The Effect Of Water On Bituminous Mixtures

by

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CERTIFICATION OF APPROVAL

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Approved by,

_____

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2012

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 reference and acknowledgements, and the original work contained herein have not undertaken or done by unspecified sources or persons.

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(MOHD ANAS BIN ADANAN)

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ABSTRACT

Water related damage in bituminous pavements is a major distress form in any road design. One of the main causes of distress in asphalt pavements is damage due to water (Dow, 2008). This study will focus on laboratory work on the effect of water on bituminous mixtures. Presence of water can cause loss of strength and durability of the bituminous mixtures. The loss of adhesion between the bitumen and the aggregates is a mechanism acknowledged by the highway engineers called stripping. The stripping is one type of moisture damage which in turn contributes to the damage of pavement thus shortening its service life. Study needs to be conducted in conjunction of dealing with the moisture effect. Therefore, the use of retained stability ratio obtained from laboratory tests is useful to determine quantitatively the moisture damage on bituminous mixes. Different types of binders are chosen that are a virgin bitumen of 80pen grade and polymer modified bitumen and comparisons are made between them.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background Of Study

Bituminous materials are used widely all over the world in highway construction. The bituminous materials used in highway construction are either asphalts or tars. A typical flexible structure in Malaysia consists of asphaltic concrete wearing and binder course, unbound granular base, and sub-base overlying the subgrade (Arshad, 2007). Water has a lot of adverse effects on the pavement performance. It is a well-known fact that water in pavement systems is one of the principal causes of premature pavement failure. Moisture damage in bituminous mixtures is a global concern.

These detrimental effects can be reduced by preventing water from entering the bituminous mix structures, providing adequate drainage to remove infiltration, or building the main structure of the pavement strong enough to resist the effect of water. Hence, it's a need to identify and understand the problem and isolate the contributing factors to the damage of the bituminous mixtures. It's also a need to improve the pavements service life as all the engineers and professionals need to provide first class facilities to the community.

This study will focus on some of the major failure mechanisms associated with the presence of water in bituminous materials. It is an important measure to identify these failure mechanisms as there are many highway construction projects being implemented by the government throughout the country nowadays. The study is essential in order to obtain positive benefits as its outcomes i.e. save time and costs and reduce the risk of traffics accidents due to the damage of road pavements.

1.2 Problem Statement

Rain falling on the ground will run overland or soak into the ground. When water gets into the pavement, significant weakening can occur, eventually causing differential heaving of the pavement in addition to the weakening of the bituminous materials as part of the pavement structures. Moisture damage can be defined as the loss of strength and durability in asphalt mixtures caused by the presence of water. Moisture damage is induced by the loss of bond between the bituminous mixture's components. This type of damage can lead to the loss of strength of the pavement structure.

The majority of studies on moisture or water damage in asphalt mixtures deals with a phenomenon called stripping. Stripping is the displacement of asphalt films from aggregate surfaces that occurs when the aggregate has greater attraction for water than the asphalt. There are also other types of moisture damage other than stripping such as bleeding, rutting and cracking.

This work is to assess the effect of water damage on bituminous mixtures and identify the initiatives to overcome these constraints.

1.3 Objective

The objective of this work is to study on the effects of water on bituminous mixtures. This work will also focus on obtaining the most suitable type of binder in order to minimize the effect of the moisture damage that is stripping.

1.4 Scope of Study

The scope of this study will be divided into three (3) phases:

1) Literature reviews
2) To test the samples under Retained Marshall Stability test
3) To vary the usage of binders such as 1, 2, and 3% PP (Polypropylene) and LLDPE (Linear-Low Density Polyethylene)

1.5 Relevancy and Feasibility of the Project

This work is relevant in the author's field of study as it deals with civil engineering's areas of study. One of the main causes of distress in asphalt pavements damage is due to water (Dow, 2008). In order to maintain or replace the stripped materials or part of the pavements, this would involve a certain amount of additional cost and totally not a good practice. This work will help to evaluate and determine the type of binder that is suitable in order to minimize the stripping effect due to the presence of water so that it can maintain or retain the structural integrity of the pavement for an extended period of time.

The project is feasible since it is within the scope and time frame. The Retained Marshall Stability test is already started and the remaining works will be completed according to the schedule.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains the characteristics and materials being used in bituminous mixtures. This chapter will also explain on the problem of premature failure of bituminous mixtures. Of great interest is the problem associated with stripping. At the end of this chapter, it will explains about the different types of mechanisms associated to stripping.

2.2 Bituminous Mixtures

Bituminous materials are used widely all over the world in highway construction. These hydrocarbons are found as natural deposits or are obtained as a product of the distillation of crude petroleum. The bituminous materials used in highway construction are either asphalts or tars.

All bituminous materials consist primarily of bitumen and have strong adhesive properties with colors ranging from dark brown to black. They vary in consistency from liquid to solid; thus they are divided into liquids, semisolids and solids. The solid form is usually hard and brittle at normal temperatures but will flow when subjected to long, continuous loading. The liquid form is obtained from the semisolid or solid forms by heating, dissolving in solvents, or breaking the material into minute particles and dispersing them in water with an emulsifier to form an asphalt emulsion.

Bituminous mixtures are a uniformly mixed combination of bitumen, coarse aggregate, fine aggregate and other materials, depending on the type of bituminous mixture. Bituminous mixtures are used widely in most of the country around the world nowadays. When used in the construction of highway pavements, it must resist deformation from imposed traffic loads, be skid resistant even when wet, and not be affected easily by weathering process. It depends on how the design of the bituminous mix in order to achieve this characteristics.

2.3 Polymer Modified Bitumen

Significant increase in traffic loading in modern days comes to worry the traffic and highway engineers due to the increase of road repair works and maintenance. So in order to cope with the problems arising from the higher maintenance of roads, the modification of the virgin bitumen has become one of the preferred solutions.

Polymer modification is considered as one of the solution to improve fatigue life, reduce rutting and thermal cracking in the pavement (Airey, 2004). Most commonly used polymer globally include approximately 75% elastomeric modified binder, 15% plastomeric and remaining 10% belongs to either rubber or other modification (Bardesi, 1999).

When a polymer and compatible base bitumen are mixed, the polymer strands absorbs part of the low molecular weight oil fraction of the base bitumen and become swollen, the swollen strands connect together at nodes and form a three dimensional network which significantly affects the mechanical properties of the binders and ultimately the bituminous binder mixes (Chen, 2002).

2.3.1 Polypropylene (PP)

Polypropylene (PP) which is also known as polypropene, is a thermoplastic polymer used in a wide variety of applications including packaging and labeling, textiles and others. Polypropylene is tough and flexible and has good resistance to fatigue. Moreover, it is reasonably economical. Addition of polymer as a mix altogether with the virgin bitumen will alter the original properties of the bitumen in terms of its viscosity, durability, adhesion, and other related engineering properties. The engineering property varies with the type of polymer added.

Thermoplastic when mixed with bitumen even at ambient temperature increases the viscosity and thus stiffness at service temperature but unfortunately do not show any significant elastic behavior (Lu & Isacsson, 1997). Thermoplastics, when used as modifier alters mechanical properties of the mixture by enhancing its mechanical behavior in significant manner (Tapkin et al, 2009).

Thus thermoplastic when used as modifier gives rigidity to the binder and reduces the deformation under load (Stastna et al, 2002).

2.3.2 Linear Low-Density Polyethylene (LLDPE)

Linear low-density polyethylene (LLDPE) is a linear polymer. It endures different manufacturing processes of LLDPE and LDPE. LLDPE is used for plastics bags, plastic wrap, pipes and other plastic-based products.

For LLDPE the concentration up to 2.5% shows better results in terms of Marshall Stability, resilient modulus, water susceptibility and fatigue life of the modified binder (Hadidiy & Tan, 2009). Polyethylene which belongs to plastomer gives rigidity to the binder and reduces the deformation under loads (Stastna et al, 2002).

Polyethylene morphology is strongly affected under stress and deformation as sliding of chains with respects to entanglements occurs at nodes (Aleskey & Yuan, 2003).

Addition of bitumen improves deformation resistance as the viscosity of blend enhanced tremendously which is observed with increase in softening point and decrease in penetration values (Hadidiy & Tan, 2009).

2.4 Stripping

Moisture damage can be defined as the loss of strength and durability in asphalt mixtures caused by the presence of water. Moisture damage is induced by the loss of bond between the asphalt cement and the aggregates. Moisture damage accelerates as moisture permeates and weakens the binder, making it more susceptible to moisture during cyclic loading (Yilmaz and Sargin, 2012).

Stripping is a phenomenon in which the asphalt binder in an asphalt pavement loses its ability to bond to the aggregate and the pavement material loses its structural integrity (Johnson and Freeman, 2002). The result is a pavement that fails under ordinary traffic loads. It has been speculated that asphalt may be able to strip from an aggregate under dry conditions, especially after it has aged many years, but most losses of adhesion are attributed to the action of water (Yilmaz and Sargin, 2012).

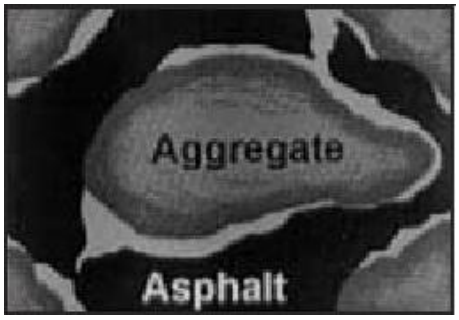

FIGURE 2-1: Stripping of asphalt film from the aggregate surface. (Adopted from: http://www.scribd.com/doc/36634614/Moisture-Sensitivity-of-Asphalt-Pavements)

2.4.1 Pavement Distress

Scholz and Rajendran (2009) have identified the following pavement distresses as an outcome from stripping:

1) **Ravelling:** It can be described as a loss of pavement material from the surface downward and is caused by the loss of asphalt binder (deterioration due to moisture effect), ultraviolet exposure, traffic frequency, weather conditions, asphalt mix design, and compaction of the asphalt during construction. Also, as the binder wears away, aggregate particles begin to break away. This begins with fine aggregate particles breaking away and, consequently, exposing the coarse aggregate.
2) **Rutting:** It is a form of depression or groove worn into a road or path by the travel of wheels. Or in other words, it is a surface depression in the wheelpath.
3) **Alligator Cracking:** It is a series of interconnected cracking of the pavement surface due to repeated traffic loading. Cracking begins at the bottom on the asphalt surface (base) where tensile stress and strain are highest under a wheel load. The cracks propagate to the surface initially as a series of parallel longitudinal cracks.

