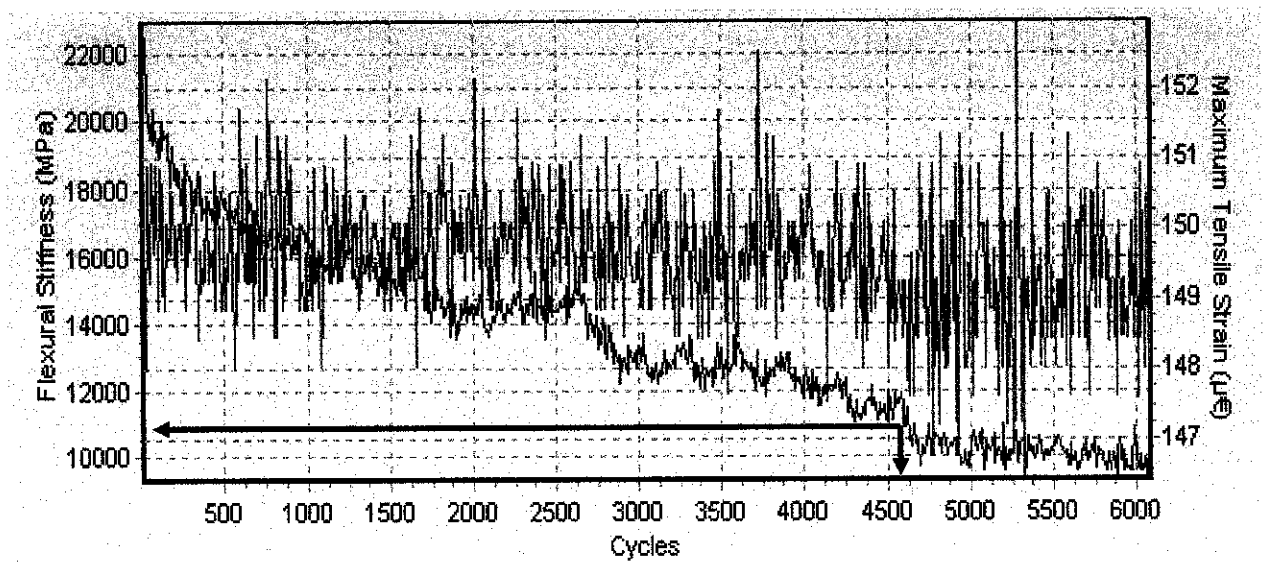


Figure 5.10: Flexural stiffness vs Cycles for PFA mixture

Flexural Stiffness

Maximum Tensile Strain

5.3.2 Results Discussion (Beam Fatigue Test)

This obtained results show the flexural stiffness comparison between conventional and PFA mixture. Only 2 significant results out of 6 samples, one for each mixture are obtained in this test, due to instability of the samples during sample testing, causing the samples to fail before obtaining any significant results.

Both mixtures exhibit the same deterioration trend, whereby both samples deteriorate exponentially. From **Figure 5.9** (conventional mixture), the recorded initial flexural stiffness is 13000 MPa, and the test stopped after approximately 5700 cycles, with the recorded final flexural stiffness recorded at approximately 7000 Mpa.

Meanwhile from **Figure 5.10** (PFA mixture), the recorded initial flexural stiffness is 22000 MPa and the test stopped after approximately 6100 cycles, with the recorded final flexural stiffness of approximately 10000 MPa. In comparison, although the PFA mixture has higher flexural stiffness as compared to conventional mixture however the fatigue life is slightly lower. This analysis and the discussion will be discussed extensively in the next chapter.

Chapter VI

Results Analysis and Discussions

6.1 Introduction

This chapter will discuss extensively based on the results obtained from performance tests conducted (as been shown in Chapter 5). The performances tests involved are **Wheel Tracking Test** and **Beam Fatigue Test.** The discussions will include all the technical terms and highway engineering aspects, in order to have a proper explanation for the results obtained.

6.2 Marshall Mix and Determination of Optimum Binder Content

In a study, it is desired to have samples and specimens which can undergo tests as closed as possible to the real condition in the actual location. In highway construction industry, different proportions of materials (coarse aggregates, fine aggregates and filler) to be used in a mixture will eventually have different engineering properties, such as specific gravity, bulk density and porosity. All these properties contribute towards the mixture stability and strength.

It is hard to deny the fact that the packing (gradation) properties of aggregates will significantly influence the mixture engineering properties, however, the amount of binder content required is essentially important, to provide better stability and strength to the mixture. This is because if adequate amount of binder content is used, the mixture will have low stability, since the mixture can not hold itself properly, while if too much binder is applied, the mixture will become too soft and is not suitable to be used in reality. For this reason, Marshall Mix is an essential procedure in highway industry to determine the optimum binder content to be used in the mixture.

From the results obtained through Marshall Mix, the optimum binder content for conventional mixture and PFA mixture is 5.58% and 5.45% respectively, in correlation with 55% coarse aggregates, 40% fine aggregates and 5% filler. The obtained value had taken porosity, bulk density, Marshall Stability and flow into considerations.

