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Studying the Effect of Adding Glass Fiber on the Mechanical Properties of Asphalt Mixtures (Wearing Course Layer)

دراسة تأثير إضافة الألياف الزجاجية على الخواص الميكانيكية للخليط الاسفلتي (الطبقة السطحية)

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Infrastructure Management – Civil Engineering

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إقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

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دراسة تأثير إضافة الألياف الزجاجية على الخواص الميكانيكية للخليط الاسفلتي (الطبقة السطحية)

Studying the Effect of Adding Glass Fiber on the Mechanical Properties of Asphalt Mixtures (Wearing Course Layer)

وبعد المناقشة التي تمت اليوم الخميس 17 جمادي الثانية 1438هـ، الموافق 2017/03/16م الساعة العاشرة صباحاً، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

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وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في كلية *الهندسة*/ قسم الهندسة المدنية- البنى التحتية.

واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

نائب الرئيس لشئون البحث العلمي والدراسات العليا

أ.د. عبدالرؤوف علي المناعمة

Dedication

I proudly dedicate this thesis to my father & mother for making me who I am today, my dear wife, my brothers, sisters and my friends for giving me all the inspiration and support I need.

With love & respect …

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Abstract

As the modern highway transportation has high speed, high traffic density and heavy load, bituminous concrete pavements are subjected to various types of distress such as fatigue cracking, rutting and raveling. Modification of the asphalt binder is one approach taken to improve pavement performance. Generally, fibers and polymers are two important materials used for this purpose.

It is thought that the addition of glass fibers to asphalt mixtures enhances material strength and fatigue characteristics.

In this research, Glass Fiber are used to investigate the potential prospects to enhance asphalt mixture properties. Study aims include studying the effect of adding different percentages of Glass Fiber on the properties of asphalt mix comparing it with the local and international requirements, besides identifying the optimum percent of Glass fiber to be added in the hot mix asphalt.

Glass fiber (12mm) were added to the asphalt mixture. Marshal mix design procedure was used, first to determine the Optimum Bitumen Content (OBC) and then further to test the modified mixture properties. In total, (33) samples were prepared, 12 samples were used to determine the OBC and the remaining were used to investigate the effects adding different Glass fiber percentages to asphalt mix. The OBC was 5.4 % by the total weight of asphalt mix. Six proportions of Glass fiber by the total weight of mix were tested (0.1, 0.2, 0.4, 0.6, 0.8 and 1%), besides testing of ordinary asphalt mix. Tests include the determination of stability, bulk density, flow and air voids.

Results indicated that Glass fiber can be conveniently used as a modifier for asphalt mixes to improve performance of some asphalt mix properties. Glass fiber content of 0.27 % by the total weight of mix is recommended as the optimum Glass fiber content.

Asphalt mix modified with 0.27 % Glass fiber meet the requirements of local and international specifications.

Study recommends that further studies are needed in various types of fibers and others percent of bitumen. And its required to establish a Palestinian standard for the Modified asphalt mixes.

ملخص الدراسة

تتميز شبكات الطرق الحديثة بالسرعات العالية، الكثافة المرورية العالية والأحمال الثقيلة، وبالتالي تتعرض الرصفات الاسفلتية لأنواع مختلفة من الضغوط والتشوهات. الخلطات الاسفلتية المعدلة تعتبر احدى طرق تحسين أداء هذه الخلطات. بشكل عام الألياف الصناعية والبوليمرات تعتبر من أهم المواد المستخدمة لهذا الغرض.

يعتقد بأن اضافة الألياف الزجاجية الي الخلطات الاسفلتية يحسن من قوة هذه الخلطات ومقاومتها للتشوهات. في هذا البحث، تم استخدام الألياف الزجاجية للتحقق من احتمالات اسهامها في تحسين خصائص الخليط الأسفلتي (الطبقة الاسفلتية السطحية). أهداف الدراسة تشمل تحديد تأثير إضافة نسب مختلفة من الألياف الزجاجية على خصائص الخليط الأسفلتي ومقارنتها مع متطلبات المواصفات المحلية والدولية، إلى جانب تحديد نسبة الألياف المثالية لإضافتها للخليط الاسفلتي.

تم اضافة الألياف الزجاجية بطول ١٢ مم للخليط الأسفلتي. وقد استخدمت طريقة مارشال لتصميم الخلطة الاسفلتية لتحديد محتوى البيتومين الأمثل (OBC) وكذلك لاختبار خصائص الخليط الأسفلتي المضاف إليه الألياف، تم إعداد ٣٣ عينة، وقد استخدمت ١٢ عينة لتحديد محتوى البيتومين الأمثل واستخدم العدد المتبقي من العينات لدراسة آثار اضافة النسب المختلفة من الألياف الزجاجية الى الخليط الأسفلتي . نتائج فحص عينات مارشال بينت أن محتوى البيتومين الأمثل هو ٥,٤% من وزن الخليط الأسفلتي. تم اختبار تأثير اضافة ٦ نسب من الألياف الزجاجية على خصائص الخليط الأسفلتي محسوبة من وزن الخليط الكلي وهي (٠,١ – ٠,٢ – ٠,٤ – ٠,٦ – ٠,٨ – ١%)، إلى جانب اختبار خصائص الخليط الأسفلتي العادي .الاختبارات شملت تحديد درجة الثبات والانسياب والكثافة الظاهرية ونسبة فراغات الهواء في الخليط الأسفلتي.

أشارت النتائج أنه يمكن استخدام الألياف الزجاجية كمحسنات لبعض خواص الخلطات الإسفلتية (الطبقة الإسفلتية السطحية) وان إضافة الألياف الزجاجية بنسبة ٠,٢٧٪ من وزن الخليط الكلي يعتبر النسبة المثلى لتحسين أداء الخلطة الإسفلتية حيث أن الخليط الأسفلتي المعدل بهذه النسبة يلبي المتطلبات الميكانيكية للمواصفات المحلية والدولية.

أوصت الدراسة بإجراء مزيد من الدراسات باستخدام أنواع أخرى من الألياف ونسب مختلفة من البيتومين وأوصت كذلك بالعمل على نشر مواصفة فلسطينية خاصة بالخلطات الاسفلتية المعدلة باستخدام الألياف.

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Abbreviations

MPWH	Ministry of Public Works & Housing
AC	Asphalt Concrete
AASHTO	American Association of State Highway & Transportation Officials
HMA	Hot Mix Asphalt
OBC	Optimum Bitumen Content
ASTM	American Society of Testing and Materials
PS	Palestinian Standard
d_{25}	Density of bitumen at 25ºC
ρ_{bit}	Theoretical maximum density of asphalt mix
ρ_A	Density of Asphalt mix
$\rho_{\min}$	Density of aggregate in the blend
SSD	Saturated surface dry condition
VFB	Voids Filled Bitumen
VMA	Voids Mineral Aggregates
Vb	Bitumen Volume
$\mathbf{m_b}$	Percent of Bitumen

Chapter One

Introduction

1.1 Background:

A good roadway infrastructure is an essential component of a strong and stable economy. Asphalt Concrete (AC), a mixture of bitumen and aggregate is a widely-employed material for pavement construction.

As the modern highway transportation has high speed, high traffic density, heavy load and channelized traffic, bituminous concrete pavements are subjected to various types of distress such as fatigue cracking, rutting and raveling (Remadevi, et al., 2014). Modification of the asphalt binder is one approach taken to improve pavement performance. Generally, fibers and polymers are two important materials used for this purpose (Abtahi, et al., 2013).

The principal functions of fiber as reinforcement material is to provide additional tensile strength in the resulting composite. This may increase the amount of strain energy that can be absorbed during the fatigue and fracture process of the mix.

Attempts of using non-synthetic fibers in pavement have been reported in the literature. Cotton fibers and asbestos fibers were used but these were degradable and were not suitable as long term reinforcement. Metal wires have also been proposed but they were susceptible to rusting with the penetration of water. Asbestos was also used until it was determined as a health hazard (Mahrez, et al., 2005).

This study investigates on the characteristics and properties of glass fiber reinforced Asphalt, which may have the benefit of improving the performance of road pavement.

1.2 Statement of the Problem:

Asphalt is used in road pavements as the binder of aggregates in a great extent all around the world. Asphalt pavements must undergo heavy loads and unfavorable environmental conditions for an acceptable period of time. High-temperature rutting and low temperature cracking are the most considerable limitations of unmodified and pure asphalts. Therefore, modification and reinforcement of asphalt binder is necessary (Zahedi, et al., 2014).

It is thought that the addition of glass fibers to asphalt mixtures enhances material strength and fatigue characteristics while adding ductility. Because of their excellent mechanical properties, glass fibers might offer an excellent potential for asphalt modification (Mahrez, et al., 2005).

This research presents an experimental investigation of fiber reinforced asphalt made from aggregate and binder with and without fibers. This work is aimed at developing and testing mechanical properties (Marshall stability, Plastic flow, Stiffness, voids) of asphalt modified with glass fiber.

1.3 Objectives:

This research aims to produce distinct asphalt mixes with optimum proportions which consist of aggregate, binder and glass fibers. This mix has more strength, more resistance for cracking and modified properties.

The objectives of this study are:

1. Produce optimum asphalt mix which consist of aggregate, binder and glass fibers.
2. Studying the behavior and properties of glass fiber modified asphalt mix (stability, Plastic flow, Stiffness, voids).

1.4 Methodology:

To achieve the objectives of this research, the following tasks will be executed:

1. Conducting a literature review about hot mix asphalt and fibers.
2. Collection of material for laboratory testing and executing the testing program.
3. Preparing the mix design using fiber, with different percentages "i.e. 0%, 0.1%, 0.2%, 0.4%, 0.6%, 0.8% & 1%" by the total weight of asphalt mix.
4. Testing of the samples:
5. Measure the stability, flow, stiffness, VA (%), VMA (%) and VFB (%) for each sample.
6. Preparing the mix design using recommended percentage of glass fiber.
7. Analysis of results, and recommendations.

1.5 Thesis structure

The thesis includes five chapters and six appendices. A brief description of the chapters' contents is presented below:

Chapter 1: Introduction

This chapter is a brief introduction, which highlights the concept of research. In addition, statement of problem, aim, objectives and methodology of research are described.

Chapter 2: Literature review

Brief introduction related to hot mix asphalt, Fibers and its utilization in asphalt mix is included in this chapter. Moreover, previous researches relevant to Fiber modified asphalt mixes are reviewed.

Chapter (3) Materials and study program

This chapter handles two topics:

1- The preliminary evaluation of used materials properties such as aggregates, bitumen and glass Fiber.

2- The description of experimental work which has been done to achieve the study objectives.

Chapter (4) Results and data analysis

The achieved results of laboratory work are illustrated in this chapter through three stages. First stage handles the results of blending aggregates to obtain asphalt wearing course gradation curve. In the Second stage, Marshal Test results are analyzed in order to obtain the optimum bitumen content (OBC). The following stage discusses the effect of adding different percentages of Glass Fiber on asphalt mix properties; finally, the optimum Glass Fiber content is obtained.

Chapter (5) Conclusion and recommendations

Conclusions derived from experimental results are presented. Moreover, the recommendations for the present study and other further studies are also provided in this chapter.

Chapter Two

Literature Review

2.1 Introduction

Asphalt pavement is a composite material consisting of mineral aggregates, asphalt binder and air voids. The load-carrying behavior and resulting failure of such material depends on many mechanisms that are strongly related to the local load transfer between aggregate particles (Sadd et al., 2004).

Due to the rapid urbanization and industrialization of the world over the last century, the construction and maintenance of transportation roadways is a constant demand in both urban and rural areas. Furthermore, due to excessive traffic loads and environmental factors, many existing pavements have already reached the end of their service life and other pavements will soon require maintenance (Siriwardane, et al., 2010).

As the world continues to urbanize and construct transportation roadways, the need for quality sustainable pavement is a constant need. Due to these demands, transportation experts and engineers focused on improving the performance and life of pavements.

More specifically, pavement design research has focused on the application of various fibers in asphalt binders and mixtures to improve performance. Since the 1950s, research studies reported on the performance of many different fibers, from polyester to used tire shreds, which have shown success in their applications throughout various constructions (Jahromi, et al., 2008).

Some fibres have high tensile strength relative to bituminous mixtures, thus it was found that fibres have the potential to improve the cohesive and tensile strength of bituminous mixes.

2.2 Hot mix asphalt

Hot-Mix Asphalt (HMA) is the most widely used paving material around the world. It's known by many different names: HMA, asphaltic concrete, plant mix, bituminous mix, bituminous concrete, and many others. It is a combination of two primary ingredients aggregates and asphalt binder. Aggregates include both coarse and fine materials, typically a combination of different size rock and sand. The aggregates total approximately 95% of the total mixture by weight. They are mixed with approximately 5% asphalt binder to produce HMA. By volume, a typical HMA mixture is about 85% aggregate, 10% asphalt binder, and 5% air voids. Additives are added in small amounts to many HMA mixtures to enhance their performance or workability. Because asphalt concrete pavement is much more flexible than Portland cement concrete pavement, asphalt concrete pavements are sometimes called flexible pavements (A manual for design of hot mix asphalt with commentary, 2011).

Asphalt concrete pavements are engineered structures composed of a group of layers of specific materials that is positioned on the in-situ soil (Sub Grade). Figure (2.1) shows a vertical section of typical asphalt concrete pavement structure.

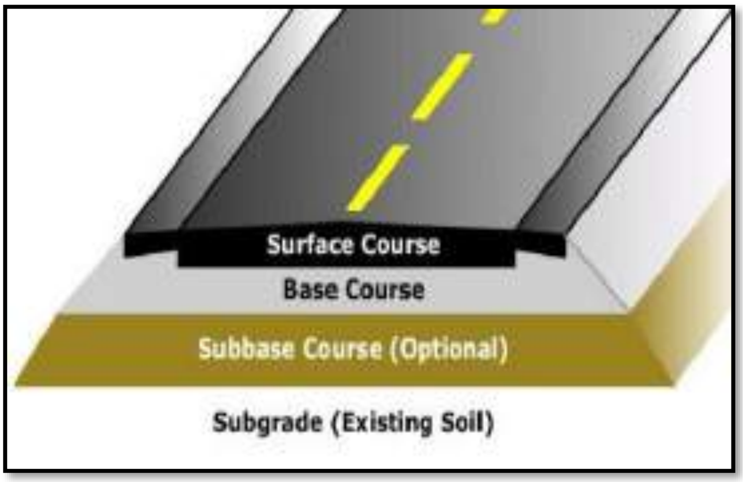

Figure (2.1): Vertical section of asphalt concrete pavement structure

2.2.1 Basic materials in hot mix asphalt

2.2.1.1 Aggregates

Aggregates (or mineral aggregates) are hard, inert materials such as sand, gravel, crushed rock, slag, or rock dust. Properly selected and graded aggregates are mixed with the asphalt binder to form HMA pavements. Aggregates are the principal load-supporting components of HMA pavement.

Because about 95% of the weight of dense-graded HMA is made up of aggregates, HMA pavement performance is greatly influenced by the characteristics of the aggregates. Aggregates in HMA can be divided into three types according to their size: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36-mm sieve. Fine aggregates are those that pass through the 2.36-mm sieve and are retained on the 0.075-mm sieve. Mineral filler is defined as that portion of the aggregate passing the 0.075-mm sieve. Mineral filler material - also referred to as mineral dust or rock dust - consists of very fine, inert mineral with the consistency of flour, which is added to the hot mix asphalt to improve the density and strength of the mixture. It shall be incorporated as part of the combined aggregate gradation (Transportation research board committee, 2011).

2.2.1.2 Asphalt binder (bitumen)

Asphalt binder (bitumen) which holds aggregates together in HMA is thick, heavy residue remaining after refining crude oil. The physical properties of asphalt binder vary considerably with temperature. At high temperatures, asphalt binder is a fluid with a low consistency similar to that of oil. At room temperature, most asphalt binders will have the consistency of soft rubber. At subzero temperatures, asphalt binder can become very brittle. Many asphalt binders contain small percentages of polymer to improve their physical properties; these materials are called polymer modified binders. Most of asphalt binder specification was designed to control changes in consistency with temperature (A manual for design of hot mix asphalt with commentary, 2011).

2.2.2 Desirable properties of asphalt mix

Mix design seeks to achieve a set of properties in the final HMA product. These properties are related to some or all variables which include asphalt binder content, asphalt binder characteristics, degree of compaction and aggregate characteristics such as gradation, texture, shape and chemical composition (Lee et al., 2006). Some of the desirable properties are listed in the following Table (2.1).