4) **Longitudinal Cracking:** Longitudinal cracks are parallel to the pavement's centerline. It can also be a caused by a poorly constructed paving lane joint. Joints are generally the least dense areas of a pavement. Therefore, they should be constructed outside of the wheelpath so that they are only infrequently loaded.

2.4.2 Stripping Mechanisms

There are some different mechanics of stripping and they are described as follows:

1) **Detachment:** It is the microscopic separation of a binder film from the aggregate surface by a thin layer of water with no obvious break in the binder film. The binder will then peel cleanly from the aggregate. The thin film of water probably results from either aggregate that was not completely dried, interstitial pore water which vaporized and condensed on the surface, or possibly water which permeated through the asphalt film to the interface (Kiggundu and Roberts, 1998).
2) **Displacement:** Displacement occurs when the binder is removed from the aggregate surface by water. In this type of stripping, as compared to detachment, the free water gets to the aggregate surface through a break in the binder coating. The break may be from incomplete coating during mixing or from binder film rupture (Asphalt Institute, 1981).
3) **Spontaneous Emulsification:** Spontaneous emulsification occurs when an inverted emulsion (water droplets in binder rather than binder droplets in water as found in common emulsified asphalt) is formed. In its emulsified state, the binder is less tenacious. This mechanism seems to be enhanced under traffic on mixtures laden with free water (Kiggundu and Roberts, 1998).

4) **Film Rupture:** Film rupture, while not a stripping mechanism on its own, is believed to initiate stripping. Film rupture is marked by fissures that occur under stresses of traffic at sharp aggregate edges and corners where the binder film is the thinnest. Once a break in the film is present, water is able to find its way to the interface and initiate stripping (Asphalt Institute, 1981).
5) **Pore Pressure:** A build-up of pore pressure is another possible stripping mechanism. Stripping from pore pressure build-up begins when water is allowed to circulate freely through the interconnected voids of a high void asphalt mixture. Traffic effects cause the void space to be reduced and passages between voids to be closed thus trapping water. The continued action of traffic can then cause pore pressures to build up to the point of stripping the binder from the aggregate (Asphalt Institute, 1981).
6) **Hydraulic Scouring:** Hydraulic Scouring occurs more in surface courses than the lower courses of an asphalt pavement. When the pavement is saturated, wheel action causes water to be pressed into the pavement in front of the tires and to be sucked out behind the tires. This water tends to strip the binder from the aggregate. This scouring action can be worsened by the presence of abrasives, such as dust, on the surface of the roadway (Asphalt Institute, 1981).

2.5 Void Structure in Bituminous Mixtures

In partial saturation and moisture conditioning processes, water is allowed to enter the air voids in the sample. Kumar and Goetz (1977) conducted a laboratory study to examine the influence of asphalt film thickness, voids and permeability on asphalt hardening in asphalt mixtures and came out with a hypothetical model of the air voids system in the compacted bituminous mixtures. Different water saturation techniques were employed in their study included a 24 hours soaking and vacuuming at different absolute pressures. The model divides the air voids system into three categories; through passage

accessible air voids, dead end accessible air voids and non-accessible air voids. Partial saturation process done by vacuuming water into the specimen allows the water to enter through passage accessible air voids and some portion of dead end accessible air voids. The air void study is important in order to maintain the highest possible degree of saturation without damaging the sample in order to obtain the retained strength of the sample.

2.6 Tests Method

2.6.1 Preparing the Moisture-Conditioned (Wet) Sample

The procedures used to prepare the moisture condition sample of asphalt mixtures is carried out according to ASTM D4867. Samples are compacted to a void content of 6 to 8% range corresponding to void levels expected in the field.

Two samples are prepared for the test. The average air voids of the two samples should be approximately equal. The porosity of the sample can be calculated as follows:

$$Porosity\ (\%) = \left(1 - \frac{SG_{bulk}}{SG_{mix}}\right) x100\%$$

Where,

$$SG_{bulk} = \frac{W_a}{W_a - W_w}$$

And,

$$SG_{mix} = \frac{\%AGG + \%Bit}{(\frac{\%AGG}{SG_{agg}} + \frac{\%Bit}{SG_{Bit}})}$$

And,

$$SG_{agg} = \frac{\%CA + \%FA + \%Filler}{(\frac{\%CA}{SG_{CA}} + \frac{\%FA}{SG_{FA}} + \frac{\%Filler}{SG_{Filler}})}$$

SG_{bulk} = Bulk Specific Gravity (g/g)
SG_{mix} = Specific Gravity of Mixture (g/g)
SG_{agg} = Specific Gravity of Aggregates (g/g)
SG_{CA} = Specific Gravity of Coarse Aggregates (g/g)
SG_{FA} = Specific Gravity of Fine Aggregates (g/g)
SG_{Filler} = Specific Gravity of Filler (g/g)
SG_{Bit} = Specific Gravity of Bitumen (g/g)
W_a = Weight in air (g)
W_w = Weight in water (g)

One of the sample is to be tested dry while the second sample is partially saturated with water and moisture conditioned. The dry sample is stored and to be tested dry at room temperature. The second sample is to be moisture conditioned with distilled water at room temperature using a vacuum chamber.

Then, determine the degree of saturation of the water in the sample and express it in percentage form. The volume of the absorbed water can be determined by subtracting the air-dry mass of the sample from the partially saturated sample. The degree of saturation of the sample is calculated by dividing the volume of the absorbed water by the volume of voids and the result is expressed in percentage. The volume of water in the sample should be between 55 and 80%. If the percentage of water exceeding 80% so the sample is considered to be broken and is discarded.

The degree of saturation is calculated as follows:

$$Degree\ of\ Saturation\ (\%) = \frac{Volume\ of\ Absorbed\ Water}{Volume\ of\ Pores} x100\%$$

The sample is partially saturated, by applying a partial vacuum such as 70 kPa or 525mm Hg for a short time i.e. five minutes. Next, the sample is then soaked in water at 60 ± 1°C for 2 hours. Then adjust the temperature of the moisture-conditioned sample at 25 ± 1°C for 1 hour. The height, volume, water absorption and the degree of saturation is then measured from the moisture-conditioned sample. At this stage, the degree of saturation exceeding 80% is acceptable.

Then, the swell of the partially saturated sample is determined by dividing the change in sample volume with the initial recorded volume. The swell of the sample is calculated in the formula below:

$$Swell\ (10^{-4}) = \frac{Volume\ of\ (Soaked\ Sample - \ Dry\ Sample)}{Volume\ of\ Dry\ Sample}$$

Then, both samples, dry and moisture-conditioned samples are ready to be tested for their stability strength. Break the sample open after the test has been completed and the degree of moisture damage is determined, if any.

2.6.2 Retained Marshall Stability Test

Stability can be simply described as the ability of the bituminous mixture to resist excessive permanent deformation and bituminous mixtures are typically designed for stability, if no other distress mechanism, because stability problems typically occur within a few years or even months or weeks after construction (Kok and Kuloglu, 2007).

In order to test for the moisture damage, for the Retained Marshall Stability Test, two samples are prepared. One to be tested dry while the second sample is partially saturated with water and moisture conditioned. The procedures on how to prepare for the moisture conditioned sample as what has been discussed in 2.5.1.

The test is being done on both samples. The prepared dry and wet samples are placed in the Marshall testing rig. The breaking head of Marshall testing apparatus is conditioned to 60°C. Load the sample radially at a constant rate of strain of 50.8 mm/min. Determine the stability of each sample until maximum load has been reached. The stability value obtained need to be corrected as in Table 3-1.

The retained Marshall Stability value is calculated as follows:

$$Retained\ Stability\ (\%) = \frac{Soaked\ Stability}{Dry\ Stability} x100\%$$

Value of more than 75% retained Marshall stability is always regarded as acceptable (Whiteoak, 2003).

CHAPTER 3

METHODOLOGY

3.1 Process Work Flow for FYP

In this study, some laboratory testing will be carried out in order to determine the effect of water on bituminous mixtures. Figure 3-1 below shows the methodological path on how the study will be completed.