6.3 Wheel Tracking Test

Based on **Figure 6.1**, the resistance of asphalt concrete mixture against permanent deformation or rutting had been greatly improved, whereas the rut depth for PFA is recorded as 9.90 mm, compared to 13.94 mm for conventional mixture, after being subjected to 45 minutes of continuous cyclic loading (approximately 2000 cycles). From the results, the difference between both mixtures is approximately 4.04 mm upon taking the average value of 3 samples for each mixture, under same applied load and duration of test. The total reduction in rut depth for PFA mixture is approximately about 29% as compared to rut depth recorded for conventional mixture.

As can be observed from **Figure 6.1,** the rate of rutting for both PFA and conventional mixtures are linear, with a slope or gradient less than 1 as been showed in **Table 5.3** and **Table 5.4.** This is likely because as the mixtures being subjected to further compaction, the smaller particles size component, such as fine aggregates and filler will eventually filled in the voids/pore spaces between the coarse aggregates. Hence, the mixture will become more compact, and the rut depth is decreased as time passed.

This improvement is likely to be due to reduction of porosity by using PFA as compared to OPC. This is shown in **Figure 4.5** and **Figure 4.9,** whereby the PFA mixture has lower porosity or voids as compared to conventional mixture. This phenomenon is likely because of the PFA particle size distribution, finer than OPC. Therefore, the smaller particles will eventually fill in the voids in between the coarse aggregates and fine aggregates, producing a well graded asphalt concrete mixture.

As a result of lower porosity, when is subjected to compaction from applied loads, the recorded deformation or rutting will be lower. In spite of this, application of PFA will improve the asphalt concrete mixture workability, and thus will enhance the compaction effort while the mixture is still hot phase. From **Figure 4.3** and **Figure 4.7,** Marshall Stability for PFA mixture is relatively higher as compared to conventional mixture. This indicates that, PFA mixture has higher strength than the conventional mixture. As a result, the permanent deformation/rutting effect for PFA mixture will be smaller compared to conventional mixture under same applied load.

Lastly, from **Figure 4.6** and **Figure 4.10,** the PFA mixture has relatively lower flow properties as compared to conventional mixture, and therefore, giving higher stability to the mixture. A higher flow value has lower stability, because the mixture will tend and subject to fail under certain applied load. This is because a higher flow value indicates that the bonding properties among the components, which are coarse aggregates, fine aggregates and fillers in the mixture are relatively poor and thus these components are keen to slide pass each other (soft properties) when is subjected to applied load.