Table (2.1): Summary of properties Asphalt- Aggregates mixes (Lee et al., 2006)

Property	Definition	Examples of mix variables which have influence
Stiffness	Relationship between stress and strain at a specific temperature and time of loading	- Aggregate gradation - Asphalt stiffness - Degree of compaction - Water sensitivity - Asphalt content
Stability	Resistance to permanent deformation (usually at high temperature and long times of loading- conditions of low S(mix).	- Aggregate surface texture - Asphalt gradation - Asphalt stiffness - Asphalt content - Degree of compaction - Water sensitivity
Durability	Resistance to weathering effects (both air and water) and to the abrasive action of traffic.	- Asphalt content - Aggregate gradation - Degree of compaction - Water sensitivity
Fatigue Resistance	Ability of mix to bend repeatedly without fracture	- Aggregate gradation - Asphalt Content - Degree of compaction - Asphalt stiffness
Fracture Characteristics	Strength of mix under single tensile stress application.	- Aggregate gradation - Aggregate type - Asphalt Content - Degree of compaction - Water sensitivity - Asphalt stiffness
Skid Resistance (surface friction characteristics)	Ability of mix to provide adequate coefficient of friction between tire and pavement under "wet" conditions	- Aggregate texture and resistance to polishing - Aggregate gradation - Asphalt content
Permeability	Ability of air, water, and water vapor to move into and through mix	- Aggregate gradation - Asphalt content - Degree of compaction
Workability	Ability of mix to be placed and compacted to specified density	- Asphalt content - Asphalt stiffness at Placement - Aggregate surface texture. - Aggregate gradation.

2.2.3 Gradation specifications for asphalt wearing course

An aggregate's particle size distribution, or gradation, is one of its most influential characteristics. In hot-mix asphalt, gradation helps to determine almost every important property including stiffness, stability, durability, permeability, workability, fatigue resistance, and resistance to moisture damage. Gradation is usually measured by a sieve analysis. We are going to discuss the Palestinian specification PS 171, American Society for Testing and Materials ASTM D3515 and German Specification ZTV Asphalt – StB 94 for the gradation of asphalt wearing coarse.

2.2.3.1 Palestinian specification PS 171/1998:

The gradation of the PSI requirements is shown in Table (2.2) and Figure (2.2).

Table (2.2): Gradation of asphalt wearing course for PSI requirements (PS 171,1998)

Sieve size (mm)	Percentage by Weight Passing	
	Lower Level	Upper Level
14.0	85	100
4.75	60	80
2.36	45	65
0.6	20	35
0.150	10	20
0.075	5	10

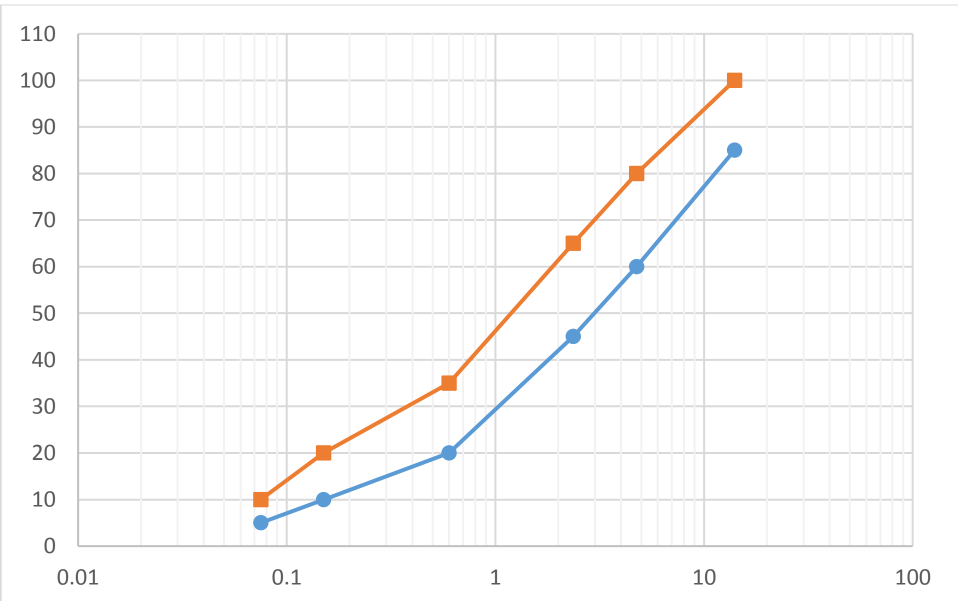

Figure (2.2): Gradation of asphalt wearing course for PSI requirements (PS 171,1998)

2.2.3.2 American Society for Testing and Materials specification (ASTM D3515)

The gradation of ASTM D3515 (Mix Designation D-5) requirements is shown in Table (2.3) and Figure (2.3).

Table (2.3): Gradation of asphalt wearing course for ASTM D3515

Sieve size (mm)	Percentage by Weight Passing	
	Lower Level	Upper Level
19.0	100	100
12.5	90	100
4.75	44	74
2.36	28	58
0.3	5	21
0.075	2	10

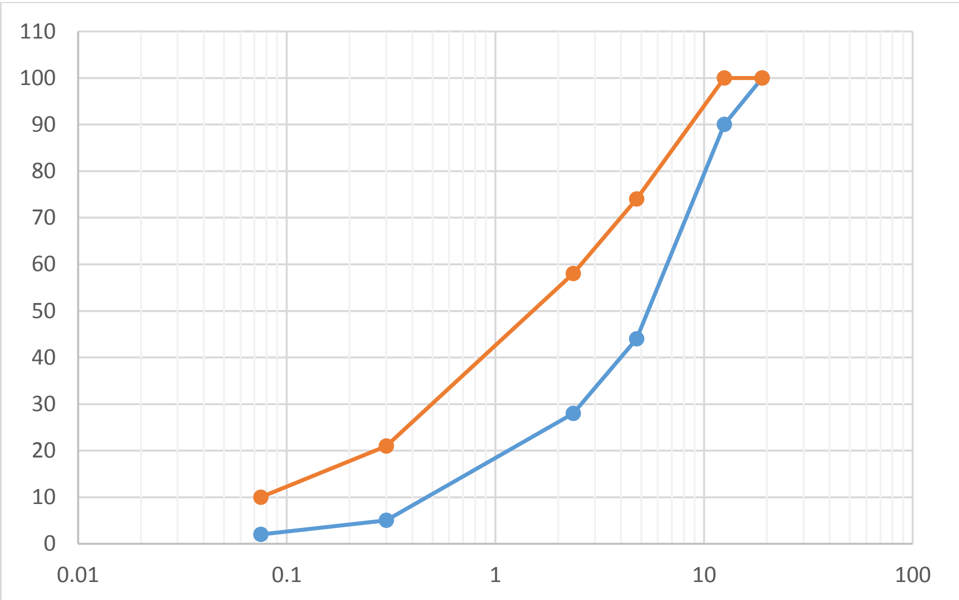

Figure (2.3): Gradation of asphalt wearing course for ASTM D3515

2.2.3.3 German Specifications ZTV Asphalt – StB 94:

The German specifications have five gradations for the asphalt wearing course. They are 0/16S, 0/11S, 0/11, 0/8 and 0/5, we chose the grade 0/11S and drew it in Figure 2.4. The gradation and the bitumen ratio are illustrated in Table 2.4.

Table (2.4): Gradation of Asphalt Wearing Course (ZTV Asphalt – StB 94 / Jendia, 2000)

Sieve size (mm)	Percentage by Weight Passing	
	Lower Level	**Upper Level**
11.2	90	100
8.0	70	85
5.0	58	70
2.0	40	50
0.71	27	40
0.25	14	28
0.09	6	10

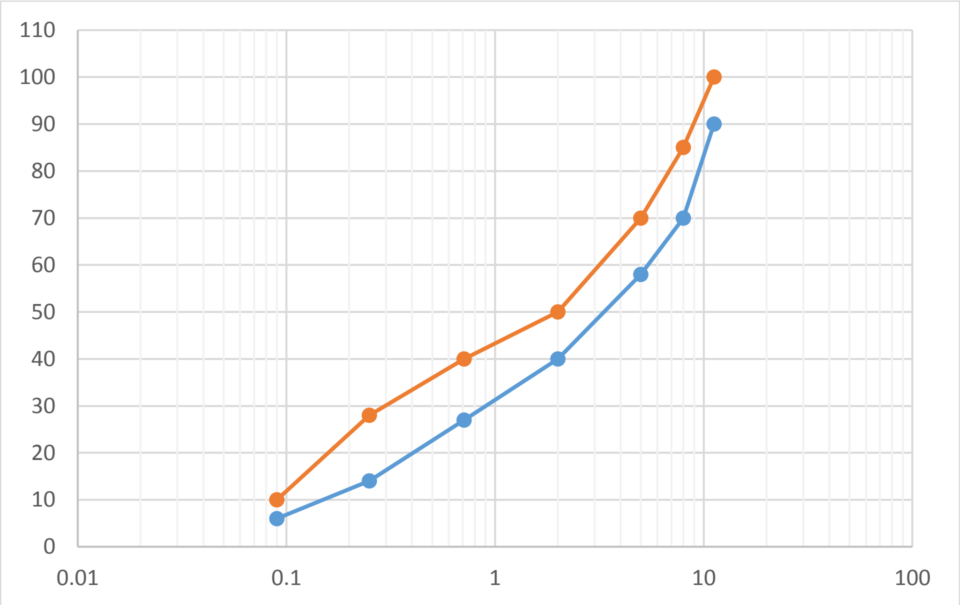

Figure (2.4): Gradation of asphalt wearing course Course (ZTV Asphalt – StB 94 / Jendia, 2000)

In this thesis, we will use the ASTM Gradation (D-5) and Marshal method of mix design. The Marshall test procedures have been standardized by the American Society for Testing and Materials. Procedures are given by ASTM D 1559.

Table (2.5): Gradation of Asphalt wearing Course (ASTM D5315)

Sieve No.	Sieve size (mm)	Percentage by Weight Passing	
		Min	Max
3/4"	19	100	100
1/2"	12.5	90	100
3/8"	9.5	67	88
#4	4.75	44	74
#8	2.36	28	58
#30	0.6	16	39
# 50	0.3	5	21
# 80	0.18	3	15
#200	0.075	2	10

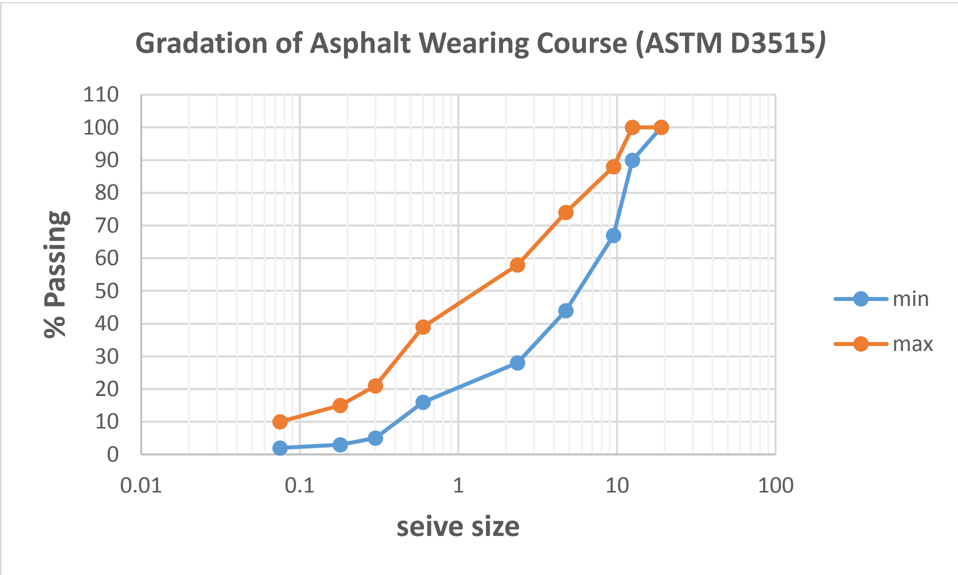

Figure (2.5): Gradation of Asphalt Wearing Course (ASTM D3515)

2.2.4 Mechanical properties specifications for asphalt binder course

Two specifications for the mechanical properties of asphalt wearing course are reviewed. First is the Ministry of Public Works & Housing (MPWH) local projects specification. Second is the Asphalt Institute specification (MS-4). Table (2.6) summarizes these specifications.

Table (2.6): Mechanical properties specifications for asphalt wearing course (MPWH, 2004 ; Asphalt Institute, 2007)

Property	Local Spec. (MPWH, 2004)		International Spec. (Asphalt Institute, 2007)	
	Min.	Max.	Min.	Max.
Stability (kg)	900	*	817	*
Flow (mm)	2	4	2	3.5
Percent Voids in Mineral Aggregate (VMA)%	14	*	13	*
Percent Air-Voids (Va)%	3	5	3	5
Percent Voids Filled with Asphalt (VFA)%	60	75	65	75
Bulk density (gm/cm3)	2.3	*	2.3	*

2.3 Fiber modified asphalt mix

2.3.1 Introduction

In order to improve the performance of asphalt pavements, many fibers have been incorporated in asphalt mix as additives.

A multitude of fibers and fiber materials were introduced and are continuously being introduced in the market as new applications such as polyester fiber, asbestos fiber, glass fiber, polypropylene fiber, Carbon fiber, Cellulose fiber, etc. (Serfass, et al., 1996).

Some fibers have high tensile strength relative to bituminous mixtures, thus it was found that fibers have the potential to improve the cohesive and tensile strength of bituminous mixes.

This high tensile strength reinforcement may increase the amount of strain energy that can be absorbed during the fatigue and fracture process of the mix.

Previous researches showed that the addition of the fiber into bitumen increased the stiffness of the asphalt binder resulting in stiffer mixtures with decreased binder drain-down. The fiber modified mixtures showed improved Marshall properties by increasing the stability values and decrease in the resulting air void content compared to the control mix (Mahrez, et al., 2005).

2.3.2 Fibers properties & classification:

Fibers have been defined by the Textile Institute as units of matter characterized by flexibility, fineness and a high ratio of length to thickness. (Morton, et al., 2008).

Fibers can be natural, both vegetable and animal in origin and also synthetic. They are long, fine forms of matter with diameter generally of the order of 10 microns and lengths ranging from a few millimeters to virtually being continues.

Natural fibers have been used by people throughout their history, synthetic fibers are much more recent newcomers. Even so, since their initial development, synthetic fibers have grown to rival and in some markets, replace natural fibers. These fibers where first produced in 1947 (Bunsell, 2009).

2.3.2.1 Fiber classification:

The fibers may be divided into two major groups

(a) Natural fibers

Natural fibers include those produced by plants, animals, and geological processes. They are biodegradable over time. They can be classified according to their origin.

(b) Man-made fibers

Fibers produced by industrial processes, whether from natural polymers transformed upon the action of chemical reagents or through polymers obtained by chemical synthesis (synthetic fibers).

2.3.2.2 Typical fiber properties:

Table (2.7) give typical properties of many types of fibers (Bunsell, 2009).

Table (2.7): Fibers typical properties

Fiber	Diameter μm	Specific gravity	Strength σ (GPa)	Strain to failure (%)
Polyester	15	1.38	0.8	15
Polyethylene	38	0.96	3	3.5
Cotton	10 - 27	1.54	0.6	7
Silk	12	1.4	0.4	25
Cellulose	4 - 60	1.52	0.5	25
Glass	10 - 13	2.54	3.5	4.5
Carbon	7 - 10	2.1	3.7	0.9

2.3.3 Fiber materials and mixtures

It is generally understood that asphalt is strong in compression and weak in tension. Adding fibers with high tensile strength can help increase the tensile strength of a mixture. In theory, stresses can be transferred to the strong fibers, reducing the stresses on the relatively weak asphalt mix. To effectively transfer stresses, there must be good adhesion between the fiber and the asphalt binder; a greater surface area on the fibers can aid this adhesion. In addition, the fiber needs to be uniformly dispersed in the mixture to avoid stress concentrations (A manual for design of hot mix asphalt with commentary, 2011).

2.3.3.1 Types of Fibers

Many types and forms of fibers have been used in asphalt mixtures, either experimentally or routinely. Cellulose, mineral, and polymer fibers are the most common. The most commonly used types of fibers and their reported benefits and disadvantages are summarized in Table 2.8 (A manual for design of hot mix asphalt with commentary, 2011).

Table (2.8): Reported benefits and disadvantages of common fiber types

Fiber Type	Reported Advantages	Reported Disadvantages
Cellulose	• Stabilizes binder in open- and gap-graded stone matrix asphalt (SMA) mixtures. • Absorbs binder, allowing high binder content for more durable mixture. • Relatively inexpensive. • May be made from a variety of plant materials. • Widely available.	• High binder absorption increases binder cost. • Not strong in tensile mode.
Mineral	• Stabilizes binder in open- and gap-graded SMA mixtures. • Not as absorptive as cellulose. • Electrically conductive fibers have been used for inductive heating for deicing purposes or to promote healing of cracks.	• Some may corrode or degrade because of moisture conditions. • May create harsh mixes that are hard to compact and may be aggressive, causing tire damage if used in surfaces.
Polyester	• Resists cracking, rutting, and potholes. • Increases mix strength and stability. • Higher melting point than polypropylene. • High tensile strength.	• Higher specific gravity means fewer fibers per unit weight added. • Cost-effectiveness not proven/varies.
Polypropylene	• Reduces rutting and cracking. • Derived from petroleum, so compatible with asphalt. • Strongly bonds with asphalt. • Resistant to acids and salts. • Low specific gravity.	• Lower melting point than some other fiber materials require control of production temperatures. • Begins to shorten at 300°F..
Aramid	• Resists cracking, rutting, & potholes. • Increases mix strength and stability. • High tensile strength. • May contract at higher temperature, which can help resist rutting.	• Cost-effectiveness not proven/varies.
Aramid and polyolefin	• Controls rutting, cracking, and shoving. • Combines benefits of aramid and polyolefin (polypropylene) fiber types.	• Cost-effectiveness not proven/varies.
Glass fiber	• High tensile strength. • Low elongation. • High elastic recovery. • High softening point.	• Brittle. • Fibers may break where they cross each other. • May break during mixing and compaction.