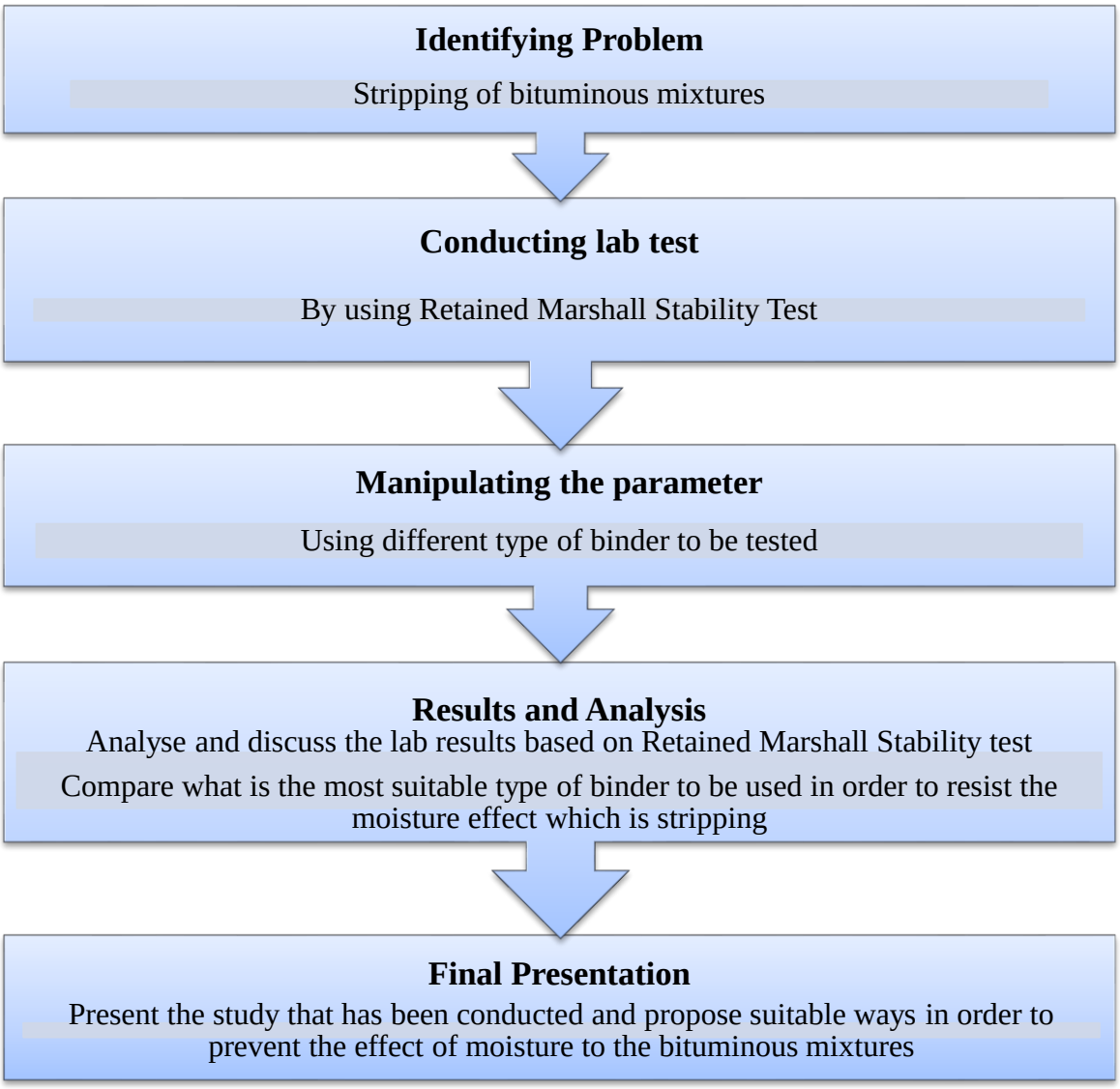

Figure 3-1: Process Work Flow for FYP

3.2 Process Work Flow for Lab Tests

3.2.1 Preparing the Moisture-Conditioned Sample

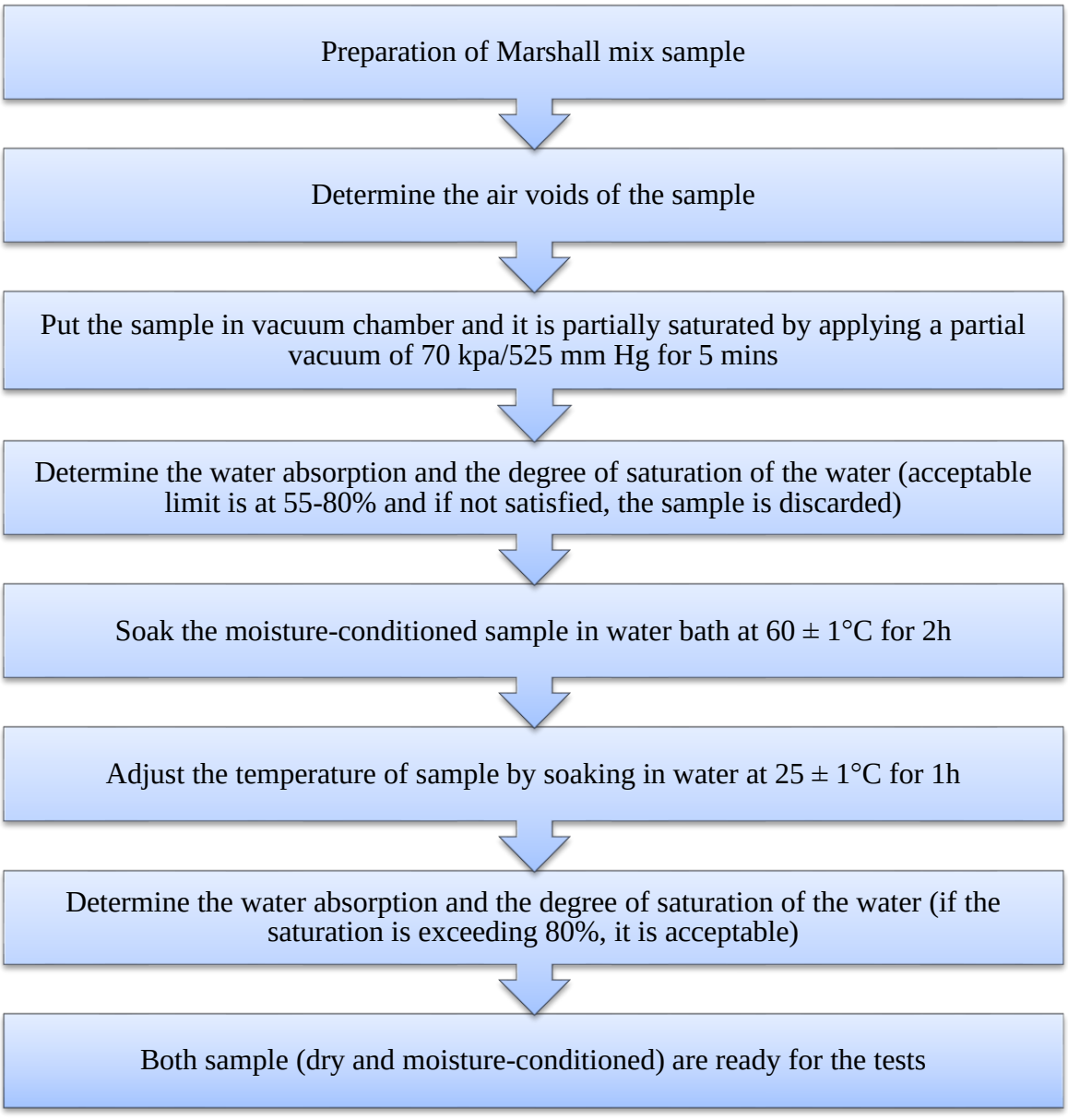

Figure 3-2: Flow of Preparation for Moisture-Conditioned Sample

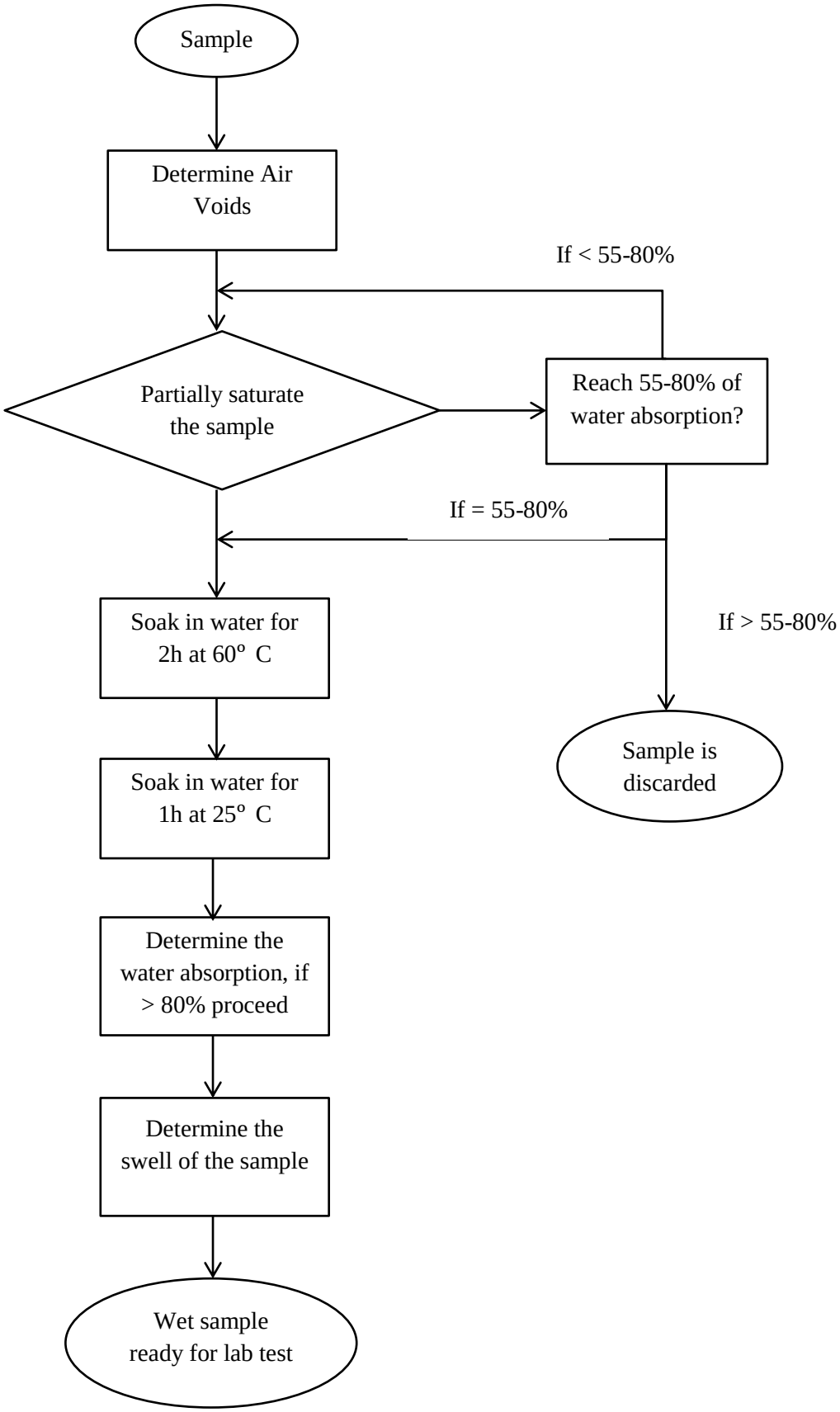

Figure 3-3: Flow Chart of Preparation for Moisture-Conditioned Sample

3.2.2 Retained Marshall Stability Test

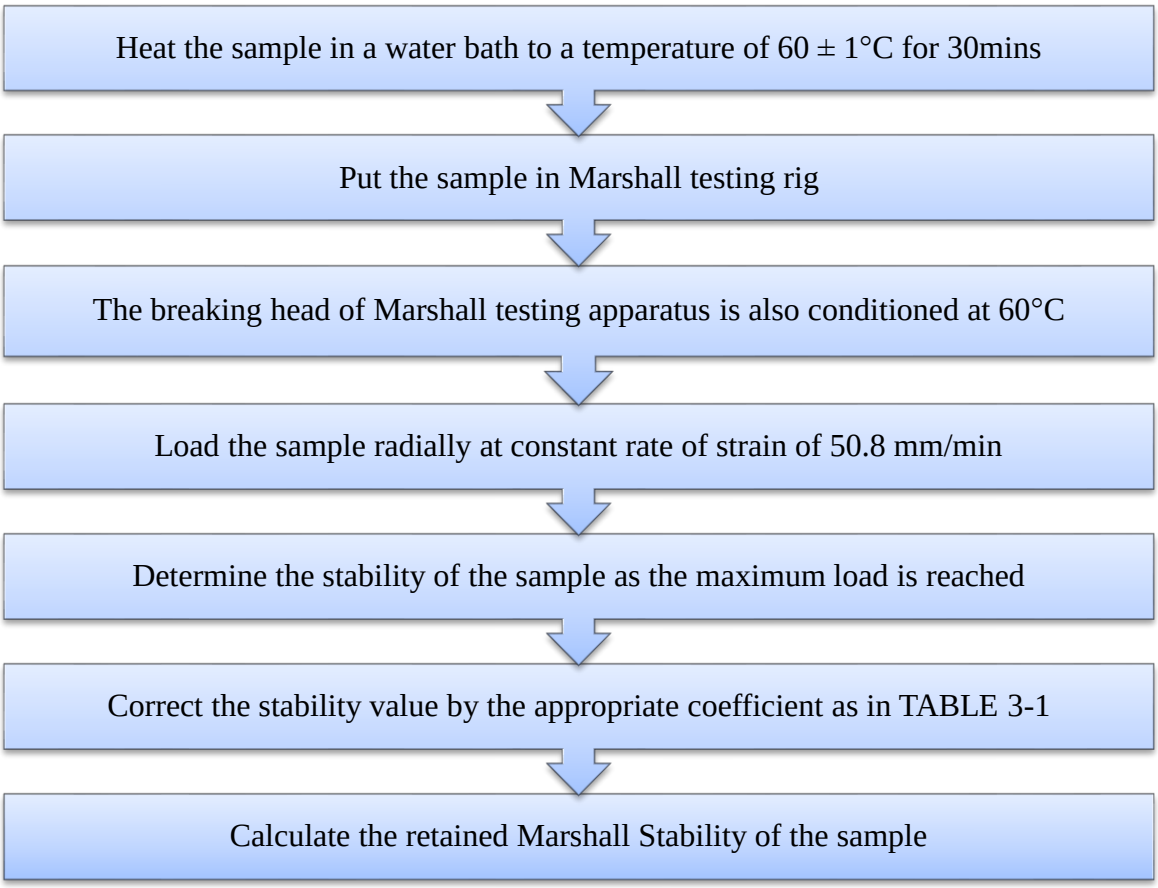

Figure 3-4: Flow of Procedures for Retained Marshall Stability Test

Volume of Specimen (cm^3)	Thickness of Specimen (mm)	Correlation Ratio
200 to 213	25.4	5.56
214 to 225	27.0	5.00
225 to 237	28.6	4.55
238 to 250	30.2	4.17
251 to 264	31.8	3.85
265 to 276	33.3	3.57
277 to 289	34.9	3.33
290 to 301	36.5	3.03
302 to 316	38.1	2.78
317 to 328	39.7	2.50
329 to 340	41.3	2.27
341 to 353	42.9	2.08
354 to 367	44.4	1.92
368 to 379	46.0	1.79
380 to 392	47.6	1.67
393 to 405	49.2	1.56
406 to 420	50.8	1.47
421 to 431	52.4	1.39
432 to 443	54.0	1.32
444 to 456	55.6	1.25
457 to 470	57.2	1.19
471 to 482	58.7	1.14
483 to 495	60.3	1.09
496 to 508	61.9	1.04
509 to 522	63.5	1.00
523 to 535	64.0	0.96
536 to 546	65.1	0.93
547 to 559	66.7	0.89
560 to 573	68.3	0.86
574 to 585	71.4	0.83
586 to 598	73.0	0.81
599 to 610	74.6	0.78
611 to 625	76.2	0.76

Table 3-1: Coefficient Factor (C.F) for Adjusting Stability Values

3.3 Gantt Chart for FYP II

Activity / Week (date)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	17/9	24/9	1/10	8/10	15/10	22/10		5/11	12/11	19/11	26/11	3/12	10/12	17/12	24/12
Project Work Continues (Marshall Stability Testing)															
Submission of Progress Report															
Pre-EDX															
Submission of Draft Report															
Submission of Dessertation (Soft Bound)															
Submission of Technical Paper															
Oral Presentation															
Submission of Project Dissertation (Hard Bound)															

Mid Semester Break

Figure 3-5: Gantt Chart for FYP II

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will discuss the results obtained up to the present work progress. This chapter will also analyze the results that have been gathered and roughly predicts the expected findings for achieving the objectives of the study based on the results obtained.

4.2 Analysis of Results

4.2.1 Calculated Porosity (%)

The calculated value of Specific Gravity of aggregates (SG_{mix}) is displayed in the table as well as the optimum bitumen content for each type of binder. The SG_{mix} value will be used in order to determine the calculated porosity which will be explained briefly later in **4.2.2**.

The calculated value of SG_{agg} is 2.6649. The voids or porosity is essential in calculating the degree of saturation of sample during the moisture conditioning process.

Polymer Content	OBC (%)	Weight (g)
Control Mix	5%	63
1% PP	5%	63
2% PP	5.2%	65.8 ≈ 66
3% PP	5.2%	66
1% LLDPE	5.2%	66
2% LLDPE	5.4%	68.5
3% LLDPE	4.7%	59.2

Table 4-1: Optimum Bitumen Content (OBC) and Weight for All Binders

Polymer Content	SG_{mix} (g/g)
Control Mix	2.472
1% PP	2.465
2% PP	2.459
3% PP	2.459
1% LLDPE	2.471
2% LLDPE	2.462
3% LLDPE	2.490

Table 4-2: Calculated SG_{mix} for All Binders