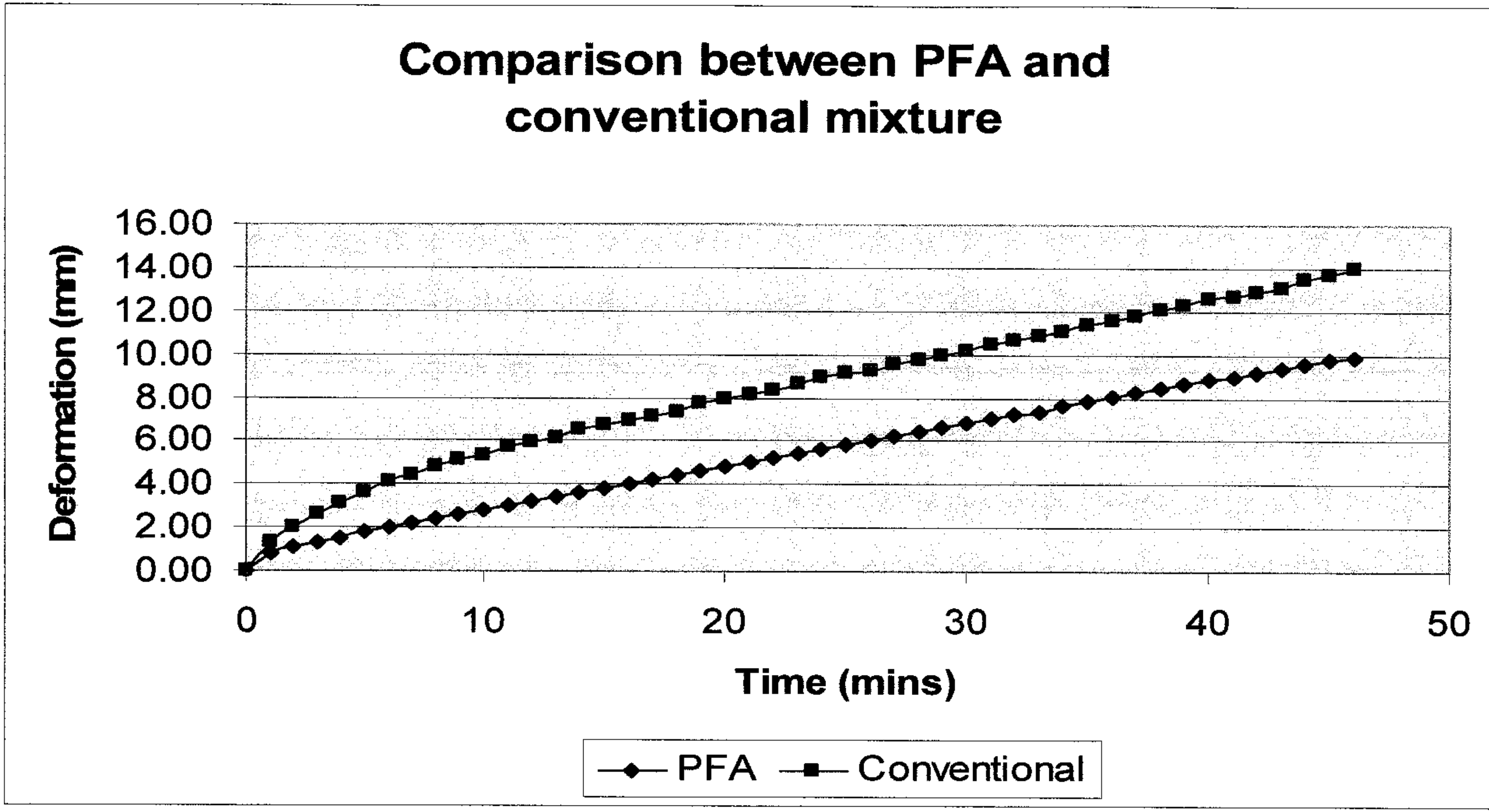


Figure 6.1: Comparison of Wheel Tracking Test for PFA and Conventional mixture

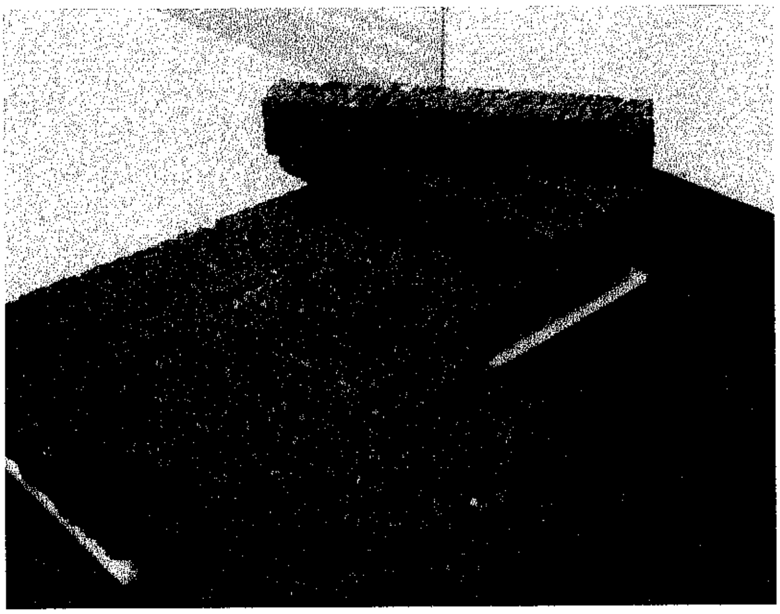


Figure 6.2: Specimens for Wheel Tracking and Beam Fatigue Test

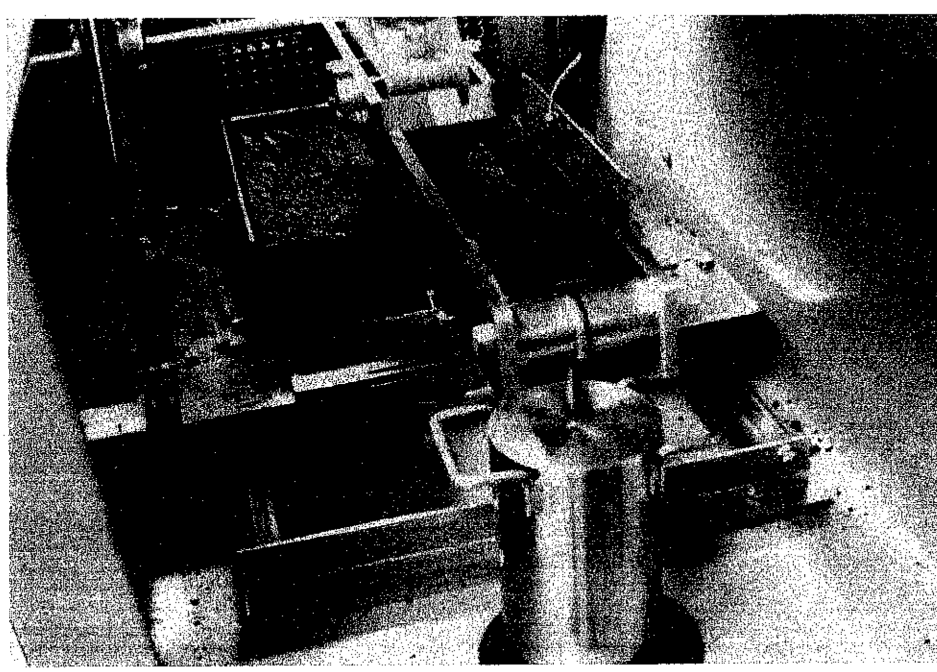


Figure 6.3: Wheel Tracking Test

6.4 Beam Fatigue Test

Fatigue life of asphalt concrete mixture referred to the number of cycles that the pavement can sustain before its flexural stiffness is reduced to half from its initial flexural stiffness under continuous cyclic loading. This phenomenon is illustrated and as shown below in **Figure 6.4.**

