The Islamic University of Gaza
Deanship of Research and Graduate Studies
Faculty of Engineering
Master of Civil Engineering
Infrastructure Management

الجامعـــــــة الإســـلاميـة بغـزة
عمادة البحث العلمي والدراسات العليا
كـليـــــــــــة الهندســــــــــــة
ماجستيـــــر الهندســـة المدنيـــــة
إدارة البنيـــــــــة التحتيـــــــة

Studying the Effect of Adding Crumb Rubber on the Mechanical Properties of Asphalt Mixtures (Wearing Course Layer)

دراسة تأثير إضافة فتات المطاط على الخواص الميكانيكية للخليط الأسفلتي (الطبقة السطحية)

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

Dec/ 2017

إقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

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The Islamic University of Gaza
عمادة البحث العلمي والدراسات العليا
هاتف داخلي: 1150

الرقم ج س غ/35/ Ref
التاريخ 2018/09/03م Date

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والله ولي التوفيق،

توقيع الطالب

هادي الحداد

إدارة المكتبة المركزية

Abstract

The rising number of motor vehicles in industrialized and developing nations generates millions of used tires annually**.** About 1.4 billion tires are sold globally each year. These tires are among the biggest and most problematic sources of waste due to the large production volume and limited durability.

Many research projects and field applications have proven that the addition of a crumb rubber modifier to asphalt/bitumen to be an effective method of improving the performance grade of asphalt and enhance its properties. This also provides an environmental-friendly option for the disposal of the scrap tires.

In this research, crumb rubber is used to investigate the potential to enhance the properties of asphalt mixture. The study aims, among other things, to investigate the effect of adding different percentages of crumb rubber on the properties of asphalt mix in comparison with local and international requirements. The study also aims to indentify the optimum percentage in weight of crumb rubber to be added in the hot mix asphalt.

Crumb Rubber (5.0 mm) 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, (30) samples were prepared, 12 samples were used to determine the OBC and the remaining were used to investigate the effects adding different Crumb Rubber percentages to asphalt mix. The OBC was 5.4 % by weight of asphalt mix. Four percentages of Crumb Rubber by weight of bitumen as aggregate of mix were tested (10, 15, 20, 25 and 30%), besides testing of ordinary asphalt mix. Tests include the determination of stability, bulk density, flow and air voids.

Results indicated that Crumb Rubber can be conveniently used as a modifier for asphalt mixes to improve performance of some asphalt mix properties. Crumb Rubber content of 17 % by weight of bitumen is recommended as the optimum Crumb Rubber content.

Asphalt mix modified with 17 % Crumb Rubber by weight of bitumen meet the requirements of local and international specifications.

the study recommends that further studies are needed, and that required to establish Palestinian standard for modified asphalt mixes.

ملخص البحث

زيادة عدد المركبات في الطرقات في الدول الصناعية والمتقدمة يؤدي الى ملايين الإطارات المهترئة كل عام. تقريبا 1.4 بليون إطار تباع حول العالم سنوياً. هذه الإطارات تعد من بين أكبر وأعقد مصادر النفايات نظراً لحجمها الكبير وديمومتها.

إن إضافة فتات المطاط المطحون إلى الاسفلت تمت مناقشته ودراسته في العديد من مشاريع الأبحاث ومجالات التطبيق ليكون فعال ومفيد في زيادة درجة أداء الاسفلت وتحسين خواصه. كما أنها تعتبر حل بيئي للتخلص من بقايا الإطارات.

في هذا البحث، تم استخدام فتات المطاط للتحقق من احتمالات إسهامها في تحسين خصائص الخليط الأسفلتي (الطبقة الاسفلتية السطحية). أهداف الدراسة تشمل تحديد تأثير إضافة نسب مختلفة من فتات المطاط على خصائص الخليط الأسفلتي ومقارنتها مع متطلبات المواصفات المحلية والدولية، إلى جانب تحديد نسبة فتات المطاط المثالية لإضافتها للخليط الاسفلتي.