Three (3) dry and three (3) wet samples are tested under Marshall stability test and retained Marshall stability values will be obtained by calculating the ratio of the wet-dry stability values. The dry and wet samples can be identified in the tables as follow.

Virgin Bitumen (Control)					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1246.4	707.8	2.314	530.864	6.386
2) *dry*	1250.2	711.6	2.321	532.570	6.100
3) *dry*	1252.3	713.9	2.326	533.460	5.908
4) *wet*	1254.0	715.8	2.330	535.000	5.745
5) *wet*	1255.4	713.3	2.316	529.565	6.318
6) *wet*	1264.7	715.2	2.302	539.450	6.895

Table 4-3: Bulk Specific Gravity and Percentage of Voids for Control Mix

1% PP					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1240.2	700.3	2.297	538.900	6.812
2) *dry*	1252.2	711.7	2.317	544.484	6.014
3) *dry*	1262.3	718.2	2.312	542.903	5.883
4) *wet*	1260.7	715.1	2.311	552.621	6.261
5) *wet*	1254.0	715.0	2.327	529.667	5.617
6) *wet*	1259.5	715.2	2.314	543.985	6.127

Table 4-4: Bulk Specific Gravity and Percentage of Voids for 1% PP

2% PP					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1268.0	715.6	2.295	544.839	6.651
2) *dry*	1249.5	707.5	2.305	553.635	6.248
3) *dry*	1246.7	746.8	2.494	534.856	6.417
4) *wet*	1262.2	705.1	2.302	558.400	6.389
5) *wet*	1259.2	713.1	2.306	527.950	6.230
6) *wet*	1258.0	712.9	2.308	538.019	6.147

Table 4-5: Bulk Specific Gravity and Percentage of Voids for 2% PP

3% PP					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1260.1	712.8	2.302	542.993	6.369
2) *dry*	1272.1	716.5	2.290	540.991	6.889
3) *dry*	1258.5	712.3	2.304	535.709	6.299
4) *wet*	1251.3	709.5	2.310	529.194	6.079
5) *wet*	1260.9	715.1	2.310	531.793	6.052
6) *wet*	1271.4	716.8	2.292	538.181	6.773

Table 4-6: Bulk Specific Gravity and Percentage of Voids for 3% PP

1% LLDPE					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1279.4	724.5	2.306	545.066	6.692
2) *dry*	1262.3	717.7	2.318	547.194	6.198
3) *dry*	1266.7	718.0	2.309	536.713	6.574
4) *wet*	1266.3	717.6	2.308	534.369	6.604
5) *wet*	1264.6	717.5	2.311	535.277	6.456
6) *wet*	1261.3	716.1	2.313	533.787	6.375

Table 4-7: Bulk Specific Gravity and Percentage of Voids for 1% LLDPE

2% LLDPE					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1262.8	714.7	2.304	544.172	6.419
2) *dry*	1271.7	718.7	2.300	537.212	6.595
3) *dry*	1262.3	714.1	2.303	544.063	6.473
4) *wet*	1269.5	715.7	2.292	535.657	6.891
5) *wet*	1268.9	715.2	2.292	537.851	6.918
6) *wet*	1262.8	714.9	2.305	531.932	6.385

Table 4-8: Bulk Specific Gravity and Percentage of Voids for 2% LLDPE

3% LLDPE					
Samples	Wa (g)	Ww (g)	Bulk Specific Gravity (g/cm^3)	Volume of Sample (cm^3)	Voids (%)
1) *dry*	1247.3	713.8	2.338	545.284	6.106
2) *dry*	1264.3	723.4	2.337	534.228	6.128
3) *dry*	1260.2	719.7	2.332	538.969	6.364
4) *wet*	1271.7	725.7	2.329	539.978	6.461
5) *wet*	1258.6	718.5	2.330	535.67	6.413
6) *wet*	1270.1	724.9	2.330	542.044	6.442

Table 4-9: Bulk Specific Gravity and Percentage of Voids for 3% LLDPE

4.2.2 Moisture-Conditioned and Marshall Stability Test Results

The degree of saturation (%) is determined after the partial saturation process and also after the static soaking of the wet samples. The results are tabulated in the following tables for each type of binder content. The degree of saturation after complete saturation process, if exceeding 80% is considered as acceptable.