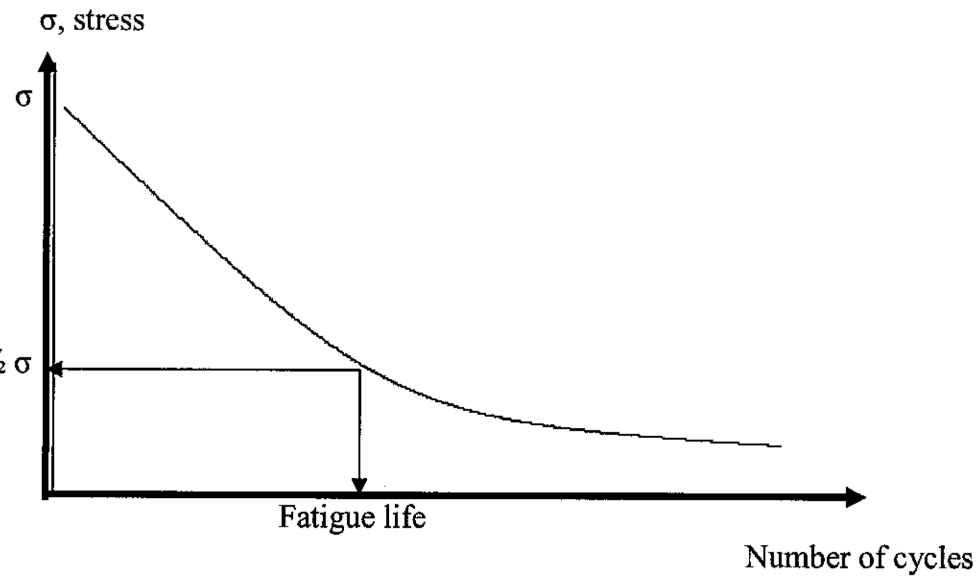


Figure 6.4: Fatigue life

From **Figure 5.9,** the conventional mixture has initial flexural stiffness of approximately 13,000 MPa, hence this mixture will reach its fatigue life resistance when the initial flexural stiffness is reduced by half, 6,500 MPa at approximately 4,800 cycles. Comparatively, for PFA mixture with an initial flexural stiffness of 22,000 MPa, its fatigue life resistance will be located when its initial flexural stiffness is reduced to 11,000 MPa, at approximately 4,500 cycles, as been shown in **Figure 5.10.**

From this analysis of the results, it can be concluded that the PFA mixture does not show any significant improvement in fatigue life, as fatigue life for both mixtures are approximately the same, in the range in between 4,500 to 5,000 cycles.

Comparatively, although PFA mixture does not improve fatigue life significantly than conventional mixture, however, PFA mixture developed higher flexural stiffness than conventional mixture. A higher flexural stiffness indicates that mixture is capable to sustain or withstand higher applied loads. This difference of flexural stiffness is likely to be due to PFA particle size properties, whereby most of PFA particles can pass through No.200 sieve (0.075 mm). Due to these fine particles, the reduction of porosity is greatly improved, (as been shown in **Figure 4.5** and **Figure 4.9**) as the PFA fine particles will fill in the voids giving a higher and more superior compacted asphalt pavement.

Secondly, the reduction of porosity by incorporating PFA into the mixtures had eventually improved the mixture Marshall Stability, and is shown in **Figure 4.3** and **Figure 4.7.** This indicates that the PFA mixture will have higher strength as compared to conventional mixture using OPC as filler.

Lastly, this is likely to be due to PFA spherical shape natures, in which has improved the workability of the mixture. An improved workability mixture will reduce the efforts of compaction during sample preparation (ease of compaction), and yet the outcomes (samples) are well compacted. A proper and well compacted mixture will be relatively stronger and smaller flow properties. This is shown in **Figure 4.6** and **Figure 4.10,** whereby PFA mixture has smaller flow properties compared to conventional mixture.