تم اضافة فتات المطاط بقطر (5 مم) للخليط الأسفلتي. وقد استخدمت طريقة مارشال لتصميم الخلطة الاسفلتية لتحديد محتوى البيتومين الأمثل (OBC) وكذلك لاختبار خصائص الخليط الأسفلتي المضاف إليه المطاط، تم إعداد 30 عينة، وقد استخدمت 12 عينة لتحديد محتوى البيتومين الأمثل واستخدم العدد المتبقي من العينات لدراسة آثار اضافة النسب المختلفة من فتات المطاط الى الخليط الأسفلتي . نتائج فحص عينات مارشال بينت أن محتوى البيتومين الأمثل هو 5.4% من وزن الخليط الأسفلتي. تم اختبار تأثير اضافة 5 نسب من فتات المطاط على خصائص الخليط الأسفلتي محسوبة من نسبة البيتومين حسب الوزن وهي (10 – 15 – 20– 25 – 30%)، إلى جانب اختبار خصائص الخليط الأسفلتي العادي .الاختبارات شملت تحديد درجة الثبات والانسياب والكثافة الظاهرية ونسبة فراغات الهواء في الخليط الأسفلتي.

بينت النتائج أنه يمكن استخدام فتات المطاط كمحسنات لبعض خواص الخلطات الإسفلتية (الطبقة الإسفلتية السطحية) وان إضافة فتات المطاط بنسبة 17٪ من نسبة البيتومين حسب الوزن 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، وأوصت كذلك بالعمل على إعداد مواصفة فلسطينية خاصة بالخلطات الاسفلتية المعدلة.

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 …

Acknowledgements

First and foremost, I humbly thank Allah the Greatest for granting me the willpower and patience to complete this work.

Secondly, I wish to express my sincere gratitude to my supervisor, Prof. Shafik Jendia for his patience as well as his professional and kind guidance throughout the period of laboratory work and report writing. Without his attention and excellent guidance, this report would not have been successfully completed.

I would like to express my deep thanks and gratitude to my father and my mother for their motivation, support and encouragement.

Furthermore, I extend my gratitude to my friend Eng. Fayez Erqaieq for his assistance in the laboratory work.

Moreover, I am also very thankful to the professionals at the Consulting Center For Quality & Calibration (CCQC) laboratory for lending a helping hand in the time of needs.

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List of Abbreviations Symbols

AASHTO	American Association of State Highway & Transportation Officials
AC	Asphalt Concrete
ASTM	American Society of Testing and Materials
CRM	Crumb Rubber Modifer
FF	Forta Ferro
HMA	Hot Mix Asphalt
MPWH	Ministry of Public Works & Housing
OBC	Optimum Bitumen Content
PS	Palestinian Standard
RMA	Rubberized Modified Asphalt
SSD	Saturated surface dry condition
Vb	Bitumen Volume
VFB	Voids Filled Bitumen
VMA	Voids Mineral Aggregates
WMA	Warm Mix Asphalt
d_{25}	Density of bitumen at 25°C
ρ_{bit}	Theoretical maximum density of asphalt mix
ρ_{A}	Density of Asphalt mix
$\rho_{\min}$	Density of aggregate in the blend

Chapter 1

Introduction

Chapter 1
Introduction

1.1 Background

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

Modern highway transportation has high speed, traffic density, load and channelized traffic; thus, bituminous concrete pavements are subject to various types of stress such as fatigue cracking, rutting and raveling (Remadevi, et al., 2014). One approach to improve pavement performance is to modify the asphalt binder.

Numerous research projects and field applications have proven that the addition of a Crumb Rubber Modifier (CRM) to asphalt/bitumen to be an effective method of increasing the performance grade of asphalt, decreasing susceptibility to permanent deformation, improving the high temperature properties, , as well as providing resistance against reflective cracking. It also provides an environmental-friendly option for the solving the scrap tires problem. (Yin, et al. 2013).