The coefficient factor (C.F) for adjusting the stability values has been determined based on the volume of each samples and has already been factored and tabulated in the tables as follow as well as the deformation (flow) of the samples.

Virgin Bitumen						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	35.472					
2) *dry*	32.774					
3) *dry*	31.596					
4) *wet*	30.896	1271.1	17.1	55.3	1273.3	62.5
5) *wet*	33.601	1274.1	18.7	55.7	1276.5	62.8
6) *wet*	37.368	1285.5	20.8	55.7	1287.0	59.7
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			22.97	1.74		
2) *dry*			22.96	3.26		
3) *dry*			22.99	1.85		
4) *wet*	535.413	7.720	13.40	2.17		
5) *wet*	529.850	5.382	14.36	2.52		
6) *wet*	539.951	9.287	9.14	2.78		

Table 4-10: Moisture-Conditioned & Marshall Stability Test Results for Control Mix

1% PP						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	36.909					
2) *dry*	33.714					
3) *dry*	32.259					
4) *wet*	34.832	1288.1	27.4	78.7	1290.3	85.0
5) *wet*	29.783	1271.2	17.2	57.8	1274.1	67.5
6) *wet*	33.564	1279.7	20.2	60.2	1282.6	68.8
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			20.68	2.01		
2) *dry*			22.28	2.04		
3) *dry*			21.58	1.97		
4) *wet*	553.023	7.274	18.66	1.25		
5) *wet*	530.126	8.666	19.93	2.25		
6) *wet*	544.312	6.011	19.48	1.41		

Table 4-11: Moisture-Conditioned & Marshall Stability Test Results for 1% PP

2% PP						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	37.518					
2) *dry*	35.709					
3) *dry*	34.322					
4) *wet*	36.436	1290.5	28.3	77.7	1294.2	87.8
5) *wet*	33.868	1278.0	18.8	55.5	1281.3	65.3
6) *wet*	33.389	1277.0	19.0	57.0	1281.1	69.2
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			23.20	2.02		
2) *dry*			22.17	1.78		
3) *dry*			23.89	2.10		
4) *wet*	558.964	10.100	16.41	2.44		
5) *wet*	528.471	9.868	20.03	2.48		
6) *wet*	538.658	11.877	23.04	1.77		

Table 4-12: Moisture-Conditioned & Marshall Stability Test Results for 2% PP

3% PP						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	35.170					
2) *dry*	37.788					
3) *dry*	34.146					
4) *wet*	31.233	1268.5	17.2	55.1	1269.7	58.9
5) *wet*	32.652	1280.7	19.8	60.6	1283.6	69.5
6) *wet*	36.892	1292.6	21.2	57.5	1295.9	66.4
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			23.16	2.50		
2) *dry*			23.19	1.87		
3) *dry*			23.94	1.72		
4) *wet*	529.752	10.544	23.96	0.76		
5) *wet*	532.269	8.951	21.12	1.12		
6) *wet*	538.651	8.733	22.14	1.69		

Table 4-13: Moisture-Conditioned & Marshall Stability Test Results for 3% PP

1% LLDPE						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	36.945					
2) *dry*	34.347					
3) *dry*	35.606					
4) *wet*	35.707	1286.2	19.9	55.7	1289.5	65.0
5) *wet*	35.259	1285.8	21.2	60.1	1287.3	64.4
6) *wet*	34.397	1282.1	20.8	60.5	1283.4	64.2
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			23.10	1.65		
2) *dry*			23.18	1.95		
3) *dry*			24.00	1.23		
4) *wet*	545.333	4.772	23.91	0.88		
5) *wet*	535.685	7.622	20.87	1.65		
6) *wet*	534.110	6.051	20.97	1.24		

Table 4-14: Moisture-Conditioned & Marshall Stability Test Results for 1% LLDPE

2% LLDPE						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	35.464					
2) *dry*	35.923					
3) *dry*	35.457					
4) *wet*	37.367	1290.4	20.9	56.0	1293.2	63.4
5) *wet*	37.461	1289.7	20.8	55.5	1290.6	57.9
6) *wet*	34.373	1282.9	20.1	58.5	1288.9	75.9
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			23.13	1.78		
2) *dry*			23.24	1.41		
3) *dry*			23.18	1.78		
4) *wet*	536.162	9.428	21.96	1.28		
5) *wet*	538.412	10.430	20.45	1.92		
6) *wet*	533.983	38.558	20.96	1.41		

Table 4-15: Moisture-Conditioned & Marshall Stability Test Results for 2% LLDPE

3% LLDPE						
Samples	Volume of voids (cm^3)	Mass of saturated sample (g)	Volume of absorbed water (cm^3)	Degree of saturation (%)	Mass of saturated sample after immersion (cm^3)	Degree of saturation after immersion (%)
1) *dry*	33.824					
2) *dry*	33.336					
3) *dry*	34.769					
4) *wet*	35.217	1291.3	19.6	55.7	1293.5	61.9
5) *wet*	34.899	1277.8	19.2	55.0	1282.5	68.5
6) *wet*	35.493	1289.7	19.6	55.2	1291.2	59.4
Samples	Volume of moisture condition sample (cm^3)	Swell of specimen (10^{-4})	Stability (kN)	Flow (mm)		
1) *dry*			23.02	1.13		
2) *dry*			23.95	1.55		
3) *dry*			23.18	1.12		
4) *wet*	541.132	21.371	20.46	1.85		
5) *wet*	536.265	11.108	22.92	1.24		
6) *wet*	540.585	9.962	20.20	1.26		

Table 4-16: Moisture-Conditioned & Marshall Stability Test Results for 3% LLDPE

The mass of each of the wet samples is again determined after the samples have been completely moisture-conditioned, as well as the degree of saturation of the samples. The degree of saturation after the static soaking or immersion is allowed to exceed 80%.

The volume of each of the wet samples is again determined after the samples have been completely moisture-conditioned. The volume of sample after immersion is determined in order to obtain the swell of the specimen. The swell value shows the change in the sample's volume. The swell is calculated in term of a number without unit just to indicate the amount of swelling of the samples. The swell also describes how much volume of water has been introduced into the sample resulting in the slight changes of the specimen's volume.

Figure 4-1 and 4-2 shows the variation between the porosity of the different type of binders between different polymer content. The calculated porosity gives a measure of all the voids in the specimens that include both the accessible voids and the non-accessible voids while the measured porosity as was obtained from the moisture conditioning process determined only the accessible voids. As shown in the tables below, the calculated porosity therefore is always greater than the measured porosity. The porosity decreases with increasing polymer content.

Polymer Content (%)	Calculated Porosity (%)	Measured Porosity (%)
1% PP	6.45	4.22
2% PP	6.37	4.04
3% PP	6.35	3.67
1% LLDPE	6.63	4.00
2% LLDPE	6.55	3.83
3% LLDPE	6.41	3.52

Table 4-17: Calculated and Measured Porosity for PP and LLDPE Modified Bitumen

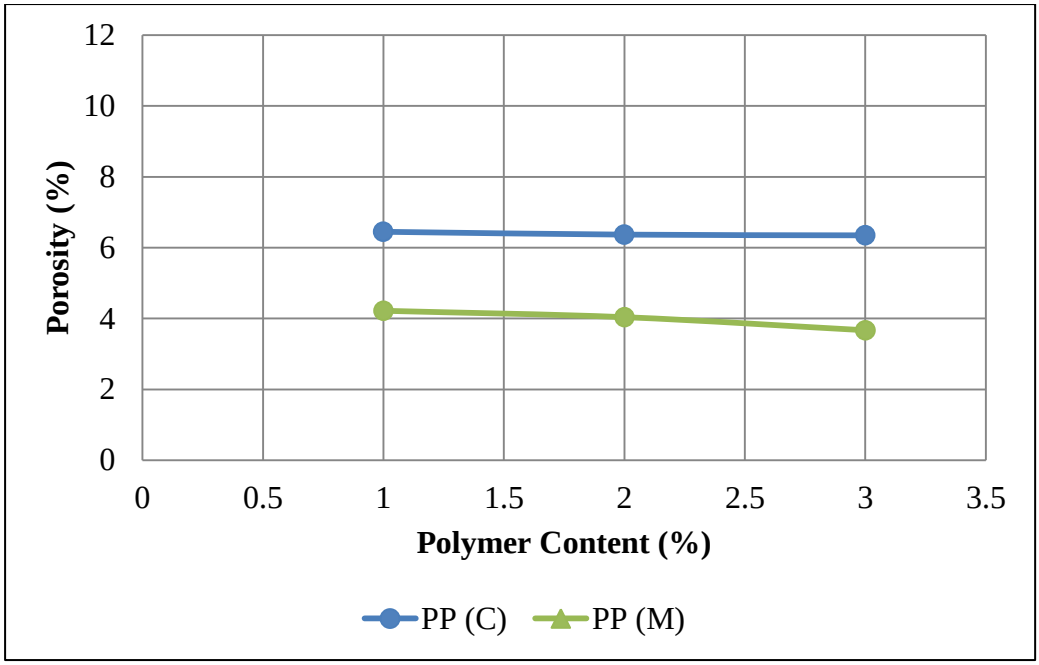

Figure 4-1: Calculated and Measured Porosity vs Bitumen Content for PP Modified Bitumen