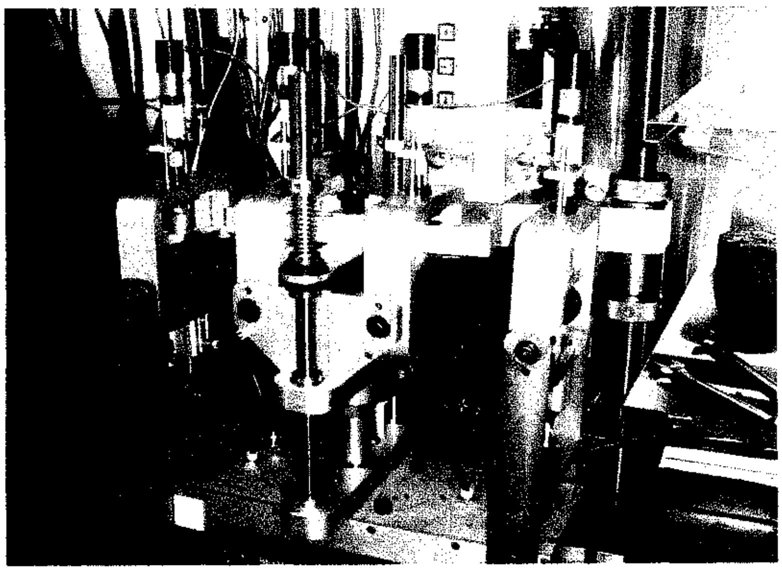
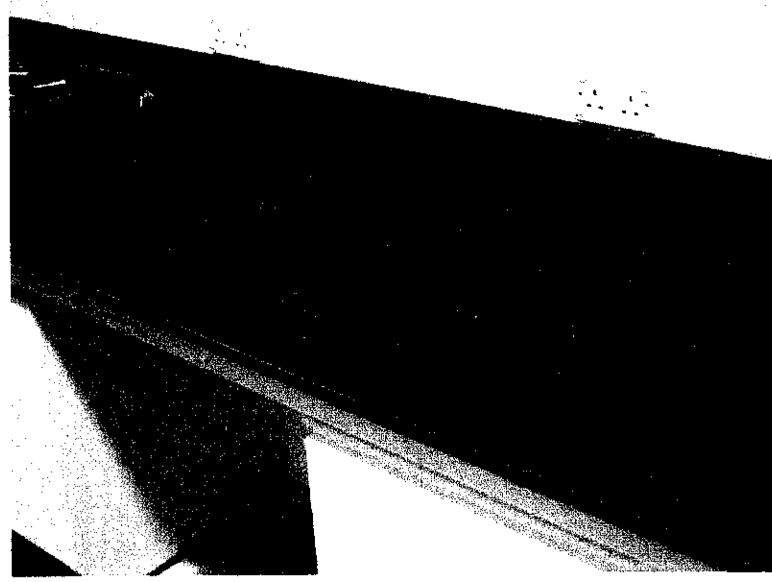


Figure 6.5: Beam Fatigue Test

Figure 6.6: Tested Beam Fatigue Specimens



6.5 Conclusion

As a summary for this chapter, PFA mixture has outperformed conventional mixture concerning permanent deformation or rutting properties based on Wheel

Tracking Test implemented. Although PFA mixture does not reveal any significant improvement in fatigue life compared to conventional mixture, however this property is totally covered or overcome by the difference of flexural stiffness developed by both mixtures. PFA mixture has totally outclassed conventional mixture in this aspect, whereby PFA had much higher flexural stiffness compared to conventional mixture.

Chemical reactions in asphalt concrete mixture are totally negligible since there is no presence of water in the mixture. Therefore, the improvements are totally dependent on PFA physical properties instead of chemical properties. The spherical shape of PFA in nature is the ultimate reason behind the improvements achieved compared to Ordinary Portland cement. The spherical shape had improved the workability; reduce the porosity and hence giving higher Marshall Stability and lower flow property for asphalt concrete mixture. **Figure 6.7** shows the microscopic photographs of fly ash and Portland cement, and as can be seen, PFA particle has relatively spherical shape while, Portland cement particle has irregular shape.

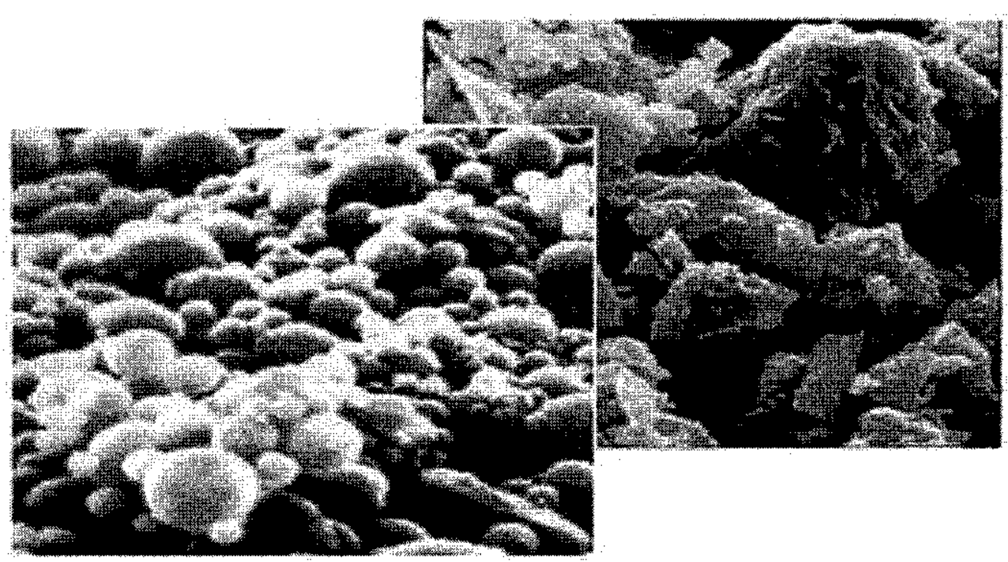


Figure 6.7: Microscopic photographs of fly ash (left) and Portland cement (right)

Chapter VII

Recommendations and Conclusion

7.1 Conclusions

All the detailed discussions and conclusions based on the results obtained from laboratory investigation implemented in this study were presented in chapter 4, 5 and 6. Thus, this chapter will outline the general conclusions and findings concerning "Application of PFA in asphalt concrete mixture".

a) Application of PFA in asphalt concrete mixture will reduce porosity (voids) in the mixture.

b) Reduction of porosity will eventually give higher value of Marshall Stability and lower flow properties.

c) Application of PFA has improved asphalt concrete mixture permanent deformation or rutting property due to the improvement in workability as well as compaction effort.

d) Fatigue life property of PFA mixture does not any show significant improvement.

e) Higher flexural stiffness is developed by incorporating PFA in asphalt concrete mixture as filler.