2.4 General Fiber Studies:

Using fibers to improve the behavior of materials is not a new concept. Fibers are widely used as reinforcing agent in concrete, however, the modern ways of fiber reinforcement started in the early 1950 (Jahromi et al., 2008).

Since fibers have higher tensile strengths compared to bituminous mixtures, they have the possibility to enhance the cohesive and tensile strength of bituminous mixes. Fibers have the ability to impart physical changes to bituminous mixtures, such as reinforcement and toughening (Brown, et al., 1990). Divided fibers provide a high surface area per unit weight, and behave much like filler materials which bulk the bitumen eliminating aggregate run off during construction (Mahrez, et al., 2003).

Both natural and synthetic fibers have been utilized in various hot mix asphalt applications. Natural fibers include asbestos, cellulose, and rock wool. While synthetic fibers include polypropylene, polyester, and aramid. Fibers do not react chemically with the asphalt but rather reinforce and stiffen the asphalt mastic.

The possible advantages of using fibers to reinforce asphalt paving mixtures include reduced fatigue, thermal and reflective cracking; increased service life; and economic benefits.

Hongou and Philips believe that the idea of using fibers to improve the behavior of materials is an old suggestion. The use of fibers can be traced back to a 4000-year-old arch in China constructed with a clay earth mixed with fibers or the Great Wall built 2000 years ago. However, the modern developments of fiber reinforcement started in the early 1950s (Abtahi et al., 2010).

Zube (1956), published the earliest known study on the reinforcement of asphalt mixtures. his study evaluated various types of wire mesh placed under an asphalt overlay in an attempt to prevent reflection cracking. The study concluded that all types of wire reinforcement prevented or greatly delayed the formation of longitudinal cracks. Zube suggests that the use of wire reinforcement would allow the thickness of overlays to be decreased while still achieving the same performance. No problems were observed with steel/AC mixture compatibility.

Simpson et al. (1994), conducted a study of modified bituminous mixtures in Somerset, Kentucky. Polypropylene and polyester fibers and polymers were used to modify the asphalt binder. Two proprietary blends of modified binder were also evaluated. An unmodified mixture was used as a control. Testing included Marshall stability, indirect tensile strength (IDT), moisture damage susceptibility, freeze/thaw susceptibility, resilient modulus, and repeated load deformation. Mixtures containing polypropylene fibers were found to have higher tensile strengths and resistance to cracking. None of the fiber modified mixtures showed resistance to moisture induced, freeze/thaw damage. Fiber modified mixtures showed no improvement in stripping potential. IDT results predict that the control and polypropylene mixtures will not have problems with thermal cracking whereas the mixtures made with polyester fibers and polymer.

Mid-range temperature resilient modulus tests showed polypropylene fiber modified mixtures were stiffest, while high temperature resilient modulus testing measured increased stiffness for all mixtures over the control. Rutting potential as measured by repeated load deformation testing was found to decrease only in polypropylene modified samples.

Qunshan, et al. (2009), used three types of fibers including polyester fibers, cellulose fibers and mineral fibers as modifiers for asphalt mixture with the dosage of 0.30 %, 0.35 % and 0.40 % by the total weight of asphalt mixture. The fatigue properties of asphalt mixture were studied at different stress ratios. Their extensive work showed that fatigue parameters of asphalt mixtures with fibers were decreased, which indicated that fatigue property could be improved by fibers modifiers.

Chen et al. (2009), studied the volumetric and mechanical properties, and design method of fiber-reinforced asphalt mixtures. Four different fiber were used: polyester, poly acrylonitrile, lignin, and asbestos fibers. Marshall tests were performed to measure the volumetric and mechanical properties of asphalt mixtures. Performance tests were also conducted to examine moisture susceptibility and dynamic stability. Results show that the optimum asphalt content, air void, void in mineral aggregate and Marshall stability increase, while bulk specific gravity decreases after adding fibers into asphalt mixtures. Optimum asphalt content, Marshall stability, and dynamic stability increase initially and then decrease with increasing fiber content.

Based on the test results, a fiber content of 0.35% by mass of mixture is recommended for the polyester fiber used in this study.

Park et al. (2015), investigated the reinforcing effect of steel fibers in asphalt concrete through indirect tension tests conducted at -20 C. Control specimens with no fibers, and test series with carbon and polyvinyl alcohol fibers are also carried out for comparison. Cracking resistance, indirect tensile strength, fracture energy, and post-cracking energy were obtained from the tests. The effects of fiber diameter, length, deformed shape, and content of steel fibers were investigated in order to provide fundamental understanding of the reinforcing mechanisms mobilized during fiber pull out and select proper reinforcing fibers. The test results demonstrate that the low temperature cracking resistance of asphalt concrete can be significantly improved by adding the proper type and amount of steel fibers, but that the improvements in mechanical properties are sensitive to fiber length and diameter. The indirect tensile strength and toughness of fiber reinforced asphalt concrete increase with an increase in fiber length within the 0.2–0.4 mm diameter range. Mechanical deformations of the fibers, e.g. presence of a hook or twisting, can induce further improvements in post-cracking energy absorption. Compared to unreinforced specimens, fiber reinforced specimens show up to 62.5% increase in indirect tensile strength, and up to 370% and 895% improvements in fracture energy and toughness, respectively. A hypothesis that explains the fiber reinforcing mechanism in asphalt concrete is proposed and critiqued based on the test data.

2.5 Specific Studies

2.5.1 Polypropylene Fiber

Polypropylene fibers are widely used as a reinforcing agent in concrete. Polypropylene fibers were also used as modifiers in asphalt concrete in the United States. Ohio State Department of Transportation (ODOT) has published a standard for the use of polypropylene fibers in high-performance asphalt concrete.

Remadevi et al. (2014), present the studies on stability, flow and volumetric properties of fiber reinforced bituminous concrete in comparison with the properties of conventional bituminous concrete. Marshall’s stability tests were conducted to determine the optimum binder content. By varying the amount of 10 mm polypropylene fibers (4%, 6%, 8% and 10% by weight of bitumen), optimum fiber content was obtained.

The results indicate that the addition of PP fibers increases the stability but decreases the flow value.

Tapkın (2008), manufactured asphalt concrete specimens with polypropylene fibers at the optimum bitumen content. It was observed for fiber reinforced specimens that the Marshall stability values increased and flow values decreased in a noticeable manner. The fatigue life of these specimens was also increased. The improvement of the properties of asphalt concrete shows the positive effect of polypropylene fibers. The fiber reinforced asphalt mixture exhibits good resistance to rutting, prolonged fatigue life and less reflection cracking. Therefore, it's concluded that the application of PP fibers alters the characteristics of asphalt mixture in a very beneficial way.

Al-Hadidy et al. (2009), investigated the benefits of modifying the asphalt and stone matrix asphalt (SMA) mixture in flexible pavement. Fifty/sixty penetration grade asphalt cement and four proportion of pyrolysis polypropylene (PP) were selected. Unmodified and modified asphalt binders were subjected to rheological and homogeneity tests. The performance tests including, Marshall stability, tensile strength and compressive strength were conducted on unmodified and modified SMA mixtures. The regression relationships between the performance tests were obtained. A mechanistic-empirical design approach was used for estimating the improvement in service life of the pavement or reduction in thickness of SMA and base layer for the same service life due to modification the SMA mixtures. The analyses of test results show that the performance of PP-modified asphalt mixtures is better when compared to conventional mixtures. The temperature susceptibility can be reduced by the inclusion of PP in the asphalt mixture. A PP content of 5% by weight of asphalt is recommended for the improvement of the performance of asphalt concrete mixtures similar to that investigated in this study. The results of multi-layer elastic analysis presented herein indicate that the pavement consisting of PP-modified SMA as a surface layer is beneficial in reducing the construction materials. Actual savings would depend upon the option exercised by the designer for reducing the thickness of an individual layer.

2.5.2 Polyester Fibers

Polyester is the polymerized product of components from crude oil of which asphalt is also a component.

Maurer et al. (1989), investigated the influence of fibers in overlay mixtures. Polyester was chosen over polypropylene because of its higher melting point. It was announced that the construction of the mixture was done without difficulty or extra equipment. The polyester fiber modified mixture was compared to several types of fiber reinforced segments and a control section, i.e. without any reinforcement. Test sections were rated for ease of construction, cost and resistance to reflection cracking.

Shiuh et al. (2005), reported that polyester fibers would be used if the strong and durable reinforcement of bitumen-fiber mastics were needed at higher temperatures.

Shopeng et al. (2008), investigated the effects of polyester fibers on the rheological characteristics and fatigue properties of asphalt.

The results indicated that the viscosity of asphalt binder is increased with increasing polyester fiber contents, especially at lower temperature. They confirmed that the fatigue property of asphalt mixture could be improved by adding fiber, especially at lower stress levels.

2.5.3 Asbestos (Mineral) Fiber

Asbestos is the only mineral substance used as a textile fiber. The substance is found in fibrous reins of serpentine or amphibole rock (Majoryl, 1986). At first, it was tried to use non-synthetic fibers in pavements; therefore, cotton fibers and asbestos fibers were used, but these were degradable and were not suitable as the long-term reinforcements. Asbestos was also used until it was recognised as a health hazard (Marais,1979).

Huet et al. (1990), published the results of a study comparing changes in void contents and hydraulic properties of plain and modified asphalt mixtures placed on the Nantes fatigue test track in France. Two of the mixtures used a polymer modifier (SBS) and the third used a mineral (asbestos) fiber to modify the base mixture. Plain and SBS modified mixtures showed similar decreases in void content and hydraulic properties after 1,100,000 load cycles. In contrast, Huet concludes that the mixtures modified with fiber "had undergone no reduction in void content; its drainage properties were practically unchanged and rutting was minimal" after the same loading.

2.5.4 Cellulose Fiber

Stuart et al. (1994), evaluated two loose cellulose fibers, a pelletized cellulose fiber, and two polymers. The mixtures were evaluated for binder drain-down and resistance to rutting, low temperature cracking, aging and moisture damage. Drain-down tests showed that all mixtures with fiber drained significantly less than those with polymers or the control. Fiber modified mixtures were the only ones to meet test specifications for drain down. The control samples were found to have excellent resistance to rutting and no significant difference was observed between the control and mixtures with modified binder. Low temperature and moisture damage results were inconclusive. Polymer modified mixtures were found to have better resistance to aging.

Partl et al. (1994), used various contents of cellulose fibers in one mix in a study of stone matrix asphalt (SMA). Mixtures were evaluated using thermal stress restrained specimen tests and indirect tensile tests. Problems with fiber clumping occurred in the mixing process. Distribution of fibers was improved by increasing mixing temperature and duration, but some clumps were still present. The study concluded that SMA with cellulose fiber did not significantly improve the mix based on the two tests conducted. The authors believe that the poor distribution of fibers may have caused the limited improvement, but suggest further research to confirm this theory.

Shaopeng et al. (2006), investigated the dynamic characteristics of fiber-modified asphalt mixture by Cellulose fiber, polyester fiber and mineral fiber were used as additives to asphalt mixture. Experimental results show that all fiber-modified asphalt mixtures have higher dynamic modulus compared with control mixture.

2.5.5 Carbon fibers

Carbon fiber is defined as a fiber containing at least 92 wt % carbon, while the fiber containing at least 99 wt % carbon is usually called a graphite fiber. Carbon fibers generally have excellent tensile properties, low densities, high thermal and chemical stabilities in the absence of oxidizing agents, good thermal and electrical conductivities, and excellent creep resistance.

The two most important precursors in the carbon fiber industry are polyacrylonitrile (PAN) and mesophase pitch (MP).

In recent years, the carbon fiber industry has been growing steadily to meet the demand from different industries such as aerospace (aircraft and space systems), military, turbine blades, construction (non-structural and structural systems), etc. (Huang, 2009)

Khattak et al. (2013), focused on the mechanistic characteristics of electrically conductive carbon nano-fiber (CNF) modified hot mix asphalt (HMA) mixtures. HMA mixtures were modified with varying percentages of CNF. The viscoelastic, strength, permanent deformation and fatigue characteristics of the neat and modified mixtures were evaluated under indirect tension mode. In order to understand the micromechanical behavior of CNF in HMA mixtures, the microstructure and morphology of fracture surfaces of HMA samples were studied using Scanning Electron Microscopy (SEM). It was found that the addition of CNF improves the performance of HMA mixtures in a unique way.

2.5.6 Nylon fibers

The term ‘‘Nylon” was derived from no-run. The name originally considered by its invertors to emphasize durability of ladies' hosiery manufactured from it. Nylon, a popular facing yarn of carpets, is used for the actual recycled carpet fibers in asphalt pavement.

Lee S. J. (2005), investigated the influence of Nylon fibers on the fatigue cracking resistance of asphalt concrete using fracture energy. The experimental program was designed with two phases: the single fiber pull-out test and the indirect tension strength test. Through pull-out tests of 15-denier single nylon fibers, the critical fiber embedded length was determined to be 9.2 mm. As for indirect tension strength tests, samples of asphalt concrete mixed with nylon fibers of two lengths, i.e. 6 and 12 mm, were prepared and tested based on the results of the pull-out tests (critical embedded length) and three volume fractions of 0.25%, 0.5% and 1%.

The use of asphalt concrete samples fabricated with fibers of 1% volume and the length of 12 mm results in 85% higher fracture energy than non-reinforced specimens, showing improved fatigue cracking resistance.

2.5.7 Glass fibers

Glass fiber is by far the most predominant fiber used in the reinforced polymer industry and among the most versatile. Although melting glass and drawing into fibers is an ancient technique, long continuous fiber drawn from glass was introduced in the 1930’s by Owens-Corning as glass wool and given the popular name fiberglass.

Fibers made from glass are manufactured in many varieties for specific uses. It typically has a silica content of greater than 50 percent, and the composition with different mineral oxides give the resulting product its distinct characteristics.

2.5.7.1 Glass fiber types

A-glass - Alkali glass made with soda lime silicate. Used where electrical resistivity of E-glass is not needed. A-glass or soda lime glass is the predominate glass used for containers and windowpanes.

AR-glass – Alkali Resistant glass made with zirconium silicates. Used in Portland cement substrates.

C-glass – Corrosive resistant glass made with calcium borosilicates. Used in acid corrosive environments.

D-glass – Low dielectric constant glass made with borosilicates. Used in electrical applications.

E-glass – Alkali free, highly electrically resistive glass made with alumina-calcium borosilicates. E-glass is known in the industry as a general-purpose fiber for its strength and electrical resistance. It is the most commonly used fiber in the fiber reinforced polymer composite industry.

ECR-glass – An E-glass with higher acid corrosion resistance made with calcium aluminosilicates. Used where strength, electrical conductivity and acid corrosion resistance is needed.

R-glass – A reinforcement glass made with calcium aluminosilicates used where higher strength and acid corrosion resistance is needed.

S-glass – High strength glass made with magnesium aluminosilicates. Used where high strength, high stiffness, extreme temperature resistance, and corrosive resistance is needed.

S-2 glass – Glass similar to, but with somewhat improved properties with, S-glass. "S-2" is a brand name originally created by Owens-Corning but spun off in 1998 and is now a registered trademark of AGY Holdings Corp.

Fibers used for structural reinforcement composites generally fall into the categories of E-glass, AR-glass and S-glass. Of all the fibers, available for structural strengthening and reinforcement, E-glass is by far the most used and is the least expensive. Glass filament typical mechanical properties are listed in the following table 2.9.

Table (2.9): Glass filament typical mechanical properties

Fiber type	Density, (g/cm3)	Tensile Strength, MPa	Modulus, GPa	Percent Elongation
A-glass	2.44	3300	72	4.8
AR-glass	2.7	1700	72	2.3
C-glass	2.56	3300	69	4.8
D-glass	2.11	2500	55	4.5
E-glass	2.54	3400	72	4.7
ECR-glass	2.72	3400	80	4.3
R-glass	2.52	4400	86	5.1
S-glass (also S-2 glass)	2.53	4600	89	5.2

The historical origin of glass and glass fibers is uncertain. The fiber-forming substance is glass. Glass fiber has high strength and its elongation is only 3–4%, but its elastic recovery is 100 percent. Fibers of glass will not burn. However, they soften at about 815◦C and their strength begins to decline at temperatures above
315◦C.

It is thought that adding glass fibers to asphalt mixtures enhances material strength and fatigue characteristics while increasing ductility. Due to their excellent mechanical properties, glass fibers might offer an excellent potential for asphalt modification. With new developments in producing glass fiber, reinforced bituminous mixtures can be more cost competitive and cost effective as compared to modified binders. The use of glass fiber-reinforced asphalt mixtures may increase the construction cost; however, this may reduce and save the maintenance cost.

Mahrez A., et al. (2005), present the characteristics and properties of glass fiber reinforced Stone Mastic Asphalt, which may have the benefit of improving the performance of road pavement. To evaluate the effect of the fiber content on the bituminous mixes, laboratory investigations were conducted on the samples with and without fibers. The testing undertaken in this research comprise the Marshall test, indirect tensile test, creep test and resistance to fatigue cracking by using repeated load indirect tensile test.