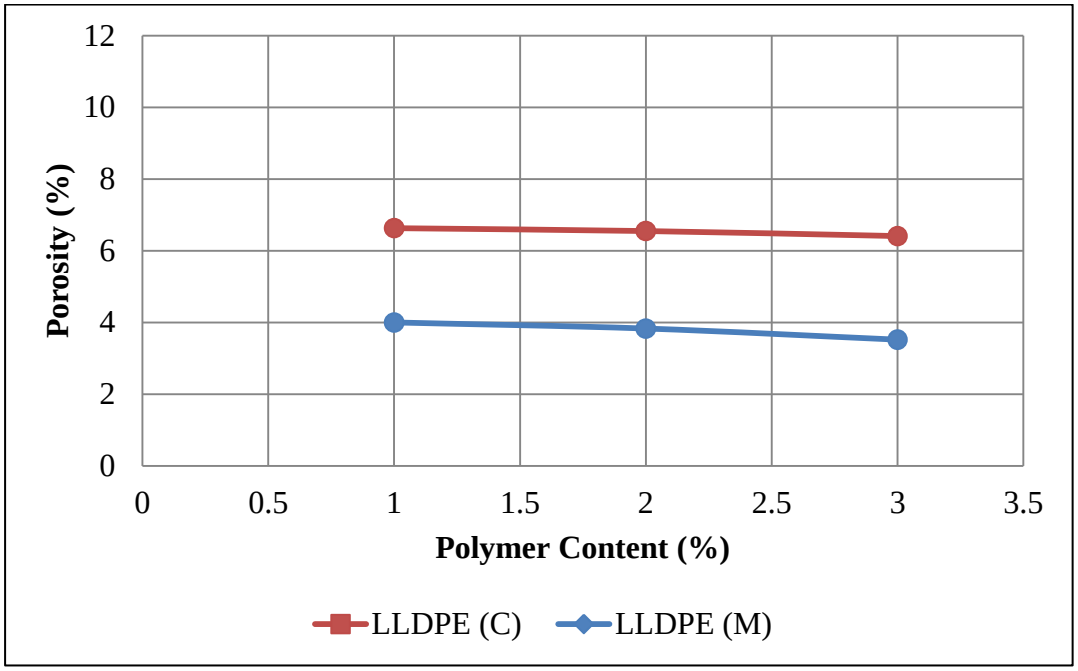

Figure 4-2: Calculated and Measured Porosity vs Bitumen Content for LLDPE Modified Bitumen

The relationship between the measured and calculated porosity is plotted in Figure 4-3 resulting in a linear relationship between both type of polymer binders. It can be observed that a point of intercept between the two linear trendline can be plotted. This gives an indication of percentage for the unconnected voids or in other word, the unaccessible voids.

Based on the general trend portrays by the relationship, it can be deduced that increasing polymer content resulted in an increase in the presence of the unconnected voids. This happens as the binder fills up the space between the mixtures constituents which are the void spaces or void channels in the mixes. Thus, this reduced the connection of voids.

Although theoretically, the porous nature of the polymer modified binders will result in higher amount of porosity, but due to the increasing optimum bitumen content wit respect to its weight, so the porosity is pronounced to be decreasing with increasing polymer content.

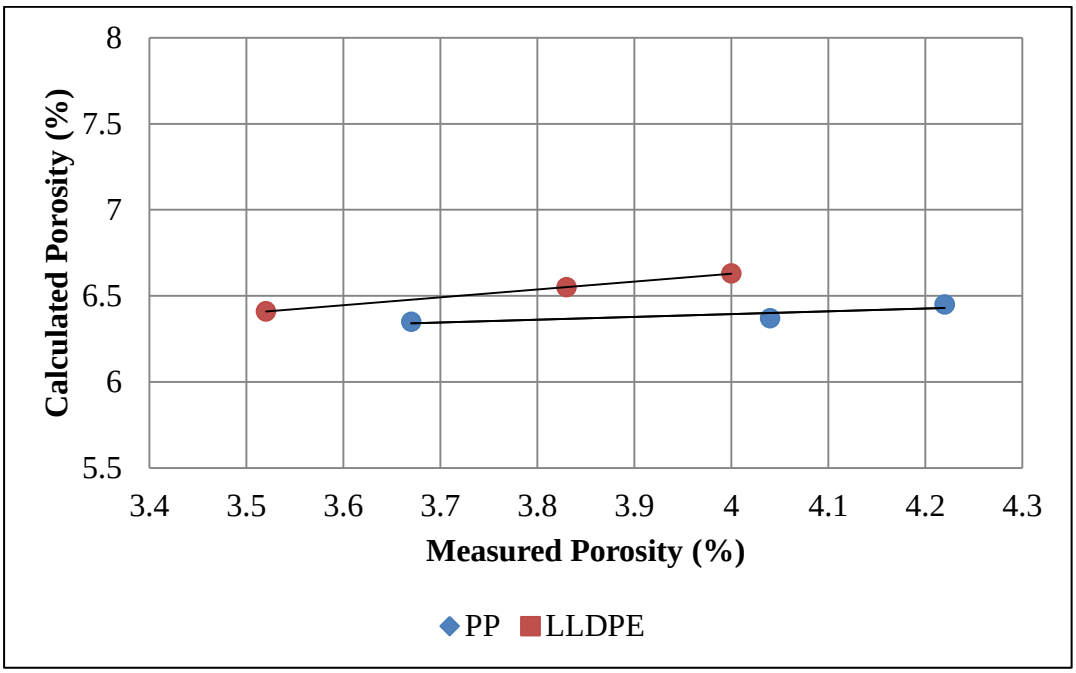

Figure 4-3: Calculated vs Measured Porosity for Different Mixtures

Figure 4-4 shows the relationship between the degree of saturation and polymer content for both types of polymer modified bitumen mixes. As shows, it can be deduced that the general trend is for the degree of saturation to decrease with increasing polymer content. Increasing polymer content in the degree of saturation trend also corresponds to the increase in the bitumen content.

For all the mixes, the saturation slope gradient appears to be about parallel to each other indicating that the degree of saturation in all the mixes decreases with increasing polymer content.

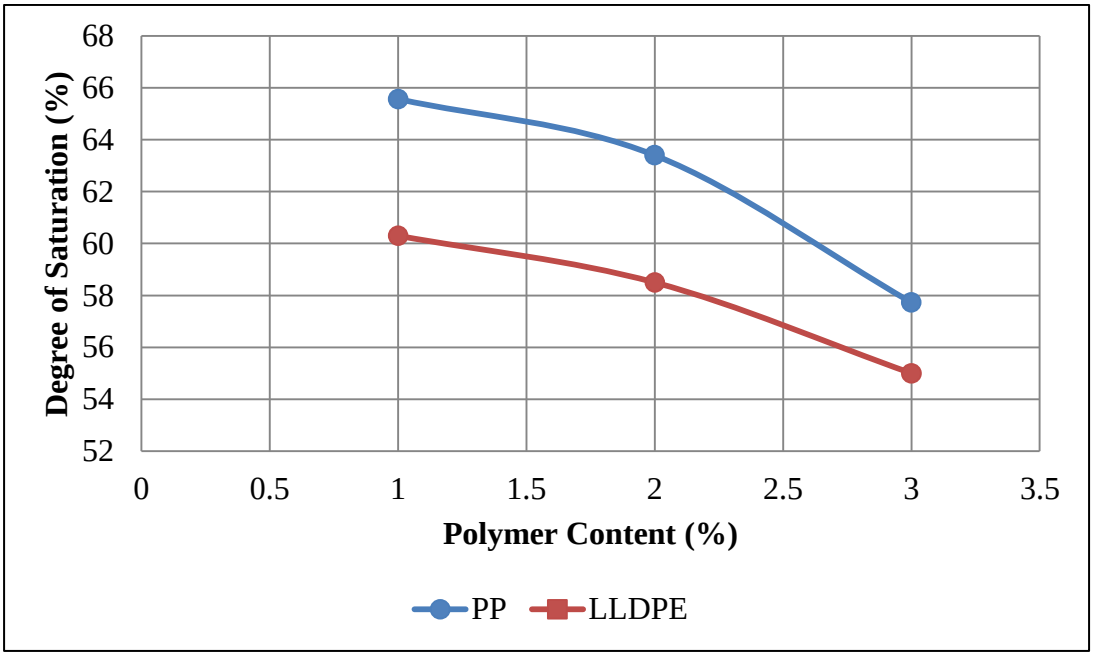

Figure 4-4: Degree of Saturation vs Polymer Content for PP and LLDPE Modified Bitumen

4.2.3 Retained Marshall Stability Results

The average value of stability and flow from the Marshall stability test on control, PP and LLDPE mixes are tabulated as follows:

Polymer Content (%)	Stability (kN)	Flow (mm)
Virgin Bitumen *Dry*	22.97	2.28
1% PP *Dry*	21.93	2.01
2% PP *Dry*	22.69	1.97
3% PP *Dry*	23.43	2.03
Virgin Bitumen *Wet*	12.30	2.49
1% PP *Wet*	19.07	1.64
2% PP *Wet*	19.83	2.23
3% PP *Wet*	21.63	1.19

Table 4-18: Average Value for Stability and Flow for Control, Dry and Wet PP Modified Bitumen

Polymer Content (%)	Stability (kN)	Flow (mm)
Virgin Bitumen *Dry*	22.97	2.28
1% LLDPE *Dry*	24.00	1.61
2% LLDPE *Dry*	23.21	1.66
3% LLDPE *Dry*	23.38	1.27
Virgin Bitumen *Wet*	12.30	2.49
1% LLDPE *Wet*	20.87	1.26
2% LLDPE *Wet*	20.71	1.54
3% LLDPE *Wet*	21.56	1.45

Table 4-19: Average Value for Stability and Flow for Control, Dry and Wet LLDPE Modified Bitumen

According to Table 4-18 and 4-19, we are able to make a conclusion on the relationship between the stability and the flow values between the dry samples and the wet samples which is the dry samples have slightly higher stability value than the wet samples. Otherwise, the wet samples showing a bigger number in deformation (flow) level than the dry samples.

The stability and flow for control, wet and dry PP and wet and dry LLDPE are plotted in Figure 4-5, 4-6, 4-7 and 4-8 as follows.