The use of CRM in hot-mix asphalt mixtures started back in the 1840's when natural rubber was added to bitumen to increase its engineering performance. Researchers and engineers have used shredded automobile tires in hot-mix asphalt (HMA) mixtures for pavements since the 1960's. And the use of recycled tire crumb rubber in HMA mixtures became popular in the late 1980's. (Huang, et al. 1996).

This study investigates the characteristics and properties of rubber mix asphalt, which may have the benefit of improving the performance of road pavement.

1.2 Statement of the Problem

Asphalt Bitumen is widely used in road pavement as the binder of aggregate. However, the use of asphalt is limited due to severe temperature susceptibility such as high-temperature rutting and low-temperature cracking of asphalt cement or coating layer.

Therefore, it is necessary to modify asphalt; and crumb rubber is the most widely used modifiers of asphalt in road pavement. (Zhang, et al. 2014).

With the development of cars number annually, over 500,000 scrap tires have been produced every year in the Gaza Strip (Ministry of national economy, 2014). Which constitutes an environmental burden. The question of how to deal with these scrap tires is an important issue all over the world, since in recent years, it became very popular to employ scrap tire into asphalt pavement.

This research presents an experimental investigation of rubber mix asphalt made from aggregate and rubber as parts of aggregate. It is aimed to developing and testing mechanical properties (Marshall Stability, Plastic flow, Stiffness, voids) of asphalt.

1.3 Aim and Objectives

This research aims to evaluate the characteristics of the mixture and the field performance of asphalt pavements that are constructed with five CRM applications in comparison with the control sections constructed with conventional HMA mixtures.

The objectives of this study are:

1- Produce an optimum asphalt mix consisting of aggregate, binder and tires crumbs rubber.
2- Study the behavior and properties of asphalt mix (stability, plastic flow, stiffness, voids).
3- Optimum content of CR.

1.4 Methodology

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

1- Conduct a literature review about hot mix asphalt used in wearing course.
2- Conduct a literature review about crumb rubber used in hot mix asphalt.
3- Testing the used material (bitumen, aggregate, rubber).

4- Implement laboratory tests to identify the optimum bitumen content (OBC) for the selected wearing course, using marshal mix design procedure (12 specimens).
5- Prepare the asphalt samples with different percentages of rubber "i.e. 0%, 10%, 15%, 20%, 25%, 30%" by weight of bitumen as aggregate (18 specimens).
6- Determine the properties of the asphalt mix (stability, flow, stiffness, VA %, VMA %, VFB %).
7- Analysis of results, and recommendations.

1.5 Thesis structure

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 that highlights the concept of the research. In addition, it describes the statement of problem, aims, objectives and methodology of the research.

Chapter 2: Literature review

The chapter introduces, briefly, previous literature pertaining to hot mix asphalt, crumb rubber and its utilization in asphalt mix. Moreover, previous research relevant to crumb rubber modified asphalt mixes are reviewed in the chapter.

Chapter (3) Materials and study program

This chapter covers two topics: 1) preliminary evaluation of used materials properties such as aggregates, bitumen and crumb rubber; and 2) description of experimental work conducted to achieve the study aims.

Chapter (4) Results and data analysis

The chapter highlights the results reached through three stages of laboratory work. The results of the first stage is that of blending aggregates to obtain asphalt wearing course gradation curve. The results of the second stage is the analysis of the outcomes of the

Marshal Test conducted to obtain the optimum bitumen content (OBC). The third stage was concerned with the impact of adding different percentages of crumb rubber on asphalt mix properties. And lastly, finally the optimum CRM content is obtained.

Chapter (5) Conclusion and recommendations

This chapter presents the conclusions derived from experimental results; as well as the recommendations for the present study and other studies.

Chapter 2

Literature Review

Chapter 2
Literature Review

2.1 Introduction

The growing volume of vehicles on the roads of industrialized and developing nations results in the cumulation of millions of used tires annually. About 1.4 billion tires are sold each year worldwide; and subsequently fall into the category of end of life tires. These tires are among the biggest and most problematic sources of waste due to the large volume produced and their limited durability (Lo Presti, 2013).