The use of Glass fiber showed consistent results and it was found the addition of fiber does affect the properties of bituminous mixes, by decreasing its stability and an increase in the flow value as well the voids in the mix. The results showed that the addition of glass fiber will be beneficial in improving some of the main properties of the flexible pavement.

Shukla et al. (2013), determined the feasibility of modifying the behavior of a standard asphalt concrete (AC) mix through the use of glass fiber. The purpose of this study was to identify and understand the factor that is responsible for improving the behavior of Glass Fiber Modified Asphalt Mixes (GFMAM). Asphalt concrete samples were prepared and tested to evaluate the mixture characteristics such as its fatigue life, skid resistance and rutting resistance. The conclusions drawn from the study on testing of GFMAM are increased stiffness and resistance to permanent deformation compared to conventional asphalt mix. Fatigue characteristics of the mixtures were also improved. As the glass fibers used were of high tensile strength, GFMAM produced a higher indirect tensile strength for paving applications.

2.6 Summary of Literature Review

It is thought that adding glass fibers to asphalt mixtures enhances material strength and fatigue characteristics while increasing ductility. Due to their excellent mechanical properties, glass fibers might offer an excellent potential for asphalt modification. The addition of glass fiber will be beneficial in improving some of the main properties of the flexible pavement. The tensile strength and related properties of mixtures containing different types of fibers were found to be improved in some cases and not in others.

Chapter Three

Materials and Experimental Program

3.1 Introduction:

The main objective of this study is to evaluate the properties of hot mix asphalt modified by glass fiber. Process and procedures on how this study is carried out will be explained in detail.

This chapter deals with two topics. First, is to evaluate the used materials properties such as aggregates, bitumen and glass fiber. Second, is to describe how experimental work has been done to achieve study objectives.

3.2 Laboratory Test Procedure

This study is based on laboratory testing as the main procedure to achieve study goals. All the testing is conducted using equipment and devices available in the laboratories of Association of Engineers – Gaza.

Laboratory tests are divided into several stages, which begin with the properties evaluation of the used materials: aggregates, bitumen, and glass fiber. Sieve analysis is carried out for each aggregate type to obtain the grading of aggregate sizes followed by aggregates blending to obtain wearing course gradation curve used to prepare asphalt mix. After that, Asphalt mixes with different bitumen contents are prepared and marshal test is conducted to obtain optimum bitumen content. The value of the optimum bitumen is used to prepare asphalt mixes modified with various percentages of glass fiber. Marshal Test are utilized to evaluate the properties of these modified mixes. Finally, laboratory test results are obtained and analyzed. Figure (3.1) shows the flow chart of laboratory testing procedure.

3.2.1 Materials collection

Materials required for this study are the component of hot mix asphalt, Figure (3.1) displays the laboratory testing procedure and Table (3.1) presents main and local sources of these materials.

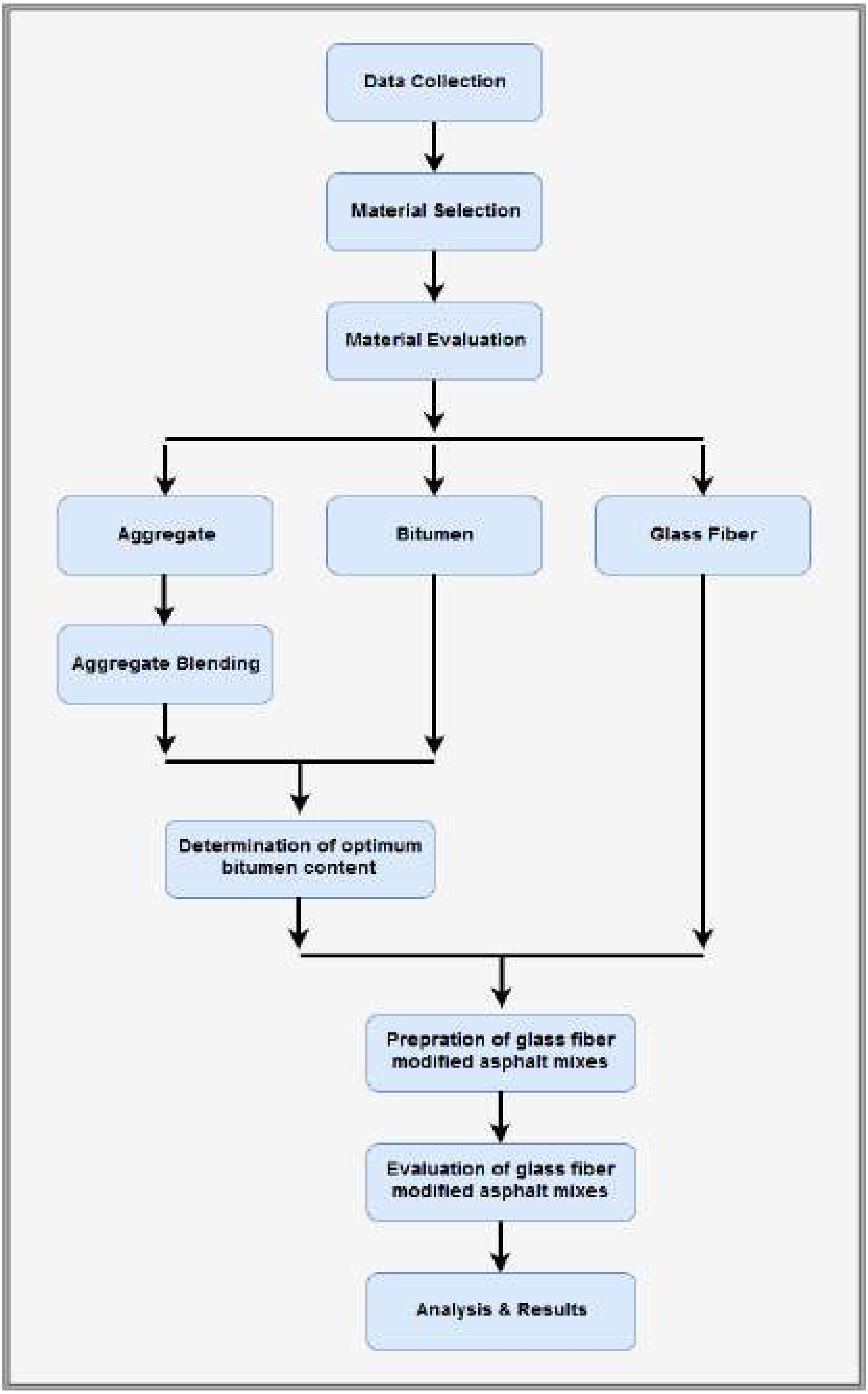

Figure (3.1): Flow chart of laboratory testing procedure

Table (3.1): Main and local sources of used materials

Material	Source	
	Main	Local
Aggregates	Crushed rocks (Occupied Palestinian Territories)	Al-Qaoud factory
Bitumen	Occupied Palestinian Territories	Al-Qaoud factory
Glass Fiber	France	Bloom Company

3.2.2 Number of samples required

First Stage:

Five percentages of bitumen were examined to determine the best percentage of bitumen for the aggregates used, which represent 4.5, 5, 5.5 and 6% by weight of the mix with 3 samples for each percentage, total samples 12.

Second Stage:

Three samples were made using the OBC for determining the mechanical properties at different percentages of glass fiber (0, 0.1%, 0.2%, 0.4%, 0.6%, 0.8%, 1.00%) by the total weight of asphalt mix, total samples 21.

Total number of samples required for two stage = approximately 33 samples.

3.2.3 Materials properties

3.2.3.1 Bitumen properties

Asphalt binder 60/70 was used in this research. In order to evaluate bitumen properties, different laboratory tests have been performed such as: specific gravity, ductility, flash point, fire point, softening point and penetration.

a) Bitumen penetration test

- Test specification: ASTM D5/D5M -13
- Container dimension: 75 mm x 55mm
- Test results is listed in Table (3.2)

Table (3.2): Bitumen penetration test results

Test	Unit	Result	Requirements	Specification
Penetration	1/10 mm	63	60-70	ASTM D5/D5M -13

b) Ductility test

- Test specification: ASTM D113-86
- Test results are listed in Table (3.3).
- Figure (3.2) show ductility test for a bitumen sample.

Table (3.3): Bitumen ductility test results

Test	Unit	Result	Requirements	Specification
Ductility	cm	+150	Min 100	ASTM D113-86

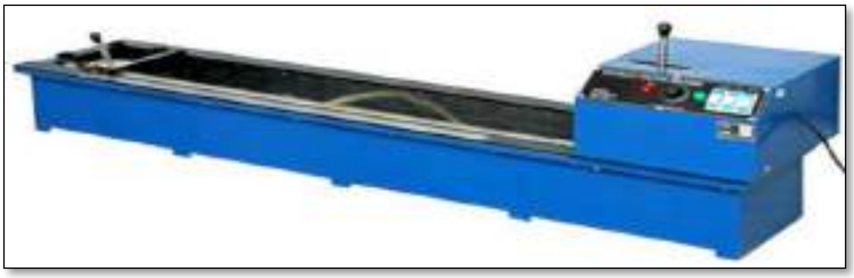

Figure (3.2): Ductility test for a bitumen sample

c) Softening point test

Softening Point: Used to determine the temperature at which a phase change occurs in asphalt cement. The ring and ball method is used for this test.

- Test specification: ASTMD36-2002
- Test results are listed in Table (3.4).
- Figure (3.3) show softening point test for bitumen samples.

Table (3.4): Bitumen softening point results

Test	Unit	Result	Requirements	Specification
Softening point	° C	49.20	48 - 56	ASTMD36-2002

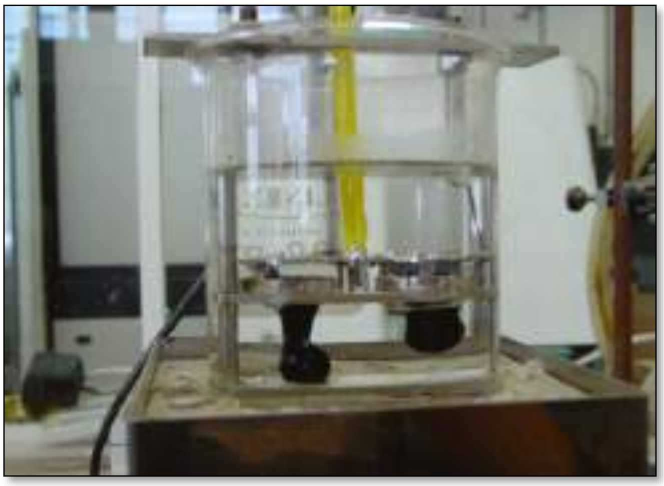

Figure (3.3): Softening point test for bitumen samples

d) Flash point test

Flash Point: the lowest temperature at which the application of test flame causes the vapors from the bitumen to momentarily catch fire in the form of a flash.

- Test specification: ASTM D92-02B
- Test results is listed in Table (3.5)

Table (3.5): Bitumen flash point test results

Test	Unit	Result	Requirements	Specification
Flash point	° C	273	Min 230 C°	ASTM D92-12b

e) Specific gravity test

- Test specification: ASTM D 3289-03
- Test results is listed in Table (3.6)

Table (3.6): Bitumen density test results

Test	Unit	Result	Requirements	Specification
Density	g/ml	1.02	0.97-1.06	ASTM D 3289-03

f) **Summary of bitumen properties**

Table (3.7): Summary of bitumen properties

Test	Specification	Results	ASTM specifications limits
Penetration (0.01 mm)	ASTM D5/D5M -13	63	60-70
Ductility (cm)	ASTM D113-86	+150	Min 100
Softening point (°C)	ASTMD36-2002	49.2	(48 – 56)
Flash point (°C)	ASTM D92-12b	273	Min 230° C
Specific gravity (g/cm^3)	ASTM D 3289-03	1.02	0.97-1.06

3.2.3.2 Glass Fiber:

Table (3.8) shows the physical property of Glass Fiber. The mixes were prepared with glass fiber of different percentages "i.e. 0.1%, 0.2%, 0.4%, 0.6%, 0.8%, 1.0%" by the total weight of asphalt mix.

Table (3.8): Glass Fiber properties

Property	Detail
Fiber type	Glass Fiber (E- class)
length (mm)	12
Density (g/cm3)	2.54
Tensile Strength (MPa)	3400

Figure (3.4): Used Glass fiber

The length of fiber (12mm) was used according to many reasons:

1- To obtain a better distribution of the fibers amount added to the mix.
2- The fiber length is proportional with the maximum aggregate size used in the asphalt mix in this thesis (1/2" wearing coarse).
3- Trial mixes with different lengths (12 and 19mm) were prepared and then we found that the mix with fiber length (12mm) is better in distribution, workability and test results.

3.2.3.3 Aggregates properties

Aggregates used in asphalt mix can be divided as shown in Table (3.9) and Figure (3.5).

Table (3.9): Used aggregates types

	Type of aggregate	Particle size (mm)
Coarse	Folia	0/ 19.0
	Adasia	0/ 12.5
	Simsimia	0/ 9.50
Fine	Trabiah	0/4.75
	Filler	

Figure (3.5): Used aggregates types

In order to define the properties of used aggregates, many laboratory tests have been done, these tests include:

a. Sieve analysis (ASTM C 136)
b. Specific gravity test (ASTM C127).
c. Water absorption (ASTM C128)
d. Los Angles abrasion (ASTM C131)
e. Sand equivalent (AASHTO T 176)

Table (3.10): Specific Gravity Test of aggregates

	Unit	Simsimia	Adasia
S.S.D Weight	g	2930.0	3130.0
Weight in Water	g	1782.5	1935
Volume of Solids	cm^3	1147.5	1195.0
Specific Gravity		2.553	2.619
Dry Specific Gravity		2.506	2.568

Table (3.11): Water Absorption Test of Aggregates

	Unit	Simsimia	Adasia
S.S.D Weight	g	2930.0	3130.0
Oven Dry Weight	g	2877	3070
Water Absorption	%	1.842	1.954

Table (3.12): Specific Gravity Test of Sand & Filler

	Unit	Filler	Fine
Dry Weight	g	340.7	127.0
Pycnometer + water	g	1816.5	1816.5
Pycnometer + water +Sample	g	2026.0	1894.0
Specific Gravity		2.649	2.617

Table (3.13): Aggregates Quality Test Results

Test Name	Adasia Aggregate	Simsimia Aggregate	Fine Aggregate	Specification limits
Abrasion Loss (500 Cycles) %	23.5	25.2	*	< 30%
Sand Equivalent %	*	*	75	>50%

3.2.3.3.1 Sieve analysis

- Specification (ASTM C 136)
- Table (3.14) and Figures (3.6 - 3.10) show aggregates sieve analysis results.