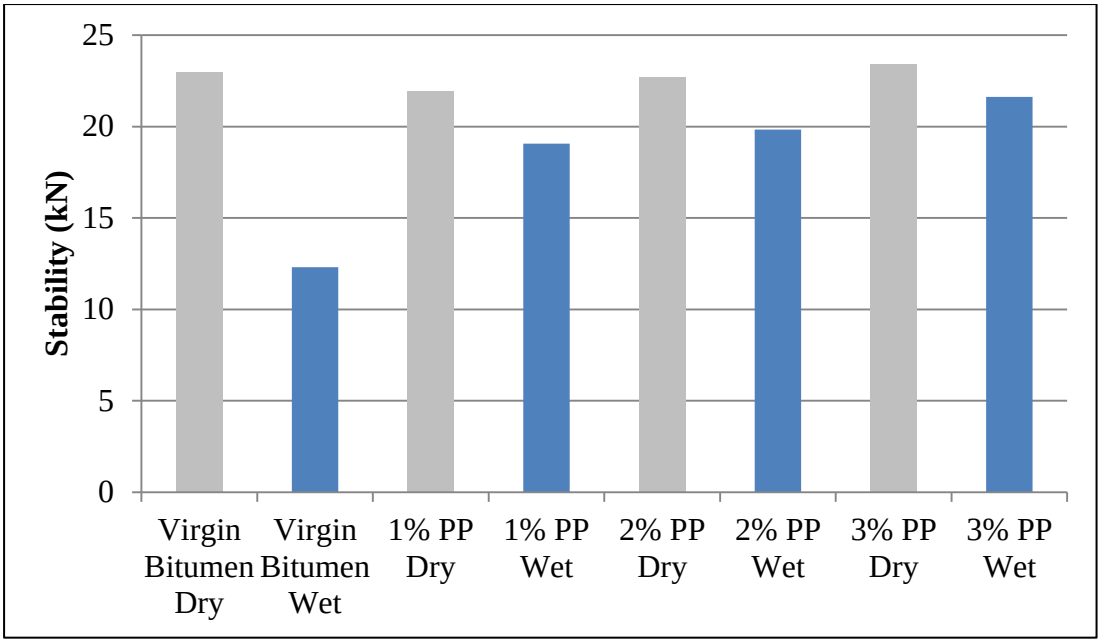

Figure 4-5: Stability vs Binder Content for Control, Dry and Wet PP Modified Bitumen

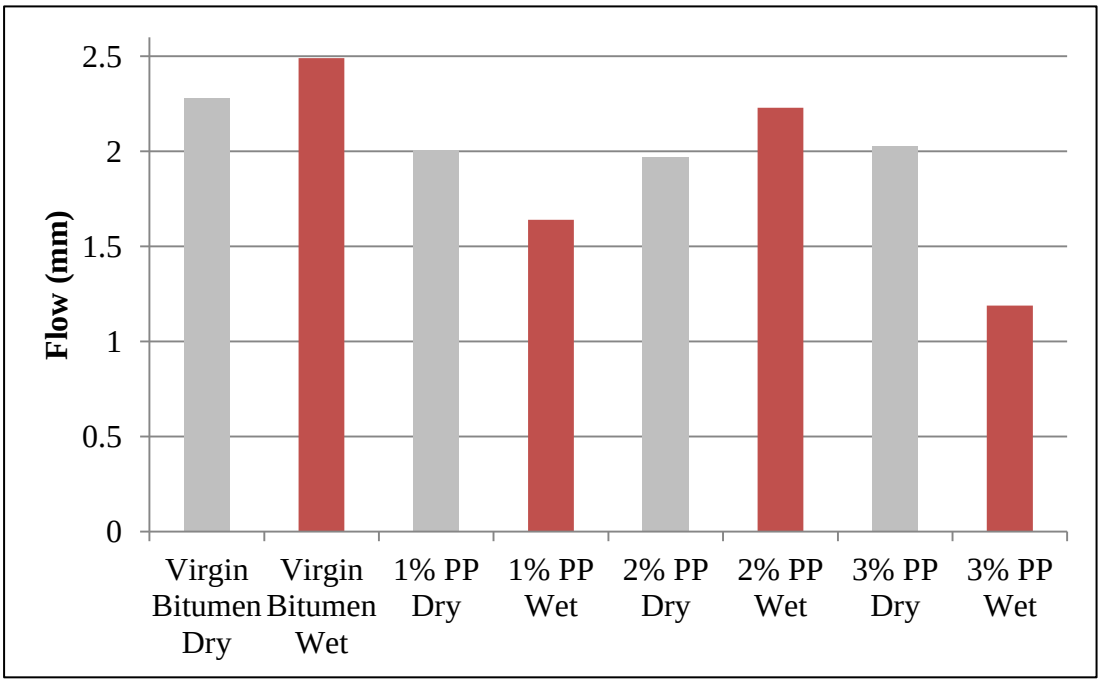

Figure 4-6: Flow vs Binder Content for Control, Dry and Wet PP Modified Bitumen

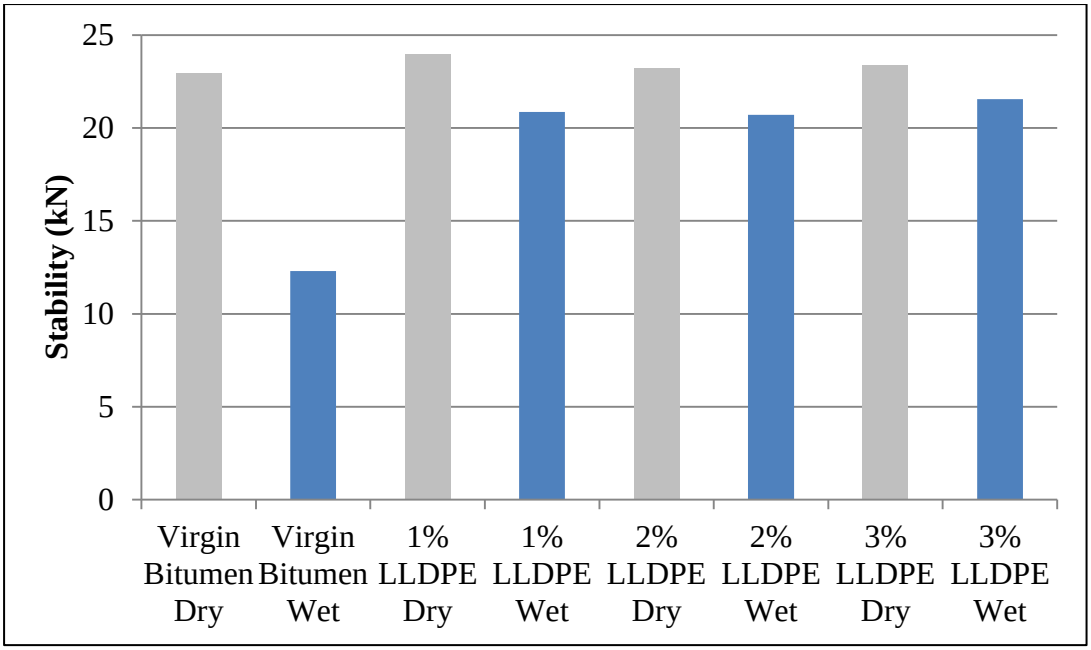

Figure 4-7: Stability vs Binder Content for Control, Dry and Wet LLDPE Modified Bitumen

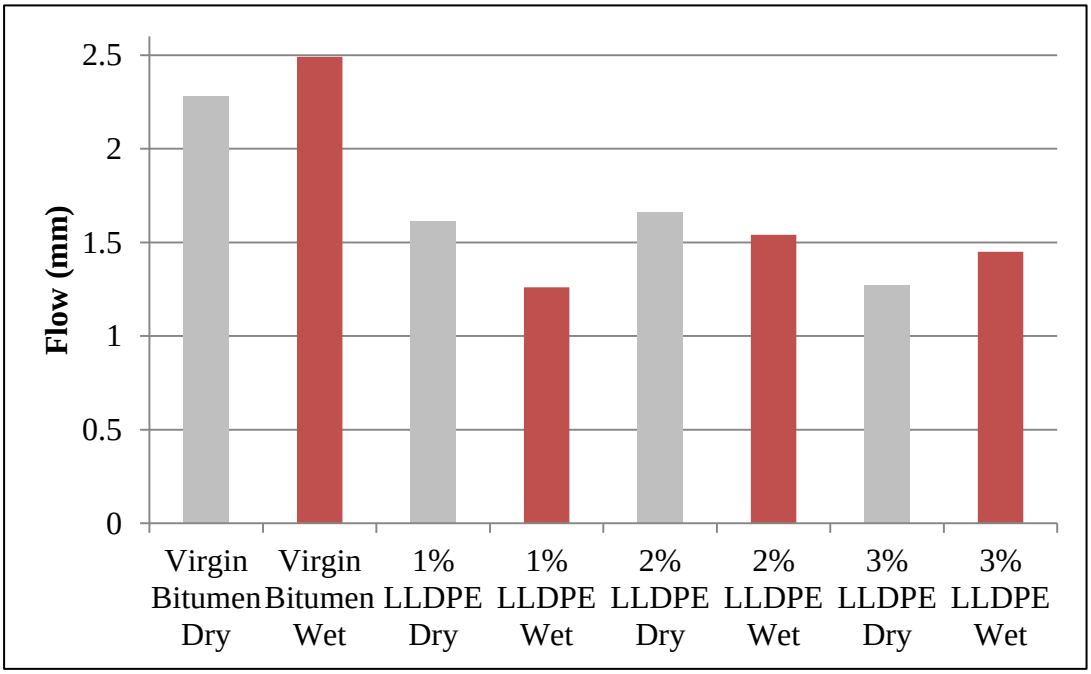

Figure 4-8: Flow vs Binder Content for Control, Dry and Wet LLDPE Modified Bitumen

Based on Figure 4-5, it shows a significant increment in stability values displayed by the PP modified bitumen. The enhanced viscosity of the wet mix is identified to be one of the causes to the increment in stability values. For PP modified bitumen, the trend that can be identified is the stability values is identified to be increasing with the polymer content.

Figure 4-6 shows the results obtained for the flow values for the wet samples and it has been identified that the flow value for 2% PP is higher than the 1% and 3% samples. The flow of the wet samples are identified to be higher than the dry mixes is due to the lubricating agent that enhance the elastic and plastic properties of the aggregates.

Both stability values for PP and LLDPE, according to Figure 4-5 and 4-7 modified bitumen shows a better stability value for the wet mixes in comparison to the control mix. The fibres appear to increase the integrity of the mixtures constituents under axial load. The deformation or flow of both polymer modified bitumen are significantly lower under Marshall stability test in comparison to the control mix. The adhesion effect caused by the presence of fibre, for both type of mixes, only allows small deformation of the sample under loading.