The use of scrap tires in asphalt mixture applications has been used in the asphalt industry for over 30 years. Although documentation of this practiceis extensive, it remains disjointed, making it difficult to make a summary of its history. However, the problem of waste tires has become so acute in recent years that warranted an urgent need to find an optimum and effective solution to use scrap tires in asphalt mixtures (Rahman, et al., 2010).

In addition, the reuse of tire rubber tires in asphalt pavements becomes more important due to the increasing cost and scarcity of resources such as aggregate and asphalt cement. The reuse the crumb rubber in an engineered manner provides technical benefits as well as potential environmental preservation (Hicks, et al., 2012).

CRM usage in asphalt mixtures increased worldwide in recent years. Numerous roads with CRM in its asphalt mixtures remain in good condition after several years of service compared with roads constructed with the conventional design. The addition of CRM to asphalt mixtures is conducted through two major processes:

- Wet process: any method that adds CRM to bitumen, and then blended well before adding the modified binder into the mix.
- Dry process: any method that adds CRM directly to the HMA mixture (Wong, et al., 2007).

2.2 Hot Mix Asphalt

Hot-Mix Asphalt (HMA) is the most commonly used paving material around the world. It's known by many different names: HMA, asphaltic concrete, bituminous concrete, plant mix, bituminous mix, and many others. HMA is a combination of two primary ingredients: asphalt binder and aggregates. Aggregates include fine and coarse materials, typically a combination of different size rock and sand. The aggregates total is approximately 95% of the total mixture weight. They are mixed with approximately 5% asphalt binder to produce HMA. The typical volume of HMA mixture is approximately 85% aggregate, 10% asphalt binder, and 5% air voids. To enhance the performance and workability of many HMA mixtures, additives are added in small amounts. Asphalt pavement is called flexible pavement because it is much more flexible than cement concrete pavement (Transportation research board committee, 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.