Table (3.14): Aggregates sieve analysis results

Sieve No.	Sieve size (mm)	Sample passing %			
		Adasia	Simsimia	Trabia	Filler
		0/ 12.5	0/ 9.50	0/4.75	
1"	25	100.00	100.00	100.00	100.00
3/4"	19	100.00	100.00	100.00	100.00
1/2"	12.5	70.14	100.00	100.00	100.00
3/8"	9.5	20.38	100.00	100.00	100.00
# 4	4.75	1.42	51.09	97.45	100.00
# 8	2.36	0.73	12.08	94.65	100.00
# 30	0.6	0.60	3.11	44.65	99.85
# 50	0.3	0.60	2.49	24.71	91.69
# 80	0.18	0.60	2.08	14.84	82.36
# 200	0.075	0.53	1.48	7.64	80.03

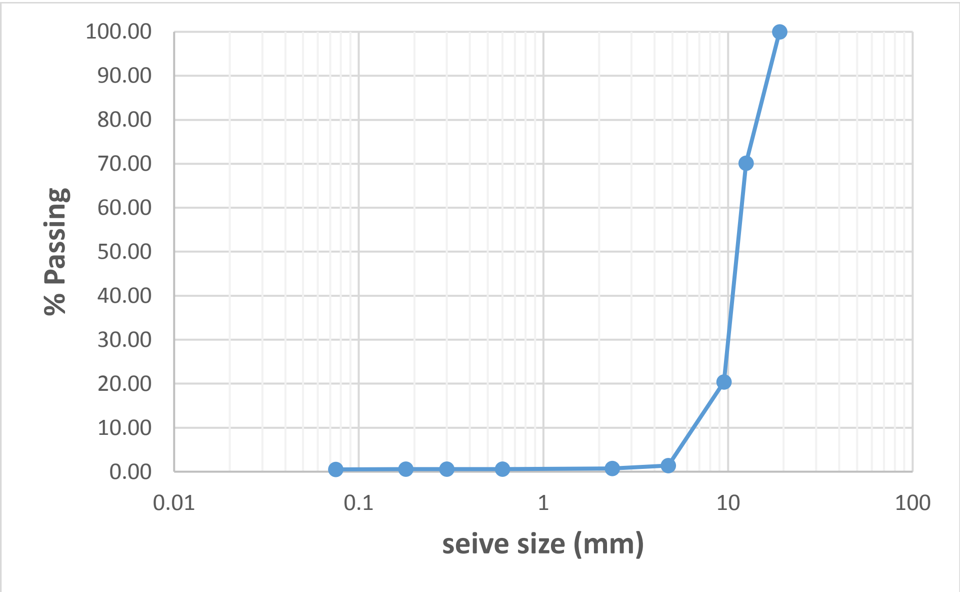

Figure (3.6): Gradation curve (Adasia 0/ 12.5)

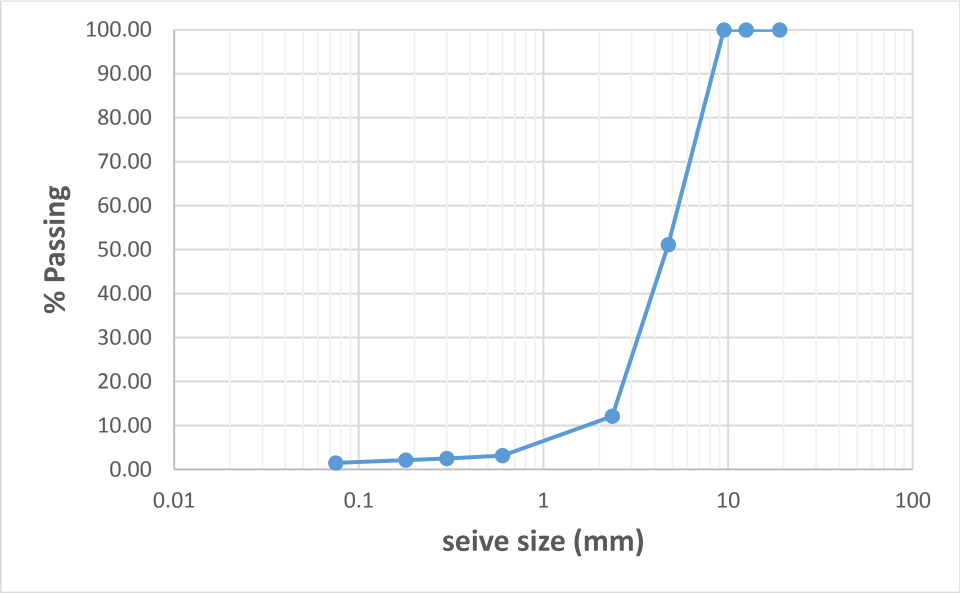

Figure (3.7): Gradation curve (Simsimia 0/ 9.5)

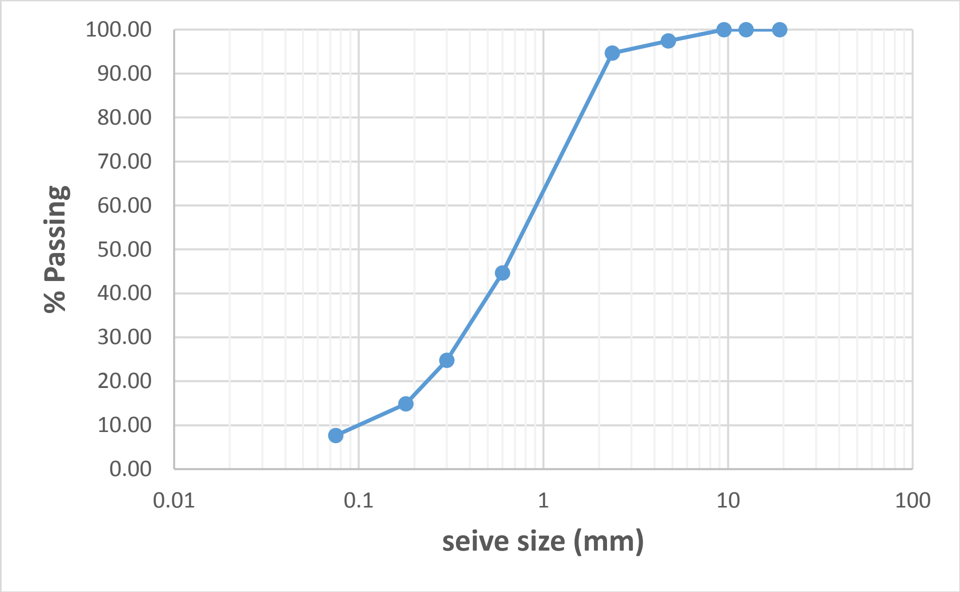

Figure (3.8): Gradation curve (Trabia 0/ 4.75)

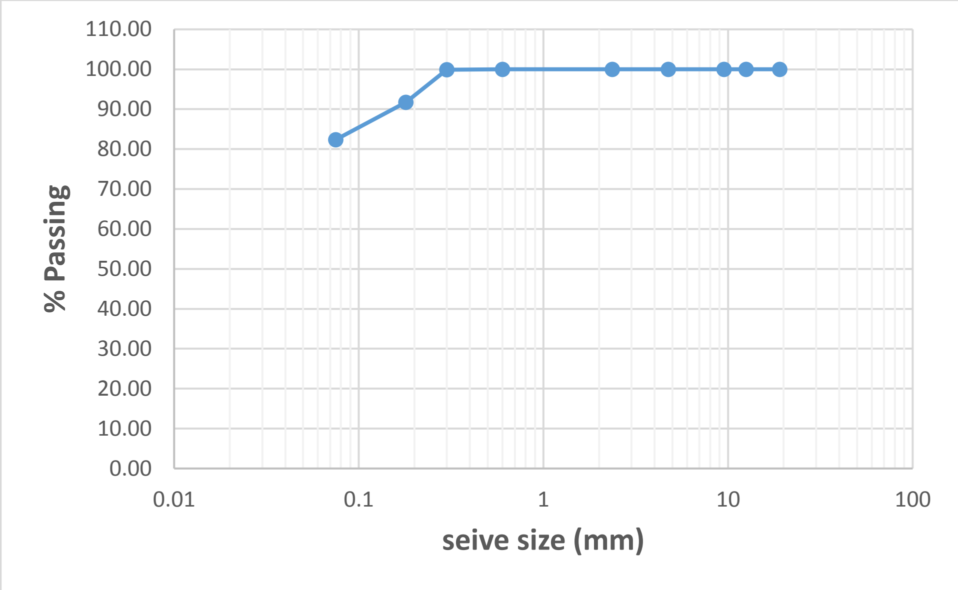

Figure (3.9): Gradation curve (Filler)

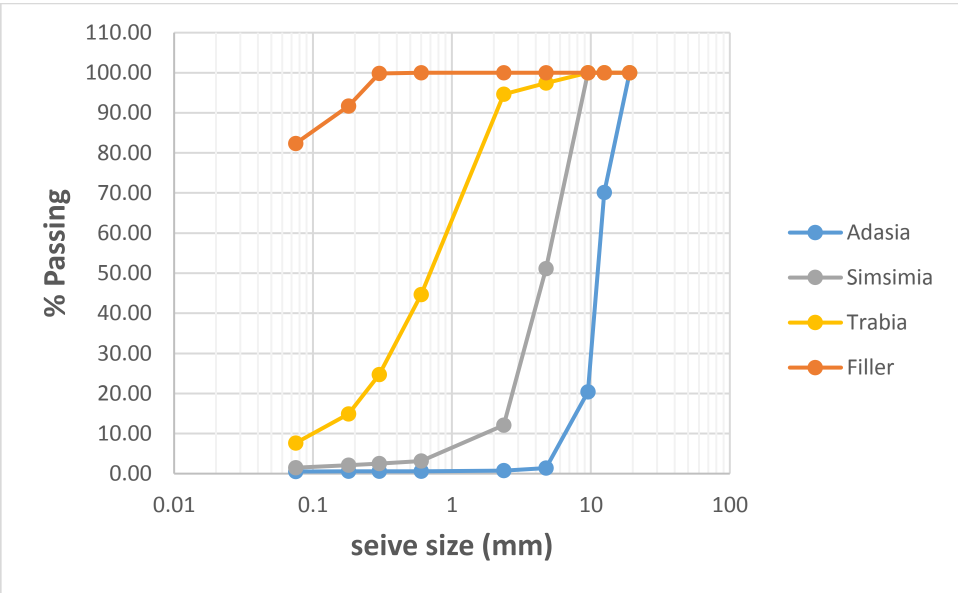

Figure (3.10): Aggregates gradation curves

3.3 Testing program

3.3.1 Blending of aggregates

Asphalt mix requires the combining of two or more aggregates, having different gradations, to produce an aggregate blend that meets gradation specifications for a particular asphalt mix.

Available aggregate materials (0/19), (0/12.5), (0/9.5), (0/4.75) and sand are integrated in order to get the proper gradation within the allowable limits according to ASTM specifications using mathematical trial method. This method depends on suggesting different trial proportions for aggregate materials from whole gradation. The percentage of each size of aggregates is to be computed and compared to the specification limits. If the calculated gradation is within the allowable limits, no further adjustments need to be made; if not, an adjustment in the proportions must be made and the calculations repeated. The trials are continued until the percentage of each size of aggregate are within allowable limits (Jendia, 2000). Aggregates blending results are presented in chapter (4) and in more detail in Appendix (B).

3.3.2 Marshal test

Marshall Method for designing hot asphalt mixtures were used to determine the optimum bitumen content to be added to specific aggregate blend resulting a mix where the desired properties of strength and durability are met. According to standard 75-blow Marshal design method designated as (AASHTO T 245-13) a number of 12 samples each of 1200 gm in weight were prepared using five different bitumen contents (from 4.5 - 6% with 0.5 % incremental). Three samples were used to prepare asphalt mixture with one-bitumen content to have an average value of Marshal Stability, bulk density and flow. Figure (3.11) show Marshal Specimens for different bitumen percentages.

Marshall Properties of the asphalt mix such as stability, flow, density, air voids in total mix, and voids filled with bitumen percentage are obtained for various bitumen contents. Then the following graphs are plotted:

a. Stability vs. Bitumen Content;
b. Flow vs. Bitumen Content;
c. Bulk Specific Gravity vs. bitumen Content;
d. Air voids (Va) vs. Bitumen Content;
e. Voids Filled with Bitumen (VFB) vs. Bitumen Content

These graphs are utilized to obtain optimum bitumen content.

Figure (3.11): Marshal specimens for different bitumen percentages

3.3.3 Determination of optimum bitumen content (OBC)

The optimum bitumen content (OBC) for proposed mix is the average of three values of bitumen content (Jendia, 2000), which include:

a. Bitumen content at the highest stability (% mb) Stability
b. Bitumen content at the highest value of bulk density (% mb) bulk density
c. Bitumen content at the median of allowed percentages of air voids (Va = 3-5%) (% mb) Va

Marshal graphs are utilized to obtain these three values.

Optimum bitumen content (OBC) % =

$$\frac{(\%\,\text{mb})_{\text{Stability}} + (\%\,\text{mb})_{\text{bulk density}} + (\%\,\text{mb})_{\text{Va}}}{3}$$

Properties of the asphalt mix using optimum bitumen content such as stability, flow, Va, bulk density and VMA are obtained and checked against the specifications.

Chapter Four
Results and Data Analysis

4.1 Introduction

Results of laboratory work had been obtained and analyzed in order to achieve study objectives which include studying the effect of adding different percentages of Glass Fiber on the mechanical properties of asphalt mix and identify the optimum percent of Glass Fiber to be added to hot mix asphalt.

Laboratory work results are presented in this chapter in three stages. First, handling the results of blending aggregates to obtain asphalt wearing course gradation curve. Second stage, Marshal Test is carried out with different percentages of bitumen which are (4.5, 5.0, 5.5 and 6.0%) and the results are analyzed in order to obtain the optimum bitumen content (OBC).

After obtaining OBC, the following step is to study the effect of adding different percentages of Glass Fiber on asphalt mix properties which are (0.1, 0.2, 0.4, 0.6, 0.8, 1%) by the weight of asphalt mix. Marshal test results for modified asphalt mixes are analyzed and finally the optimum Glass Fiber modifier content is obtained.

4.2 Blending of aggregates

The final ratio of each aggregate material in asphalt wearing course is shown in Table (4.1). The proposed aggregates gradation curve is found to be satisfying ASTM specification for asphalt wearing course gradation. The gradation of final aggregate mix with ASTM gradation limits is presented in Table (4.2) and Figure (4.1).

Table (4.1): Proportion of each aggregate material from proposed mix

Aggregate Type	% by Total Weight of Aggregates
Adasia Aggregate	22.0 %
Simsimia Aggregate	30.0 %
Fine Aggregate	45.0 %
Filler	3.0 %
Total	100.0 %

Table (4.2): Gradation of proposed mix with ASTM specifications limits

Sieve No.	Sieve size (mm)	% Passing	ASTM D5315 specification limits (%)	
			Min	Max
3/4"	19	100.0	100	100
1/2"	12.5	93.4	90	100
3/8"	9.5	82.5	67	88
#4	4.75	62.5	44	74
#8	2.36	49.4	28	58
#30	0.6	24.2	16	39
# 50	0.3	14.7	5	21
# 80	0.18	9.9	3	15
#200	0.075	6.4	2	10

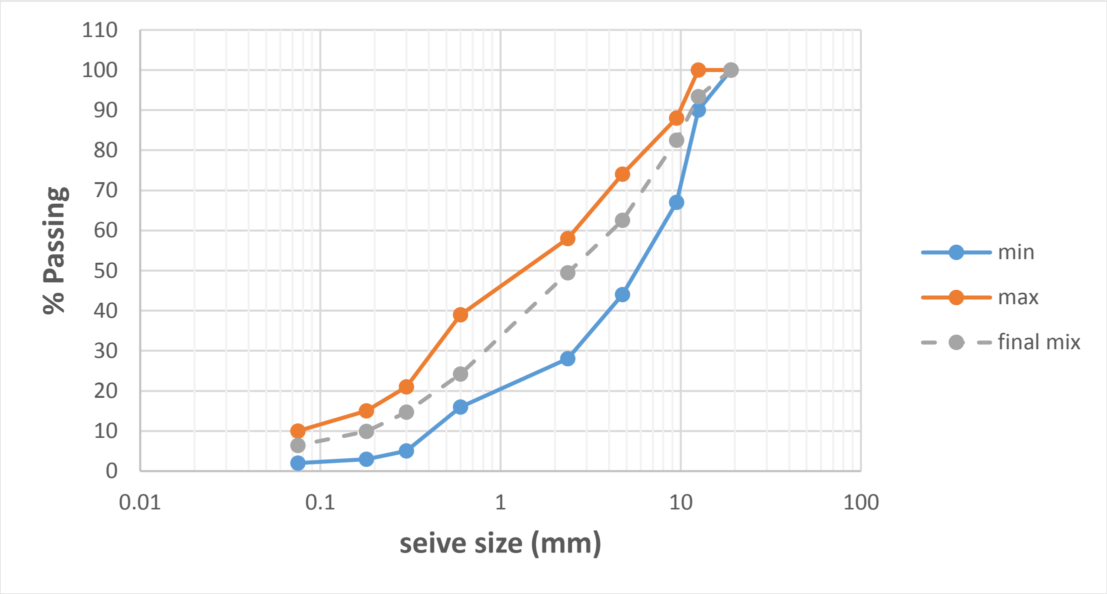

Figure (4.1): Gradation of final aggregates mix with ASTM specification range

4.3 Optimum bitumen content

As indicated in Chapter (3). A number of 12 samples each of 1200 gm approximate in weight were prepared using five different bitumen contents (from 4.5 – 6% with 0.5 % incremental) with the purpose to obtain the optimum bitumen content (OBC) for one job mix. Table (4.3) and Figures (4.2 – 4.7) show summary of Marshal Test results. Further details are offered in Appendix (D).

Table (4.3): Summary of Marshal Test results

Bitumen %(by total weight)	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
4.5	1	1596.2	2.2	2.314	5.5	15.6	64.6	760.1
	2	1565.6	2.1	2.311	5.6	15.7	64.2	711.6
	3	1591.1	2.2	2.313	5.6	15.7	64.5	757.7
	Average	**1584.3**	**2.13**	**2.312**	**5.6**	**15.7**	**64.4**	**743.1**
5	1	1693	2.4	2.322	4.4	15.7	71.8	705.4
	2	1703.2	2.5	2.321	4.5	15.7	71.5	681.3
	3	1698.1	2.5	2.322	4.4	15.7	72	679.2
	Average	**1698.1**	**2.5**	**2.322**	**4.4**	**15.7**	**71.7**	**688.7**
5.5	1	1858.7	2.8	2.328	3.6	16	77.7	663.8
	2	1815.2	2.9	2.328	3.6	16	77.8	625.9
	3	1805	2.8	2.326	3.7	16.1	77.3	644.6
	Average	**1826.3**	**2.8**	**2.327**	**3.6**	**16**	**77.6**	**644.8**
6	1	1695.6	3.1	2.316	3.1	16.6	81.1	547
	2	1750.1	3.1	2.315	3.2	16.7	81	564.6
	3	1747.5	3	2.319	3	16.5	81.7	582.5
	Average	**1731.1**	**3.07**	**2.317**	**3.1**	**16.6**	**81.3**	**564.7**

4.3.1 Stability ‐ bitumen content relationship

Stability is the maximum load required to produce failure of the specimen when load is applied at constant rate 50 mm / min (Jendia, 2000). Figure (4.2) display the stability results for different bitumen contents. Stability of asphalt mix increases as the bitumen content increase till it reaches the peak at bitumen content 5.5% then it started to drop gradually at higher bitumen content.