Based on the stability values obtained in Table 4-16 and 4-17, we can calculate the Retained Marshall stability values for each type of binder. The results are tabulated in Table 4-20 and 4-21 as follows.

Polymer Content	Retained Marshall Stability (%)
Virgin Bitumen	53.55
1% PP	86.96
2% PP	87.40
3% PP	92.32

Table 4-20: Retained Marshall Stability Value for Control and PP Modified Bitumen

Polymer Content	Retained Marshall Stability (%)
Virgin Bitumen	53.55
1% LLDPE	86.96
2% LLDPE	89.23
3% LLDPE	92.22

Table 4-21: Retained Marshall Stability Value for Control and LLDPE Modified Bitumen

The retained Marshall stability values is also identified as the stability ratio between the wet and the dry mix. Using the values obtained in both tables above, the retained values obtained in percentage (%), shows the amount of stability loss due to effect of water. In other word, it also shows level of sensitivity of the sample to moisture damage.

It has been observed that the retained Marshall stability result for control mix to show a more vulnerable behavior to moisture damage and can be concluded as more susceptible to water as indicated by the lower retained Marshall stability result. This can be compared to than that of the polymer modified mixes. A low retained Marshall stability value, significantly showing a more damage in the control mix.

According to Table 4-20 and 4-21, the retained Marshall stability results show that the control mix has the lowest ratio, which is 53.55% as compared to the fibre incorporated mixes. The Polypropylene modified bitumen which is using bitumen content range from 1-3%, indicated a retained Marshall stability value ranging from 88.28-92.32%. Whereas the Linear-Low Density Polyethylene modified bitumen which is also using 1-3% polymer content range, indicated a retained Marshall stability value ranging from 86.95-89.29%.

By referring to the retained stability ratios, it is pronounced that the fibre reinforced bitumen showed that they are of good stability reinforcement elements for bituminous mixes. In addition, at an optimum content of fibre, the asphaltic mixtures can cater with the effect of water which is the moisture damage.

The variation of the retained Marshall stability values and the degree of saturation is shown in Figure 4-9.

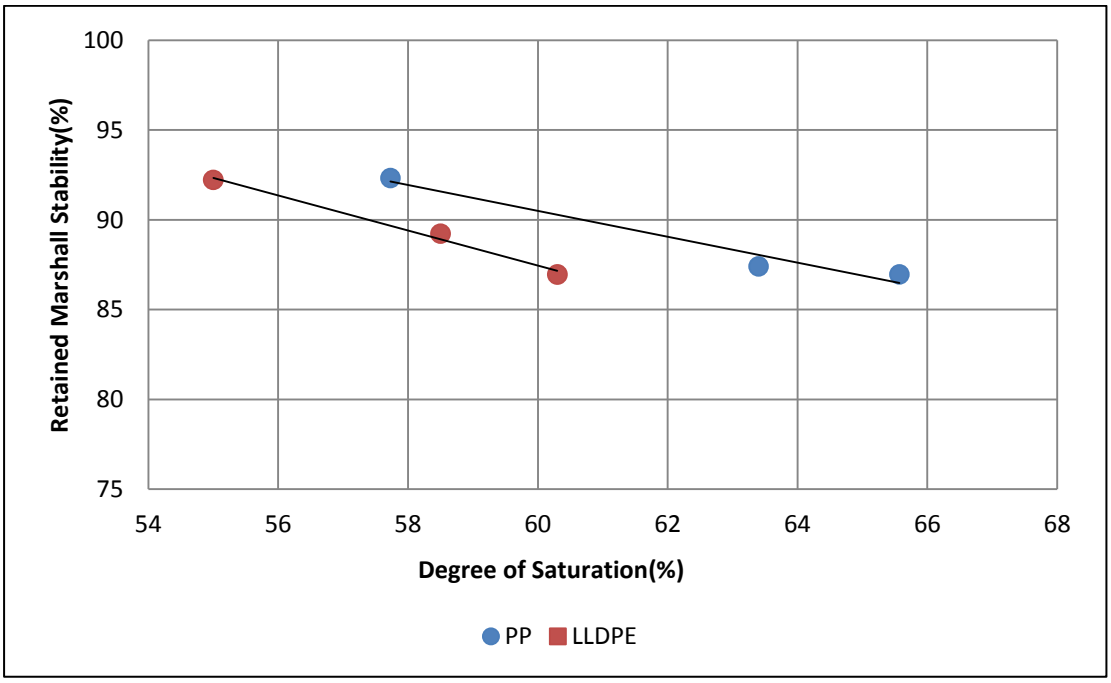

Figure 4-9: Retained Marshall Stability Value vs Degree of Saturation

The retained Marshall stability value effectively indicates the amount of stability loss due to effect of water. This can be observed based on the general trend of the line. For both modified bitumen, the retained stability ratio exhibit decreasing retained stability value with increasing degree of saturation. The gradient of the slope for both binders are almost similar, showing a decreasing trend. PP and LLDPE modified bitumen exhibit higher retained Marshall stability ratios of about 32.45-38.77%.

From the calculated porosity results, it is important to mention that the polymer modified bitumen has a slightly higher porosity than the control mix. This also allows higher level of permeability which will permit easier access to water and increase the potential for stripping to occur. However, the higher the fibre content, the higher the level of adhesion at the binder-aggregate interface which in turn, reduce the potential for stripping. It is also important to mention that, in increasing fibre content, the bitumen content in term of its weight also increasing, thus reducing the amount of porosity of the mixtures.

It is believed that detachment or de-bonding is not the only reason for the decrease in retained Marshall stability results for the wet mixes. It is also due to the softening of the binder matrix between the aggregate and the bitumen.

CHAPTER 5

CONCLUSION

4.1 Conclusion

Based on this work, the following conclusions can be drawn:

1. The stability values obtained from the test also shows the toughness of the polymer reinforced bituminous samples. This can be clearly viewed by the variation of the values over the control mix stability in both dry and wet condition. In these test, the 3% PP portrays the maximum strength in terms of stability in both its dry and wet condition.
2. High level of moisture damage can observed on the control mix. The adhesion property between the binder-aggregate interface has been altered due to the presence of moisture, as well as the cohesiveness of the bitumen molecules. With the increase in polymer content, this will promote better cohesion and adhesion properties of the polymer reinforced binder, thus reduce the potential for stripping.
3. Increase in content of polymer in mixes shows an increase in porosity of samples which in other word describes an increase in the unconnected voids as the binder fills up the channels in the samples. It is also suggested that the addition of polymer content to the binder, displays an increase in the accessible voids, thus corresponds to the nature of the fibres which is porous.

REFERENCES

Arshad, A. K. (2007) "Flexible Pavement Design: Transitioning from Empirical to Mechanistic-Based Design Methods," Jurutera, pp. 15.

Asphalt Institute, (1981) "Cause and Prevention of stripping in Asphalt Pavements," Educational Series, No 10 (ES-10), College Park, Maryland.

Airey, G. D., (2004) "Fundamental binder and practical mixture evaluation of polymer modified bituminous" The International Journal of Pavement Engineering, vol 5(3), pp 137-151

American Society for Testing and Materials (ASTM) (2000), standard Specification, Section 4, vol. 04

Bardesi A, et al. (1999) "Use of modified bituminous binders, special bitumens additives in pavement applications". Technical Committee Flexible Roads (C*) World Road Association (PIARC)

Blades, C., and Kearney, E., (2004) "Asphalt Paving Principles," New York LTAP Centre, pp. 5.

Chen Jian-Shiuh et al. (2002) "Asphalt Modified by Styrene-Butadiene Styrene Triblock Copolymer: Morphology and Modal" Journal of Materials in Civil Engineering May/June, pp. 224-229

Drozdov Aleksey. D., Yuan Q., (2003) "The viscoelastic and viscoplastic behavior of low density polyethylene" International Journal of Solid and Structure, vol. 40, pp 2321-2342

Hadidy Al, Qui Tan Yi, (2009) "Effect of Polythylene on life of flexible pavements" Construction and Building Materials vol. 23 pp. 1456-1466

Johnson, D. R., and Freeman, R. B., (2002) "Rehabilitation Technique For Stripped Asphalt Pavements," Western Transportation Institute, Civil Engineering Department, Montana State University, Final Report, pp. 5-7.

J. Stastna et al., (2002) "Viscosity functions in polymer modified asphalts" Journal of Colloid and Interface Science, vol. 259, pp. 200-209

Kiggundu, B. M., and F. L. Roberts., (1988) "Stripping in HMA Mixtures: State-of-the-Art and Critical Review of Test Methods," *NCAT Report 88-2*, National Center for Asphalt Technology, Auburn University.

Kok, B. V., and Kuloglu, N., (2007) "The Effect Of Different Binders on Mechanical Properties Of Hot Mix Asphalt" Civil Engineering Department, Engineering Faculty, Firat University, Volume 2, No 1, 41-48, pp. 3-4.

Kumar, A. and Goetz., W.H., (1997) "Asphalt Hardening As Affected By Film Thickness, Voids and Permeability in Asphaltic Mixtures", Proceedings of the Association of Asphalt Paving Technologists, Vol. 46, pp. 571-597

Lu.X and Isacsson (1997) "Compatibility and storage stability of styrene-butadiene-styrene copolymer modified bitumens" Journal of Materials and Structure, vol. 30, pp. 618-626

Scholz, V. T., and Rajendran, S., (2009) "Investigating Premature Pavement Failure Due To Moisture," Kiewit Centre for Infrastructure and Transportation, School of Civil and Construction Engineering, Oregon State University, Final Report, pp. 13.

Tapkin et al., (2009) "Polypropylene fiber modification of asphalt using mechanical and optical means" Advanced Testing and Characterization of Bituminous Materials, Loizos, Partl, Scarpans & Al-Qadi (eds), chapter 47, pp 487-496, Taylor & Francis Group, London, UK

Whiteoak, C, D., (2003) "The shell bitumen hand book" Surrey, UK, 5th Edition, pp 179

Yilmaz, A., and Sargin, S., (2012) "Water Effect On Deteriorations of Asphalt Pavements," The Online Journal of Science and Technology, Volume 2, pp. 1-6.

Adopted from http://www.scribd.com/doc/36634614/Moisture-Sensitivity-of-Asphalt-Pavements