7.2 Recommendations for further studies

This study investigates or researches on improvements achieved by incorporating PFA into asphalt concrete mixture. Among the concern properties are:

- Permanent deformation or rutting
- Fatigue life
- Flexural stiffness.

Thus, in order to gain better assessment of the performance of PFA in asphalt concrete mixture, it is encouraged to consider following recommendations for future works.

- In this study, the content of PFA applied is fixed. In order to see the actual performance achieved, it is recommended to further this study by varying the content of PFA. According to Al. Sayed(22), initial compaction and subsequent densification of asphalt paving mixtures are strongly dependent on the type and concentration of mineral filler.

- Further study can be focused on other performances tests, such as, cracking, water susceptibility, durability and creep tests.

- Lastly, study on performance by incorporating other industries wastes or by-products such as steel slag ash, blast furnace slag and municipal waste combustion ash, and compared the performance with PFA, rather than just comparison with conventional asphalt concrete mixture.

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Appendices

Waste Material	Annual Rates in Millions of Metric Tons		Current and Past Highway Uses				
	Produced	Recycled Reused	Asphalt Pavement	Concrete Pavement	Base Course	Embankment	Other
Blast Furnace Slag	??	14.1	Accepted use as an aggregate in base and surface (friction) course, research indicates good performance	Accepted use as a cement additive in granulated form, research is ongoing	Accepted use, good, hard, durable aggregate	Limited but accepted use,	Research in Roller Compacted concrete, accepted as ice control abrasive
Carpet Fiber Wastes	2	??	Experimental stages in HMA and SMA no field data	Experimental Stages, no field data	No known use	No known use	No known use
Coal Combustion Byproducts							
Coal Fly Ash	45	11	Past use as a mineral filler, research ongoing	Accepted use research ongoing	Used in soil stabilization	Used in flowable fills, embankment	Used in all types of PCC
Coal Bottom Ash or Bottom Slag	16	5	Combined ash as a fine aggregate, performance data limited	Use unknown	Use unknown	Used as a sub-base material, embankment	Lightweight concrete, abrasives
Flue Gas Desulfurization Waste	18	??	Use unknown	Used as a set retarder	Used with cement in soil stabilization	Used as an embankment material	No known use
Glass	12.0	2.4	Accepted use, long-term performance research under way	Past research indicated performance problems	Used in dense and open-graded bases	Some research projects under way	Limited use as a paint bead, pipe backfill
Mill Tailings	432	<1%	Accepted use, research indicates good performance	Limited but accepted use	Use unknown	Accepted use	Use unknown
Municipal Waste Combustion Ash	7.3	<10%	Past research indicated good performance - Environmental questions	No known use	Used in cement-stabilized bases	Used in soil stabilization	No known use

Plastic	14.7	0.3	Used as a binder additive	Expenmental stage	No known use	No known use	Used as fence or delineator posts, guardrail blockouts
Reclaimed Concrete Pavement	3	??	Limited use, long-term performance research under way	Limited use, research under way	Accepted use	Accepted use	Used as rip- rap
Reclaimed Asphalt Pavement	91	73	Variety of accepted uses	Experimental stages	Accepted use	Accepted use	Used as shoulder material
Roofing Shingle Waste Industry-Produced Re-roofing Waste	0.4 7.3	<1%	Limited use, research under way	No known use	No known use	No known use	Used as a pothole patching material
Scrap Tires	2.3	0.4	Accepted use, extensive research being conducted	Experimental Stages	Used as an insulator	Used with some success - research continuing	Being marketed for use as noise or retaining wall, molded posts, many minor uses
Steel Slag	7.5	6.9	Past research indicates good performance	Extensive research, poor performance	Limited use	Accepted use	Ice control
Waste Rock	954	<1%	Accepted use, research indicates good performance	Limited but accepted use	Use unknown		

Table A-1: Use of other industries wastes and by-products

Time	Temp	Depth
0	44.76	0.00
1	44.09	2.37
2	44.15	3.55
3	44.96	4.14
4	45.80	4.61
5	46.66	5.10
6	47.50	5.51
7	48.34	5.81
8	49.18	6.19
9	49.46	6.52
10	49.05	6.75
11	48.70	7.11
12	48.31	7.36
13	47.99	7.64
14	47.65	7.96
15	47.16	8.21
16	46.88	8.44
17	46.46	8.67
18	46.15	8.90
19	45.82	9.24
20	45.67	9.44
21	45.39	9.63
22	45.08	9.92
23	44.99	10.21
24	44.96	10.57
25	45.30	10.77
26	46.15	10.91
27	46.99	11.16
28	47.83	11.38
29	48.62	11.66
30	48.71	11.87
31	48.56	12.11
32	48.41	12.33
33	48.22	12.58
34	48.00	12.79
35	47.83	13.05
36	47.47	13.31
37	47.21	13.52
38	47.08	13.74
39	46.87	13.97
40	46.69	14.21
41	46.41	14.37
42	46.31	14.59
43	45.96	14.82
44	45.79	15.25
45	45.35	15.62
46	45.23	15.86