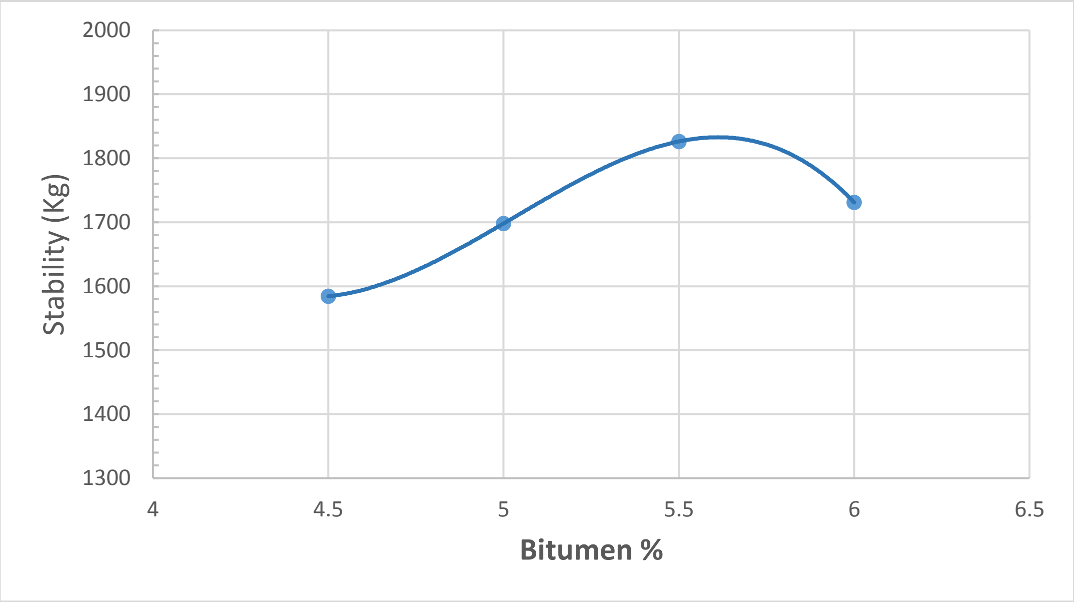

Figure (4.2): Stability vs. bitumen content

4.3.2 Flow - bitumen content relationship

Flow is the total amount of deformation which occurs at maximum load (Jendia, 2000). Figure (4.3) display the Flow results for different bitumen contents. Flow of asphalt mix increases as the bitumen content increase till it reaches the peak at the max bitumen content 6.0 %.

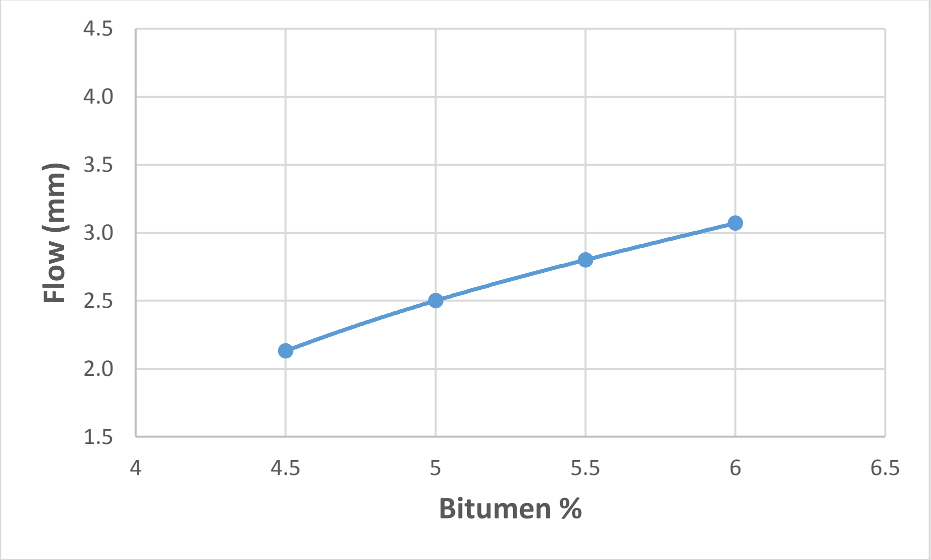

Figure (4.3): Flow vs. bitumen content

4.3.3 Bulk density – bitumen content relationship

Bulk density is the real density of the compacted mix. Figure (4.4) display the Bulk density results for different bitumen contents. Bulk density of asphalt mix increases as the bitumen content increase till it reaches the peak (2.327g/cm3) at bitumen content 5.5 % then it started to decline gradually at higher bitumen content.

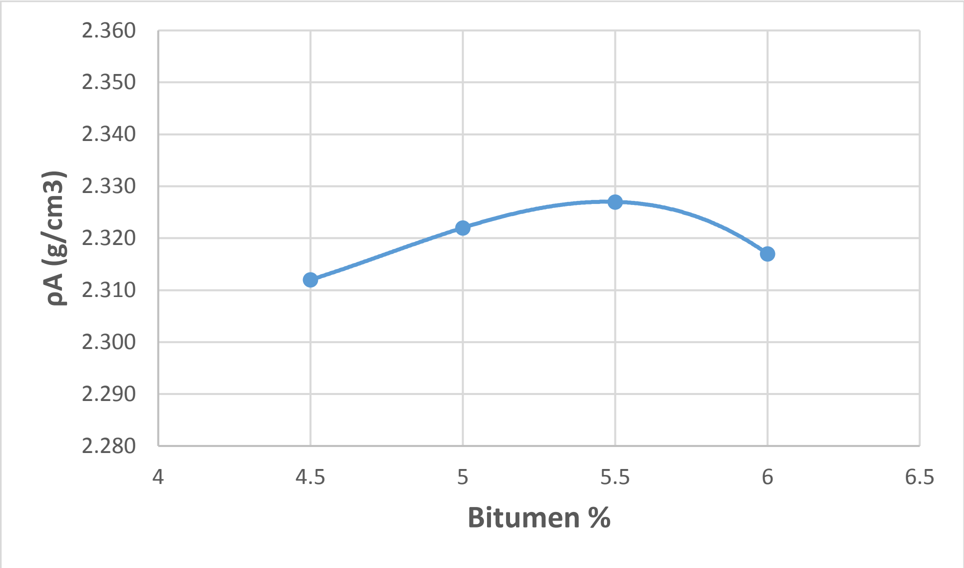

Figure (4.4): Bulk density vs. bitumen content

4.3.4 Air voids content (Va %) – bitumen content relationship

The air voids content (Va %) is the percentage of air voids by volume in specimen or compacted asphalt mix (Jendia, 2000). Figure (4.5) display the (Va %) results for different bitumen contents. Maximum air voids content value is at the lowest bitumen percentage (4.5%), (Va %) decrease steadily as bitumen content increase due to the increase of voids percentage filled with bitumen in the asphalt mix.

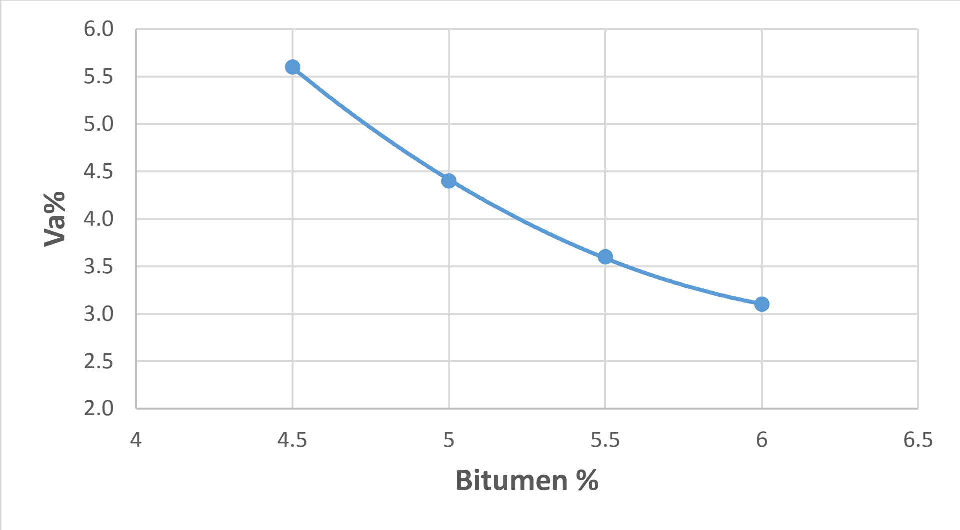

Figure (4.5): Mix air voids proportion vs. bitumen content

4.3.5 Voids Filled with Bitumen (VFB %) - bitumen content

Voids Filled with Bitumen (VFB) is the percentage of voids in mineral aggregates filled with bitumen (Jendia, 2000). Figure (4.6) display the (VFB %) results for different bitumen contents. Minimum VFB content value is at the lowest bitumen percentage (4.5%), VFB% increase steadily as bitumen content increase due to the increase of voids percentage filled with bitumen in the asphalt mix.

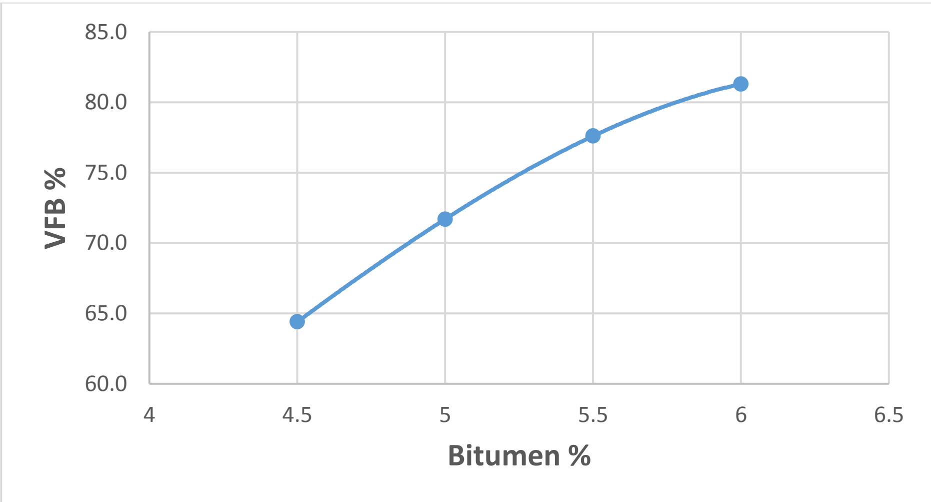

Figure (4.6): Voids filled bitumen proportion vs. bitumen content

4.3.6 Voids in Mineral Aggregates (VMA)-bitumen content relationship

Voids in Mineral Aggregates (VMA) is the percentage of voids volume in the aggregates before adding bitumen or the sum of the percentage of voids filled with bitumen and percentage of air voids remaining in asphalt mix after compaction (Jendia, 2000). Figure (4.7) display the VMA results for different bitumen contents.

VMA decrease steadily as bitumen content increase and fill higher percentage of voids in the asphalt mix.

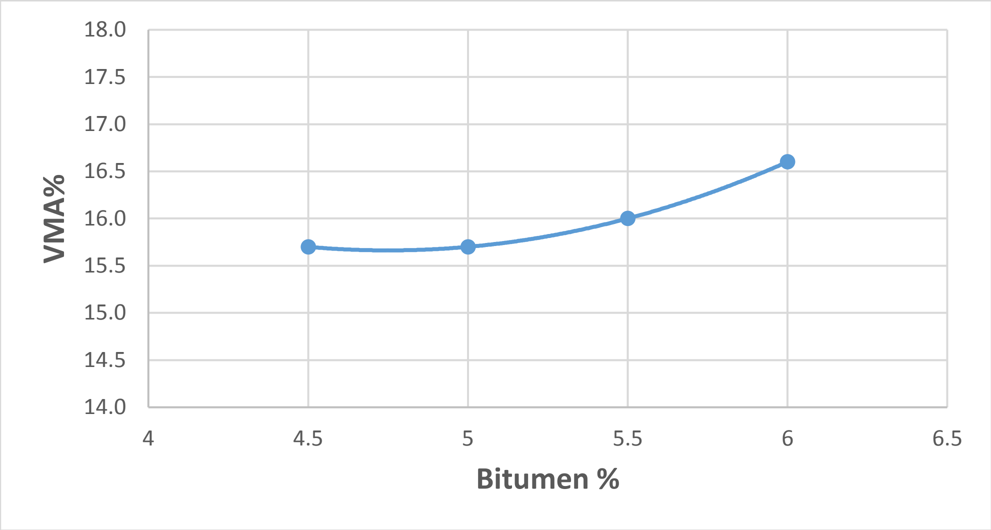

Figure (4.7): Voids of mineral aggregates proportion vs. bitumen content

4.3.7 Determination of optimum bitumen content (OBC)

Figures (4.2, 4.4 and 4.5) are used to find three values respectively.

- Bitumen content at the highest stability (% mb) Stability = 5.50 %
- Bitumen content at the highest value of bulk density (% mb) bulk density =5.50%
- Bitumen content at the median of allowed percentages of air voids (%mb) Va = 5.20%
- Optimum bitumen content (OBC) = $(5.50 + 5.50 + 5.20)/3 = 5.40\%$

At the recommended (used) asphalt content the following Characteristics are met:

Table (4.4): Recommended to select the optimum asphalt bitumen content (MPWH,2004)

	Units	Min Specified	Max Specified
Stability	Kg	900	***
Flow	mm	2.0	4.0
Bulk Specific Gravity		2.300	***
Va	%	3.0	5.0
VFB	%	60.0	75.0
VMA	%	14.0	***
Stiffness	Kg/mm	500.0	***

4.4 Effect of adding Glass Fiber on the mechanical properties of asphalt mix

4.4.1 Phase (I): Conventional asphalt mix

The mechanical properties of asphalt mix prepared with OBC (5.40 %) without addition of Glass Fiber is shown in Table (4.5).

Table (4.5): Mechanical properties of asphalt mix without addition of Glass Fiber

Bitumen %(by total weight)	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
5.4	1	1726.1	2.7	2.326	4.0	16.2	75.2	639.3
	2	1738.8	2.6	2.322	4.2	16.4	74.6	668.8
	3	1721.0	2.7	2.320	4.2	16.4	74.2	637.4
	Average	**1728.7**	**2.7**	**2.323**	**4.1**	**16.3**	**74.6**	**648.5**

4.4.2 Phase (II): Asphalt mix with Glass Fiber

According to procedure previously illustrated in Chapter (3), 18 samples were prepared at OBC to evaluate the effect of adding Glass Fiber to asphalt mixture samples by considering 6 proportions of Glass Fiber (0.1, 0.2, 0.4, 0.6, 0.8 and 1% by the weight of total mix). Table (4.6) shows the mechanical properties of asphalt mix using different percentages of Glass Fiber (By weight of total mix) at the OBC. Further details are presented in Appendix (D).

Table (4.6): Mechanical properties of asphalt mix with Glass Fiber

Glass Fiber % (by total weight of mix)	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
0.1	1	1685.4	2.9	2.319	4.7	16.8	63.9	581.2
	2	1677.7	2.9	2.319	4.6	16.8	63.2	578.5
	3	1693.0	3	2.318	4.7	16.8	63.8	564.3
	Average	**1685.4**	**2.9**	**2.318**	**4.7**	**16.8**	**63.6**	**574.7**
0.2	1	1626.8	3.2	2.316	4.5	16.6	73.0	508.4
	2	1621.7	3.1	2.315	4.5	16.6	73.0	523.1
	3	1606.4	3.1	2.313	4.6	16.7	72.6	518.2
	Average	**1618.3**	**3.1**	**2.315**	**4.5**	**16.6**	**72.9**	**516.6**
0.4	1	1642.1	3.4	2.309	4.5	16.6	72.8	483.0
	2	1593.6	3.5	2.309	4.5	16.6	72.8	455.3
	3	1606.4	3.4	2.308	4.6	16.7	72.6	472.5
	Average	**1614.0**	**3.4**	**2.308**	**4.5**	**16.6**	**72.7**	**470.3**
0.6	1	1557.9	3.7	2.303	3.9	16.0	75.4	421.1
	2	1540.1	3.5	2.301	4	16.1	75.0	440.0
	3	1550.3	3.8	2.301	4	16.1	75.1	408.0
	Average	**1549.4**	**3.7**	**2.301**	**4**	**16.0**	**75.2**	**423.0**
0.8	1	1563.0	4	2.292	3.7	15.7	76.4	390.8
	2	1535.0	4.1	2.294	3.6	15.7	76.8	374.4
	3	1555.4	4	2.292	3.7	15.7	76.3	388.8
	Average	**1551.1**	**4**	**2.293**	**3.7**	**15.7**	**76.5**	**384.7**
1	1	1463.5	4.2	2.276	3.8	15.7	76.1	348.5
	2	1453.3	4.4	2.274	3.9	15.8	75.6	330.3
	3	1483.9	4.3	2.277	3.7	15.6	76.3	345.1
	Average	**1466.9**	**4.3**	**2.276**	**3.8**	**15.7**	**76.0**	**341.3**

4.4.2.1 Stability – Glass Fiber content relationship

Generally, the stability of modified asphalt mixes is lower than the conventional asphalt mix (1728.7 kg). The maximum stability value is found nearly (1685.4 kg) at Glass Fiber content around (0.1%). Figure (4.8) shows that the stability of modified asphalt mix decreases as the Glass Fiber content increases.