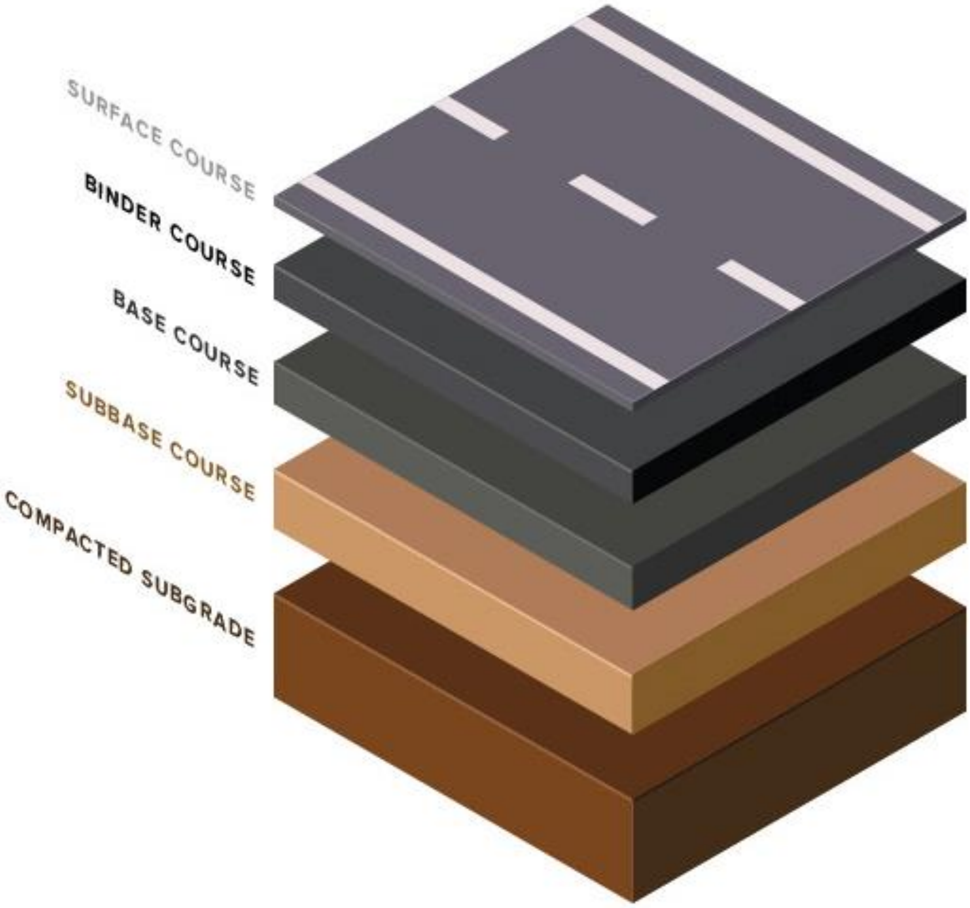

Figure (2.1): Vertical section of asphalt concrete pavement structure

2.2.1 Basic materials in hot mix asphalt

2.2.1.1 Aggregates

Aggregates are hard, inert materials such as gravel, sand, slag, crushed rock, or rock dust. Aggregates that are properly selected and graded are mixed with the asphalt binder to make 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. The performance of HMA pavements influenced significantly by the characteristics of the aggregates. HMA aggregates can be divided into three size categories: fine aggregates, coarse aggregates, and mineral filler. The 2.36 mm sieve retains coarse aggregates; while fine aggregates pass through the 2.36mm sieve and are retained by the 0.75mm sieve; and mineral dust or rock dust, an inert mineral with the consistency of flour, that is called mineral filler passes through the 0.75mm sieve. It is added to HMA to improve density and strength. It is incorporated as part of the combined aggregate gradation (Chen et al., 2009; Transportation research board committee, 2011).

2.2.1.2 Asphalt binder (bitumen)

Asphalt binder (bitumen) that holds the aggregates together in HMA is a thick, heavy residue that remains after refining crude oil. The physical properties of asphalt binder differ significantly under varying temperatures. It is fluid with a low consistency similar to that of oil at high temperatures. Generally, it has the consistency of soft rubber at room temperature. It becomes very brittle at subzero temperatures. Small percentages of polymer are added to many asphalt binders to improve their physical properties; and are called after this process "polymer modified binders. "Most of asphalt binder specification was designed to control changes in consistency with temperature (Transportation research board committee, 2011).

2.2.2 Desirable properties of asphalt mixes

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

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

Property	Definition	Examples of Mix Variables Which have Influence
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

The gradation, or particle size distribution, of an aggregate is one of its most influential characteristics. Gradation in HMA helps in determining its most important properties, such as stiffness, workability, permeability, stability, durability, fatigue resistance, and resistance to moisture damage. A sieve analysis is used to measure gradation.

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

In this thesis, we will use the gradation of ASTM D3515 (Mix Designation D-5) for wearing course and Marshal method of mix design. The graduation requirements are shown in Table (2.3) and Figure (2.3).

The American Society for Testing and Materials has standardized the Marshal Test procedures. Procedures are given by ASTM D 1559.