Table A-2: Result for Sample 1 (conventional)

Time	Temp	Depth
0	42.08	0.00
1	41.78	1.25
2	41.66	1.88
3	41.57	2.38
4	41.34	2.71
5	41.20	3.11
6	41.08	3.57
7	41.05	3.80
8	40.97	4.13
9	40.93	4.44
10	40.86	4.65
11	40.79	4.93
12	40.75	5.14
13	40.72	5.37
14	40.71	5.67
15	40.64	5.83
16	40.46	6.04
17	40.44	6.22
18	40.41	6.39
19	40.24	6.73
20	40.13	6.91
21	40.07	7.11
22	40.03	7.33
23	40.03	7.60
24	39.99	7.93
25	40.00	8.16
26	39.99	8.29
27	39.94	8.49
28	39.92	8.69
29	39.85	8.94
30	39.78	9.12
31	39.77	9.32
32	39.73	9.54
33	39.75	9.77
34	39.79	10.01
35	39.83	10.25
36	39.87	10.44
37	39.84	10.72
38	39.82	10.91
39	39.78	11.23
40	39.73	11.51
41	39.78	11.62
42	40.36	11.81
43	41.15	12.05
44	41.93	12.34
45	42.25	12.54
46	42.35	12.75

Table A-3: Result for Sample 2 (conventional)

Time	Temp	Depth
0	46.09	0.00
1	45.83	0.30
2	44.99	0.72
3	44.14	1.43
4	43.36	2.10
5	42.56	2.79
6	42.08	3.31
7	41.63	3.69
8	41.21	4.06
9	41.03	4.45
10	41.02	4.71
11	41.60	5.04
12	42.44	5.27
13	43.30	5.52
14	44.14	5.85
15	44.98	6.07
16	45.84	6.28
17	46.68	6.50
18	47.45	6.75
19	47.34	7.15
20	47.01	7.40
21	46.63	7.59
22	46.33	7.83
23	45.98	8.12
24	45.74	8.44
25	45.43	8.54
26	45.19	8.72
27	44.91	8.98
28	44.71	9.19
29	44.60	9.41
30	44.35	9.62
31	44.28	9.90
32	44.20	10.09
33	44.20	10.27
34	44.65	10.52
35	45.50	10.74
36	46.34	11.03
37	47.18	11.22
38	47.23	11.46
39	47.24	11.62
40	47.20	11.87
41	47.12	12.06
42	46.86	12.26
43	46.82	12.50
44	46.62	12.79
45	46.58	13.03
46	46.26	13.22

Table A-4: Result for Sample 3

(conventional)

Time	Temp	Depth
0	44.31	0.00
1	43.90	1.31
2	43.60	2.05
3	43.56	2.65
4	43.50	3.14
5	43.47	3.67
6	43.55	4.13
7	43.67	4.43
8	43.79	4.79
9	43.81	5.14
10	43.64	5.37
11	43.70	5.69
12	43.83	5.92
13	44.00	6.18
14	44.17	6.49
15	44.26	6.70
16	44.39	6.92
17	44.53	7.13
18	44.67	7.35
19	44.47	7.71
20	44.27	7.92
21	44.03	8.11
22	43.81	8.36
23	43.67	8.64
24	43.56	8.98
25	43.58	9.16
26	43.78	9.31
27	43.95	9.54
28	44.15	9.75
29	44.36	10.00
30	44.28	10.20
31	44.20	10.44
32	44.11	10.65
33	44.06	10.87
34	44.15	11.11
35	44.39	11.35
36	44.56	11.59
37	44.74	11.82
38	44.71	12.04
39	44.63	12.27
40	44.54	12.53
41	44.44	12.68
42	44.51	12.89
43	44.64	13.12
44	44.78	13.46
45	44.73	13.73
46	44.61	13.94

Table A-5: Average result

(conventional)

Time	Temp	Depth
0	40.09	0.00
1	39.71	1.10
2	38.99	1.51
3	38.41	1.79
4	38.53	2.06
5	38.40	2.31
6	38.69	2.47
7	39.10	2.63
8	39.58	2.83
9	40.15	3.02
10	40.76	3.34
11	41.28	3.49
12	41.90	3.64
13	42.65	3.90
14	43.35	4.10
15	43.95	4.31
16	44.51	4.51
17	45.29	4.73
18	45.89	4.91
19	46.53	5.04
20	46.99	5.21
21	47.59	5.45
22	47.55	5.61
23	47.21	5.81
24	47.25	6.08
25	46.89	6.27
26	46.83	6.48
27	46.99	6.76
28	47.11	6.92
29	47.45	7.08
30	48.01	7.29
31	48.53	7.47
32	48.95	7.66
33	49.15	7.85
34	49.51	8.09
35	49.29	8.26
36	48.89	8.45
37	48.49	8.74
38	48.35	8.94
39	48.11	9.07
40	47.96	9.24
41	47.74	9.38
42	47.64	9.63
43	47.12	9.79
44	46.54	9.94
45	46.62	10.12
46	46.38	10.30