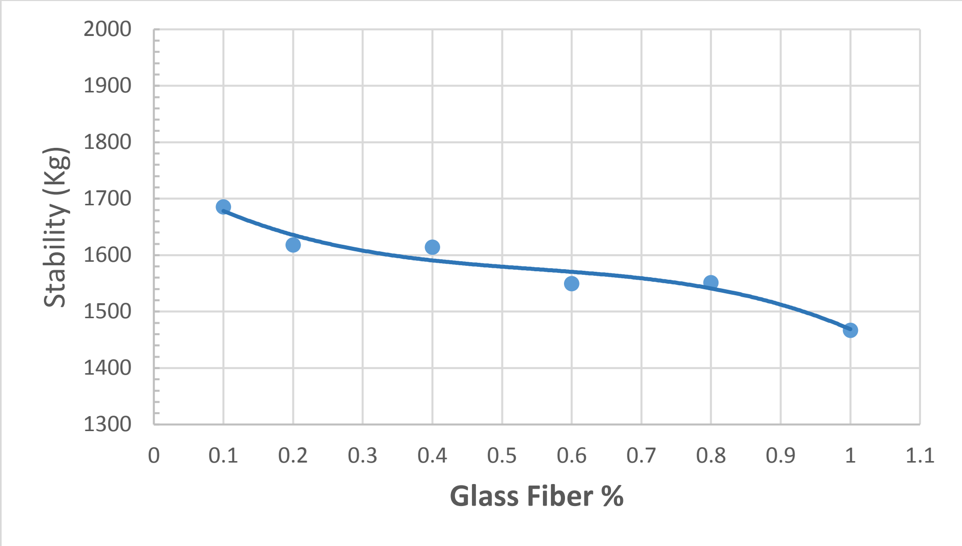

Figure (4.8): Asphalt mix Stability – Glass Fiber content relationship

4.4.2.2 Flow – Glass Fiber content relationship

Generally, the flow of modified asphalt mix is higher than the conventional asphalt mix (2.7 mm). Figure (4.9) shows that the flow increases continuously as the Glass Fiber modifier content increase. The flow value extends from (2.9mm) till it reach (4.3mm) at Glass Fiber content (1%).

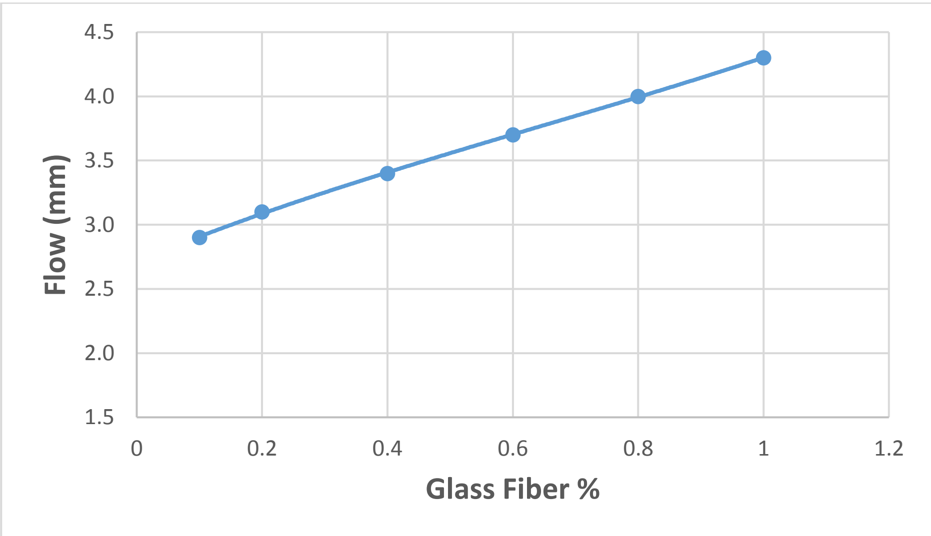

Figure (4.9): Asphalt mix flow – Glass Fiber content relationship

4.4.2.3 Bulk density – Glass Fiber content relationship

The bulk density of WPB modified asphalt mix is lower than the conventional asphalt mix (2.323 g/cm3). The general trend shows that the bulk density decreases as the Glass Fiber content increase. The maximum bulk density is (2.318 g/cm3) at Glass Fiber content (0.1%) and the minimum bulk density is (2.276 g/cm3) at Glass Fiber content (1%). This decrease of bulk density can be explained to be as a result of the low density of added fiber. Figure (4.10) displays the bulk density results for different glass fiber contents.

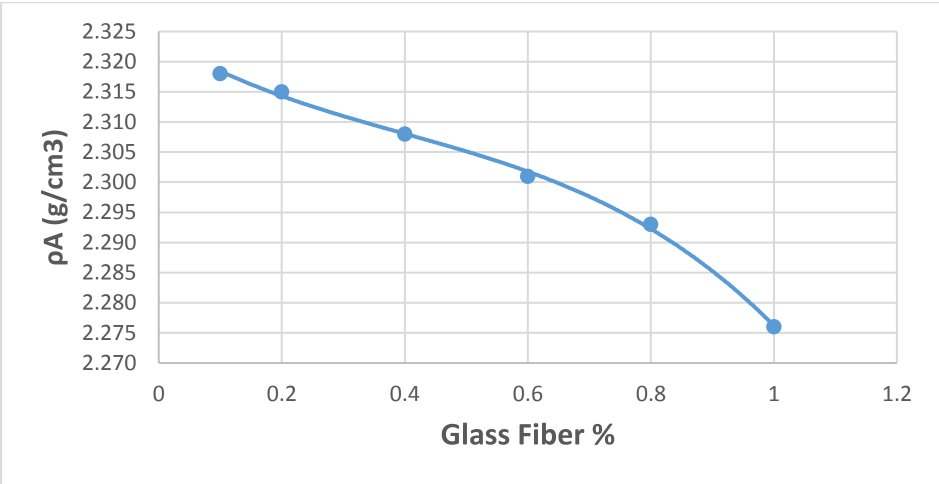

Figure (4.10): Asphalt mix bulk density – Glass Fiber content relationship

4.4.2.4 Air voids (Va) – Glass Fiber content relationship

In general, the air voids proportion of modified asphalt mixes is higher than conventional asphalt mix (4.1 %). Va % of modified asphalt mixes decreases gradually as the Glass Fiber content increase till it reaches the lowest Va% value at 1% Glass Fiber content. Generally modified asphalt mixes have Va% content within specifications range. Figure (4.11) displays the (Va%) results for different glass fiber contents.

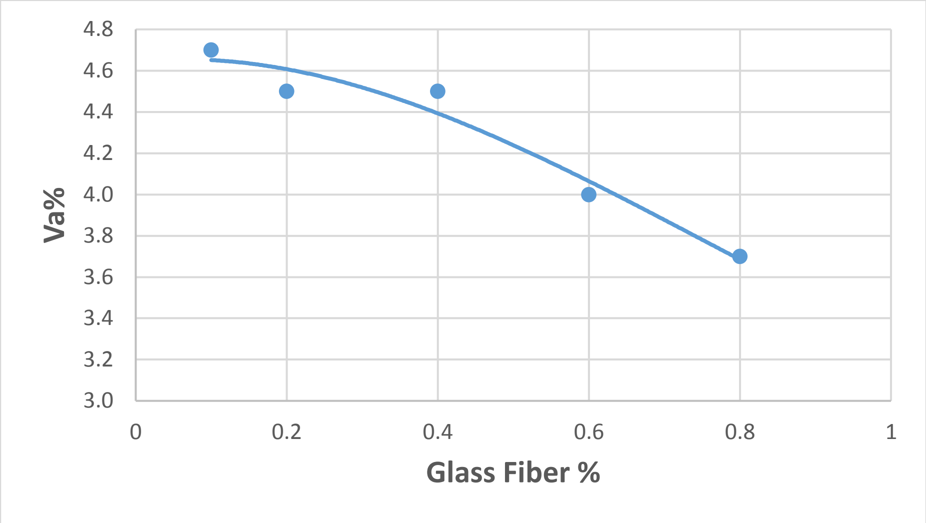

Figure (4.11): Asphalt mix air voids – Glass Fiber content relationship

4.4.2.5 Voids in mineral aggregates (VMA) – WPB content relationship

The voids in mineral aggregates percentage VMA% for asphalt mix is affected by air voids in asphalt mix Va and voids filled with bitumen. VMA % of modified asphalt mixes decreases as the Glass Fiber content increase, it reaches (15.7%) at Glass Fiber content (1%). Figure (4.12) displays the (VMA%) results for different glass fiber contents.

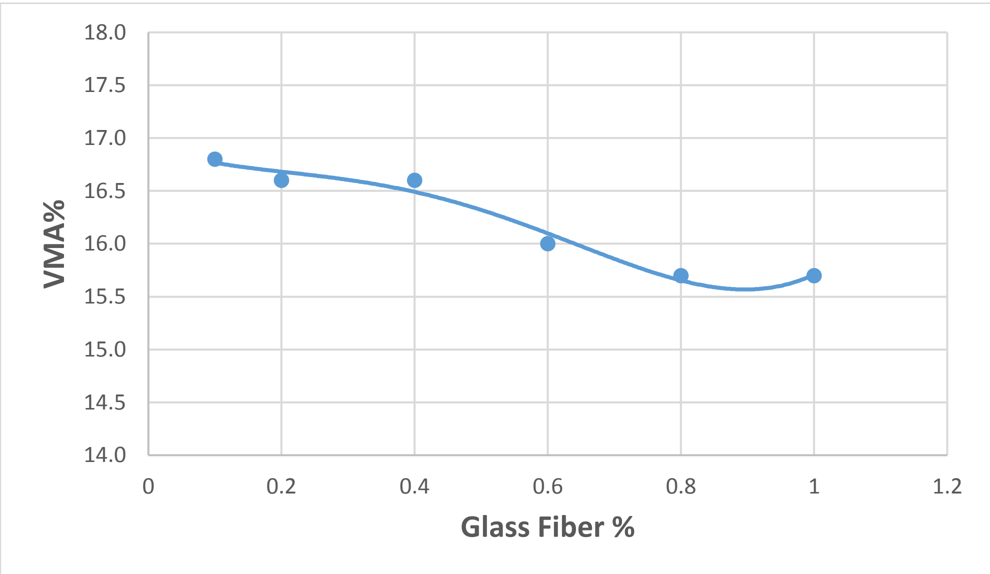

Figure (4.12): Asphalt mix voids of mineral aggregates (VMA) – Glass Fiber content relationship

4.4.3 Optimum modifier content

A set of controls is recommended in order to obtain the optimum modifier content that produce an asphalt mix with the best mechanical properties (Jendia, 2000). Asphalt mix with optimum modifier content satisfies the following:

- Maximum stability
- Maximum bulk density
- Va % within the allowed range of specifications.

Figures (4.8, 4.10 and 4.11) are utilized to find Glass Fiber percentages which satisfy these three controls. The Glass Fiber percentages which satisfy controls are summarized in Table (4.7).

Table (4.7): Summary of controls to obtain optimum modifier content

Property	Glass Fiber (By total mix Weight)
Maximum stability	0.1 %
Maximum bulk density	0.1 %
Va % within the allowed range of specifications (at the median)	0.6 %

The Optimum Glass Fiber content is the average of the previous three Glass Fiber contents.

Optimum Glass Fiber content (By total mix weight) = $\frac{0.1+0.1+0.6}{3}$ ~ = 0.27 %

4.4.4 Evaluation of Glass Fiber modified asphalt mix

The mechanical properties of Glass Fiber modified asphalt mix at the optimum Glass Fiber content (0.27 % by the total weight of mix) is shown in Table (4.8).

Table (4.8): Properties of Glass Fiber modified asphalt mix with local specifications

Property	Units	(0.27 %) modified asphalt mix	Min Specified	Max Specified
Stability	Kg	1615	900	***
Flow	mm	3.15	2.0	4.0
Bulk Specific Gravity		2.312	2.300	***
Va	%	4.55	3.0	5.0
VFB	%	72.9	60.0	75.0
VMA	%	16.6	14.0	***
Stiffness	Kg/mm	512.7	500.0	***

It's clearly shown that adding Glass Fiber to the asphalt mix (0.27 % by the total weight of mix) meet the local and international standards requirements as shown in table (4.8).
The results showed that the addition of Glass Fiber will be beneficial in improving some of the main properties of the flexible pavement such as flow and voids.
As mentioned earlier in the literature review, adding Glass fiber to the asphalt mix enhances material strength and fatigue characteristics while increasing ductility. The tensile strength and related properties of mixtures containing fibers was found to be improved but locally we couldn’t do more tests which are required to prove this.

Conclusions
and
Recommendations

5.1 Conclusions

Based on experimental work results for Glass Fiber modified asphalt mixtures, the following conclusions can be drawn:

a. Glass Fiber can be conveniently used as a modifier for asphalt mixes for improved performance of asphalt mix.
b. The optimum amount of Glass Fiber to be added as a modifier of asphalt mix was found to be (0.27 %) by the total weight of asphalt mix.
c. Asphalt mix modified with Glass Fiber meets the local and international standards requirements.
d. Asphalt mix modified with Glass Fiber exhibit higher flow value as the Glass Fiber percentage increased. However, the stiffness of the modified mix decreased .

5.2 Recommendations

a. It is recommended to use Glass Fiber content at 0.27% by the total weight of asphalt mix to improve performance of asphalt mix.
b. It is required to establish a local Palestinian specification for usage of fibers and modifiers in asphalt mixes.

5.3 Future Studies

a. Further researches are recommended to study the effect of adding other Fiber types on the asphalt mechanical properties.
b. Further researches are recommended to conduct this study using different bitumen percentages and bitumen types.
c. Further researches are recommended to conduct this study using Super Pave Method rather than Marshall.

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Appendices

Appendix A

Appendix (A)

Combined Aggregates

Table A.1: Suggested percentages for wearing course aggregate mix

Aggregate mix	Grain size (mm)										Suggested percents for final agg. Mix
	0.075	**0.18**	**0.3**	**0.6**	**2.36**	**4.75**	**9.5**	**12.5**	**19**	**25**	
Filler	80.03	2.33	9.33	8.16	0.15	0.00	0.00	0.00	0.00	0.00	**3**
	2.40	0.07	0.28	0.24	0.00	0.00	0.00	0.00	0.00	0.00	
Trabia (0/4.75)	7.64	7.20	9.87	19.94	50.00	2.80	2.55	0.00	0.00	0.00	**45**
	3.44	3.24	4.44	8.97	22.50	1.26	1.15	0.00	0.00	0.00	
Simsimia (0/9.5)	1.48	0.60	0.40	0.63	8.96	39.02	48.91	0.00	0.00	0.00	**30**
	0.44	0.18	0.12	0.19	2.69	11.71	14.67	0.00	0.00	0.00	
Adasia (0/12.5)	0.53	0.07	0.00	0.00	0.14	0.69	18.96	49.76	29.86	0.00	**22**
	0.12	0.02	0.00	0.00	0.03	0.15	4.17	10.95	6.57	0.00	
Sum	6.40	3.51	4.84	9.41	25.22	13.12	19.99	10.95	6.57	0.00	**100**
∑% passing	6.4	9.9	14.7	24.2	49.4	62.5	82.5	93.4	100.0	100.0	
Sieve size (mm)	0.075	0.15	0.3	0.85	2.36	4.75	9.5	12.5	19	25	
Wearing 0/12.5 (Min)	2	3	5	16	28	44	67	90	100	100	**ASTM Specifications D3515 – D5**
(Max)	10	15	21	39	58	74	88	100	100	100	

Table A.2: Proportion of each aggregate material from proposed mix

Aggregate Type	% by Total Weight of Aggregates
Adasia Aggregate	22.0 %
Simsimia Aggregate	30.0 %
Fine Aggregate	45.0 %
Filler	3.0 %
Total	100.0 %

Table A.3: Mix gradations of aggregates

Sieve No.	Adasia Aggregate	Simsimia Aggregate	Fine Aggregate	Filler
3/4"	100.00	100.00	100.00	100.00
1/2"	70.14	100.00	100.00	100.00
3/8"	20.38	100.00	100.00	100.00
#4	1.42	51.09	97.45	100.00
#8	0.73	12.08	94.65	100.00
#30	0.60	3.11	44.65	99.85
# 50	0.60	2.49	24.71	91.69
# 80	0.60	2.08	14.84	82.36
#200	0.53	1.48	7.64	80.03

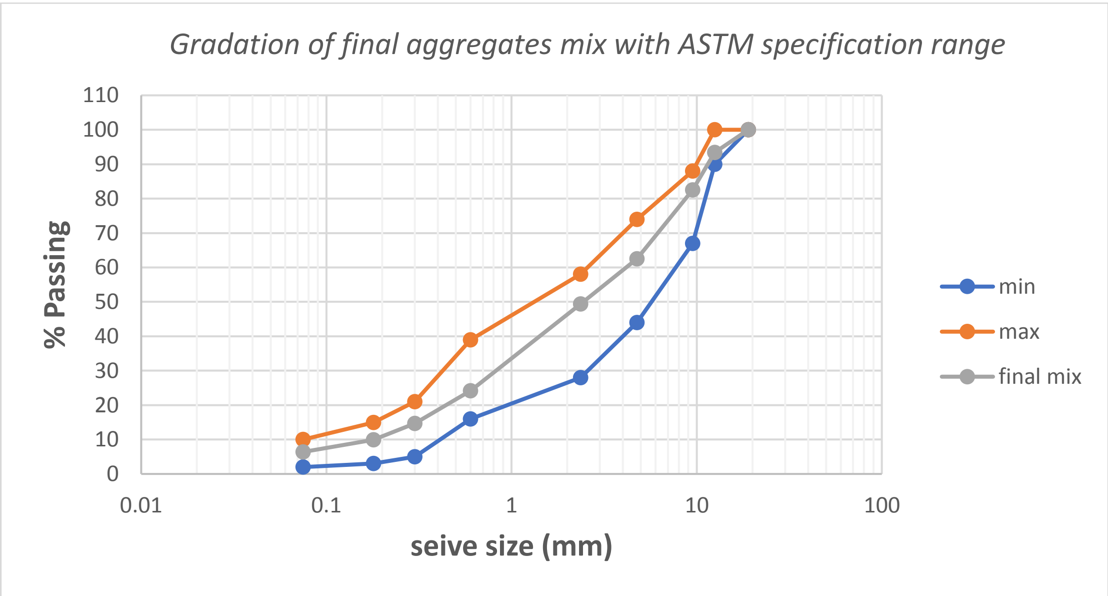

Figure 0A.1: Job Mix Gradation

Table A.4: Gradation of proposed mix with ASTM specifications limits

Sieve No.	Sieve size (mm)	% Passing	ASTM D5315 specification limits (%)	
			Min	Max
3/4"	**19**	100.0	100	100
1/2"	**12.5**	93.4	90	100
3/8"	**9.5**	82.5	67	88
#4	**4.75**	62.5	44	74
#8	**2.36**	49.4	28	58
#30	**0.6**	24.2	16	39
# 50	**0.3**	14.7	5	21
# 80	**0.18**	9.9	3	15
#200	**0.075**	6.4	2	10

Appendix B

Appendix (B)
Calculations of physical properties of aggregates

1- Specific gravity and absorption (ASTM C128-12)

- **Coarse aggregate (Adasia)**

A= Weight of oven-dry sample in air, grams = 2877 gr

B=weight of saturated - surface -dry sample in air = 2930 gr

C= weight of saturated sample in water = 1782.5 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{2877}{2930-1782.5}$=2.507
- SSD S.G =$\frac{B}{B-C} = \frac{2930}{2930-1782.5}$ =2.553
- Apparent S.G =$\frac{A}{A-C} = \frac{2877}{2877-1782.5}$ =2.628
- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.507+2.628}{2} = 2.567$
- Absorption = $\frac{2930-2877}{2877} * 100 = 1.84\%$

- **Coarse Aggregate (Simsimia)**

A= Weight of oven-dry sample in air, grams = 3070 gr

B=weight of saturated - surface -dry sample in air = 3130 gr

C= weight of saturated sample in water = 1935 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{3070}{3130-1935}$=2.569
- SSD S.G =$\frac{B}{B-C} = \frac{3130}{3130-1935}$ =2.619
- Apparent S.G =$\frac{A}{A-C} = \frac{3070}{3070-1935}$ =2.704
- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.569+2.704}{2} = 2.636$
- Absorption = $\frac{3130-3070}{3070} * 100 = 1.95\%$

2- <u>Pycnometer method</u>

- **Fine Aggregate**

(W_{P+W}) = Weight of Pycnometer filled with water = 1816.5 gr

(W_S) = Weight of the Fine sample dry = 340.7 gr

(W_{S+P+W}) =Weight of Pycnometer filled with water and the Fine sample= 2026 gr

- Specific Gravity $= \frac{340.7*1.02}{(340.7)-(2026-1816.5)}$= 2.649

- **Filler**

(W_{P+W}) = Weight of Pycnometer filled with water = 1816.5 gr

(W_S) = Weight of the Fine sample dry = 127 gr

(W_{S+P+W}) =Weight of Pycnometer filled with water and the Fine sample = 1894 gr

- Specific Gravity $= \frac{127*1.02}{(127)-(1894-1816.5}$=2.617

Appendix C

Appendix (C)
The Inputs of the Binder Course Job Mixes

Used Equations to calculate the mechanical properties of asphalt mix

$$V_a = \frac{\rho_{bit} - \rho_A}{\rho_{bit}}$$

$$V_b = m_b \frac{\rho_A}{d_{25}} \%$$

%VMA = $V_a + V_b$

%VFB = $\frac{V_b}{VMA} * 100$

V_a**:** Air voids contents in total mix.

V_b**:** Percent bitumen volume.

m_b **:** Percent of Bitumen.

ρ_A : Density of compacted mix (g/cm^3).

d_{25} : Density of Bitumen at 25°C.

ρ_{bit} : Max. Theoretical density.

VMA: Voids in mineral Aggregates.

VFB: Voids filled with bitumen

Marshal tests results

- No. of blows on each side: 75 blow
- Mixing temp: 160° C

Table C.1: Marshal Test results for 4.5% bitumen content

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1195.0	1199.5	1191.0	1195.2
Weight in water (g)	680.0	681.5	677.0	679.5
Weight in air (S.S.D) (g)	1196.5	1200.5	1192.0	1196.3
Volume (cm3)	516.5	519.0	515.0	516.8
Bulk dry specific gravity	2.314	2.311	2.313	2.312
Max specific gravity	2.449	2.449	2.449	2.449
Marshal stability reading (×5 div)	620.0	608.0	618.0	615.3
Stability correction factor	1.00	1.00	1.00	1.00
Corrected stability (kg)	1596.2	1565.6	1591.1	1584.3
Plastic Flow (mm)	2.10	2.20	2.10	2.13
Stiffness (kg/mm)	760.1	711.6	757.7	743.1
Air voids content in total mix Va (%)	5.5	5.6	5.6	5.6
Voids of mineral agg. (V.M.A)%	15.6	15.7	15.7	15.7
Voids filled with bitumen (V.F.B)%	64.6%	64.2%	64.5%	64.4%

- No. of blows on each side: 75 blow
- Mixing temp: 160° C

Table C.2: Marshal Test results for 5.0% bitumen content

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1192.5	1188.5	1191.0	1190.7
Weight in water (g)	680.5	678.0	678.5	679.0
Weight in air (S.S.D) (g)	1194.0	1190.0	1191.5	1191.8
Volume (cm3)	513.5	512.0	513.0	512.8
Bulk dry specific gravity	2.322	2.321	2.323	2.322
Max specific gravity	2.430	2.430	2.430	2.430
Marshal stability reading (×5 div)	658.0	662.0	660.0	660.0
Stability correction factor	1.00	1.00	1.00	1.00
Corrected stability (kg)	1693.0	1703.2	1698.1	1698.1
Plastic Flow (mm)	2.40	2.50	2.50	2.5
Stiffness (kg/mm)	705.4	681.3	679.2	688.7
Air voids content in total mix Va (%)	4.4	4.5	4.4	4.4
Voids of mineral agg. (V.M.A)%	15.7	15.7	15.7	15.7
Voids filled with bitumen (V.F.B)%	71.8%	71.5%	72.0%	71.7%

- No. of blows on each side: 75 blow
- Mixing temp: 160° C

Table C.3: Marshal Test results for 5.5% bitumen content

Description	**Sample No.**			**Average**
	1	**2**	**3**	
Weight in air (g)	1179.0	1192.0	1195.5	1188.8
Weight in water (g)	678.5	686.0	686.5	683.7
Weight in air (S.S.D) (g)	1185.0	1198.0	1200.5	1194.5
Volume (cm3)	506.5	512.0	514.0	510.8
Bulk dry specific gravity	2.328	2.328	2.326	2.327
Max specific gravity	2.414	2.414	2.414	2.414
Marshal stability reading (×5 div)	695.0	706.0	702.0	701.0
Stability correction factor	1.04	1.00	1.00	1.01
Corrected stability (kg)	1858.7	1815.2	1805.0	1826.3
Plastic Flow (mm)	2.80	2.90	2.80	2.8
Stiffness (kg/mm)	663.8	625.9	644.6	644.8
Air voids content in total mix Va (%)	3.6	3.6	3.7	3.6
Voids of mineral agg. (V.M.A)%	16.0	16.0	16.1	16.0
Voids filled with bitumen (V.F.B)%	77.7%	77.8%	77.3%	77.6%

- No. of blows on each side: 75 blow
- Mixing temp: 160° C

Table C0.4: Marshal Test results for 6.0% bitumen content

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1195.0	1171.5	1164.0	1176.8
Weight in water (g)	682.5	669.0	666.0	672.5
Weight in air (S.S.D) (g)	1198.5	1175.0	1168.0	1180.5
Volume (cm3)	516.0	506.0	502.0	508.0
Bulk dry specific gravity	2.316	2.315	2.319	2.317
Max specific gravity	2.391	2.391	2.391	2.391
Marshal stability reading (×5 div)	659.0	654.0	653.0	655.3
Stability correction factor	1.00	1.04	1.04	1.03
Corrected stability (kg)	1695.6	1750.1	1747.5	1731.1
Plastic Flow (mm)	3.10	3.10	3.00	3.07
Stiffness (kg/mm)	547.0	564.6	582.5	564.7
Air voids content in total mix Va (%)	3.1	3.2	3.0	3.1
Voids of mineral agg. (V.M.A)%	16.6	16.7	16.5	16.6
Voids filled with bitumen (V.F.B)%	81.1%	81.0%	81.7%	81.3%

Table C.5: Calculations of the Max. Theoretical density

Aggregate type	%	S.G
Adasia Aggregate	22.0%	2.553
Simsimia Aggregate	30.0%	2.619
Fine Aggregate	45.0%	2.649
Filler	3.0%	2.617
G_{sb}		2.618
$p_{bitumen}$		1.03
p_{mix}	**bitumen %**	**Max density**
	4.5	2.445
	5.0	2.428
	5.5	2.410
	6.0	2.393

Appendix D

Appendix (D)
Glass Fiber Modified asphalt mix tests results

Marshal tests results

Conventional mix

Glass Fiber = 0 %

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1193.0	1186.5	1198.5	1192.7
Weight in water (g)	679.5	675.5	681.5	678.8
Weight in air (S.S.D) (g)	1192.5	1186.5	1198.0	1192.3
Volume (cm3)	513.0	511.0	516.5	513.5
Bulk dry specific gravity	2.326	2.322	2.320	2.323
Max specific gravity	2.423	2.423	2.423	2.423
Marshal stability reading (×5 div)	671.0	676.0	669.0	672.0
Stability correction factor	1.00	1.00	1.00	1.00
Corrected stability (kg)	1726.1	1738.8	1721.0	1728.7
Plastic Flow (mm)	2.70	2.60	2.70	2.7
Stiffness (kg/mm)	639.3	668.8	637.4	648.5
Air voids content in total mix Va (%)	4.0	4.2	4.2	4.1
Voids of mineral agg. (V.M.A) %	16.2	16.4	16.4	16.3
Voids filled with bitumen (V.F.B) %	75.2%	74.6%	74.2%	74.6%

Marshal tests results

Glass Fiber = 0.1 % (By the total weight of mix)

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1201	1196.5	1195	1198
Weight in water (g)	684	681.5	680.5	682
Weight in air (S.S.D) (g)	1202	1197.5	1196	1199
Volume (cm3)	518	516	515.5	516.5
Bulk dry specific gravity	2.319	2.319	2.318	2.318
Max specific gravity	2.432	2.432	2.432	2.432
Marshal stability reading (×5 div)	655	652	658	655
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1685.4	1677.7	1693.0	1685.4
Plastic Flow (mm)	2.9	2.9	3	2.9
Stiffness (kg/mm)	581.2	578.5	564.3	574.7
Air voids content in total mix Va (%)	4.7	4.6	4.7	4.7
Voids of mineral agg. (V.M.A) %	16.8	16.8	16.8	16.8
Voids filled with bitumen (V.F.B) %	72.3%	72.4%	72.3%	72.3

Marshal tests results

Glass Fiber = 0.2 % (By the total weight of mix)

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1192.5	1200.5	1159	1184
Weight in water (g)	678.5	683	659	674
Weight in air (S.S.D) (g)	1193.5	1201.5	1160	1185
Volume (cm3)	515	518.5	501	511.5
Bulk dry specific gravity	2.316	2.315	2.313	2.315
Max specific gravity	2.424	2.424	2.424	2.424
Marshal stability reading (×5 div)	632	630	624	629
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1626.8	1621.7	1606.4	1618.3
Plastic Flow (mm)	3.2	3.1	3.1	3.1
Stiffness (kg/mm)	508.4	523.1	518.2	516.6
Air voids content in total mix Va (%)	4.5	4.5	4.6	4.5
Voids of mineral agg. (V.M.A) %	16.6	16.6	16.7	16.6
Voids filled with bitumen (V.F.B) %	73.0%	73.0%	72.6%	72.9

Marshal tests results

Glass Fiber = 0.4 % (By the total weight of mix)

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1199.5	1181	1196.5	1192
Weight in water (g)	681.5	671	679.5	677
Weight in air (S.S.D) (g)	1201	1182.5	1198	1194
Volume (cm3)	519.5	511.5	518.5	516.5
Bulk dry specific gravity	2.309	2.309	2.308	2.308
Max specific gravity	2.418	2.418	2.418	2.418
Marshal stability reading (×5 div)	638	619	624	627
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1642.1	1593.6	1606.4	1614.0
Plastic Flow (mm)	3.4	3.5	3.4	3.4
Stiffness (kg/mm)	483.0	455.3	472.5	470.3
Air voids content in total mix Va (%)	4.5	4.5	4.6	4.5
Voids of mineral agg. (V.M.A) %	16.6	16.6	16.7	16.6
Voids filled with bitumen (V.F.B) %	72.8%	72.8%	72.6%	72.7

Marshal tests results

Glass Fiber = 0.6 % (By the total weight of mix)

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1198.5	1194	1195.5	1196
Weight in water (g)	679.5	676	677.5	678
Weight in air (S.S.D) (g)	1200	1195	1197	1197
Volume (cm3)	520.5	519	519.5	519.7
Bulk dry specific gravity	2.303	2.301	2.301	2.301
Max specific gravity	2.397	2.397	2.397	2.397
Marshal stability reading (×5 div)	605	598	602	602
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1557.9	1540.1	1550.3	1549.4
Plastic Flow (mm)	3.7	3.5	3.8	3.7
Stiffness (kg/mm)	421.1	440.0	408.0	423.0
Air voids content in total mix Va (%)	3.9	4.0	4.0	4.0
Voids of mineral agg. (V.M.A) %	16.0	16.1	16.1	16.0
Voids filled with bitumen (V.F.B) %	75.4%	75.0%	75.1%	75.2

Marshal tests results

Glass Fiber = 0.8 % (By the total weight of mix)

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1187.5	1185	1193	1189
Weight in water (g)	671	670	674	672
Weight in air (S.S.D) (g)	1189	1186.5	1194.5	1190
Volume (cm3)	518	516.5	520.5	518.3
Bulk dry specific gravity	2.292	2.294	2.292	2.293
Max specific gravity	2.381	2.381	2.381	2.381
Marshal stability reading (×5 div)	607	596	604	602
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1563.0	1535.0	1555.4	1551.1
Plastic Flow (mm)	4	4.1	4	4.0
Stiffness (kg/mm)	390.8	374.4	388.8	384.7
Air voids content in total mix Va (%)	3.7	3.6	3.7	3.7
Voids of mineral agg. (V.M.A) %	15.7	15.7	15.7	15.7
Voids filled with bitumen (V.F.B) %	76.4%	76.8%	76.3%	76.5

Marshal tests results

Glass Fiber = 1.0 % (By the total weight of mix)

- No. of blows on each side: 75 blow
- 1/2" wearing course mix
- Bitumen = 5.4 % (By total weight)
- Mixing temp.: 160 C

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1196	1192.5	1200	1196
Weight in water (g)	672	669	674	672
Weight in air (S.S.D) (g)	1197.5	1193.5	1201	1197
Volume (cm3)	525.5	524.5	527	525.7
Bulk dry specific gravity	2.276	2.274	2.277	2.276
Max specific gravity	2.365	2.365	2.365	2.365
Marshal stability reading (×5 div)	568	564	576	569
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1463.5	1453.3	1483.9	1466.9
Plastic Flow (mm)	4.2	4.4	4.3	4.3
Stiffness (kg/mm)	348.5	330.3	345.1	341.3
Air voids content in total mix Va (%)	3.8	3.9	3.7	3.8
Voids of mineral agg. (V.M.A) %	15.7	15.8	15.6	15.7
Voids filled with bitumen (V.F.B) %	76.1%	75.6%	76.3%	76.0

Appendix E

Appendix (E)
Photos

Figure E.1: Used Glass fiber

Figure E.2: Job mix marshal samples

Figure E.3: Modified aAsphalt mixture samples in oven

Figure E.4: preparing of marshal samples

Figure E.5: Seive analysis of aggregates

Figure E.6: Modified aAsphalt samples

Figure 0E.7: Asphalt mix during compaction

Figure 0E.8: Aggregate types