Table A-6: Result for Sample 1 (PFA)

Time	Temp	Depth
0	44.54	0.00
1	44.28	0.29
2	44.18	0.45
3	44.05	0.57
4	43.99	0.73
5	43.94	1.00
6	44.00	1.21
7	44.63	1.43
8	45.49	1.65
9	46.31	1.88
10	47.15	2.07
11	48.01	2.29
12	48.85	2.46
13	48.95	2.64
14	48.73	2.84
15	48.49	3.02
16	48.26	3.20
17	48.01	3.35
18	47.56	3.52
19	47.31	3.83
20	47.02	4.00
21	46.69	4.16
22	46.47	4.43
23	46.20	4.66
24	45.97	4.96
25	45.74	5.12
26	45.44	5.26
27	45.33	5.50
28	45.19	5.68
29	44.93	5.92
30	44.73	6.09
31	44.62	6.30
32	44.53	6.46
33	44.34	6.66
34	44.27	6.87
35	44.35	7.11
36	45.01	7.33
37	45.85	7.51
38	46.71	7.69
39	47.55	7.92
40	48.39	8.15
41	48.67	8.30
42	48.58	8.44
43	48.42	8.61
44	48.25	8.83
45	47.89	8.99
46	47.14	9.18

Table A-7: Result for Sample 2 (PFA)

Time	Temp	Depth
0	45.61	0.00
1	45.64	1.07
2	46.44	1.44
3	46.34	1.55
4	46.89	1.85
5	47.25	2.11
6	47.16	2.28
7	47.17	2.52
8	46.88	2.71
9	46.18	2.84
10	45.20	3.12
11	45.28	3.28
12	45.23	3.61
13	46.24	3.77
14	46.17	3.98
15	45.68	4.12
16	44.89	4.38
17	44.14	4.60
18	44.56	4.74
19	45.25	4.91
20	46.27	5.15
21	46.58	5.34
22	47.26	5.56
23	47.69	5.72
24	47.99	5.97
25	48.21	6.20
26	47.56	6.38
27	47.19	6.57
28	46.58	6.76
29	46.19	6.88
30	45.36	7.06
31	45.12	7.31
32	44.52	7.55
33	44.10	7.66
34	43.59	7.86
35	43.23	8.08
36	43.17	8.32
37	42.58	8.56
38	42.05	8.67
39	41.89	8.85
40	42.02	9.11
41	42.56	9.29
42	43.13	9.53
43	43.96	9.68
44	44.23	9.82
45	45.69	10.06
46	46.03	10.22

Table A-8: Result for Sample 3 (PFA)

Time	Temp	Depth
0	43.41	0.00
1	43.21	0.82
2	43.20	1.13
3	42.93	1.30
4	43.14	1.55
5	43.20	1.81
6	43.28	1.99
7	43.63	2.19
8	43.98	2.40
9	44.21	2.58
10	44.37	2.84
11	44.86	3.02
12	45.33	3.24
13	45.95	3.44
14	46.08	3.64
15	46.04	3.82
16	45.89	4.03
17	45.81	4.23
18	46.00	4.39
19	46.36	4.59
20	46.76	4.79
21	46.95	4.98
22	47.09	5.20
23	47.03	5.40
24	47.07	5.67
25	46.95	5.86
26	46.61	6.04
27	46.50	6.28
28	46.29	6.45
29	46.19	6.63
30	46.03	6.81
31	46.09	7.03
32	46.00	7.22
33	45.86	7.39
34	45.79	7.61
35	45.62	7.82
36	45.69	8.03
37	45.64	8.27
38	45.70	8.43
39	45.85	8.61
40	46.12	8.83
41	46.32	8.99
42	46.45	9.20
43	46.50	9.36
44	46.34	9.53
45	46.73	9.72
46	46.52	9.90

Table A-9: Average result (PFA)

Sample Calculations

1) SG of Conventional mixture

$$= \frac{100}{(\%\ \text{of CA} / SG_{CA}) + (\%\ \text{of Sand} / SG_{Sand}) + (\%\ \text{of Filler} / SG_{Filler})}$$

$$= \frac{100}{(55\% / 2.7) + (40\% / 2.38) + (5\% / 3.16)}$$

= ***2.58***

2) SG of Conventional mixture

$$= \frac{100}{(\%\ \text{of CA} / SG_{CA}) + (\%\ \text{of Sand} / SG_{Sand}) + (\%\ \text{of Filler} / SG_{Filler})}$$

$$= \frac{100}{(55\% / 2.7) + (40\% / 2.38) + (5\% / 2.20)}$$

= ***2.53***

SG for coarse aggregates = 2.70

SG for fine aggregates = 2.38

SG for filler (OPC) = 3.16

SG for filler (PFA) = 2.20