Table (2.2): 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

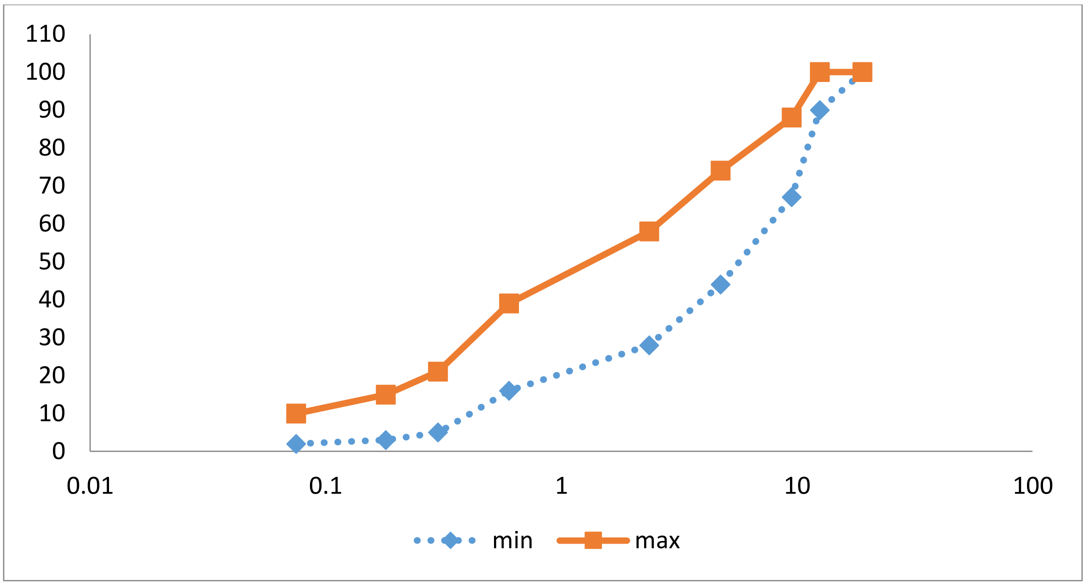

Figure (2.2): Gradation of Asphalt Wearing Course (ASTM D3515)

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 (2.3): Mechanical properties specifications for asphalt wearing course

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 Crumb Rubber modified asphalt mix

2.3.1 Introduction

Many parts of the world are giving more attention to crumb rubber in asphalt paving. This is due to the material's improved mechanical and functional performance. Furthermore, the mixture is better suited for recycling waste product (Epps, 1994) .

Scrap vehicle tires represents a global environmental problem inflated by increasing the number of vehicles. These waste tires represent a severe environmental problem due to their non-biodegradability characteristics. Commonly, the most method of waste tires disposal is either burying or burning. From the other side, waste tires contain many resources that can be used in multiple beneficial areas.

CRM is a general type of modified asphalt that contains scrap tire rubber that can be manufactured through several techniques, including the dry process and the wet process (Rahman et al., 2010).

The research and application of CRM asphalt started several decades ago in the United States, Canada and other countries. Past experience shows that CRM asphalt has higher viscosity that improves resistance to rutting. CRM also has other positive characteristics compared to the conventional method; such as reduced temperature susceptibility, better durability, lower maintenance costs, higher softening point, improved resilience, enhanced resistance to surface initiated, reduced fatigue, and reflection cracking. The improvements also include better energy efficiency and higher natural resource efficiency through the use of waste products etc (Liu, et al., 2009).

2.3.2 Rubber Modified Cement Types:

RMA is under three categories depending on the process in which they are added to the HMA. The first RMA type is a wet process-high viscosity that includes mixing. The second type is a wet process without mixing. And the third process is the dry process.

2.3.2.1 Wet Process – High Viscosity (Asphalt rubber)

The field-blended asphalt rubber (wet process) incorporates the CRM directly into the asphalt cement prior to mixing in the RMA. The temperature should be kept at 205-220 celcius when the CRM is mixed into the hot asphalt cement. After the completion of the mixture, the CRM-AC blend should be kept for 45-60 minutes at165-220 celcius to ensure the complete mixture of the blend. This CRM type mostly contains 18-22% crumb rubber, with particle sizes from 2.00-2.36mm (Sieve No. 10 to 8). This process is conducted in gap- or open- graded mixes and chip seal applications. (Hicks et al., 2012)

2.3.2.2 Wet Process – No Agitation (Terminal Blends)

The second RMA type is produced through a wet processwithout mixing the CRM with the AC. Thecrumb rubber modified particle size is under 600µm. It is mixed with hot bitumen at the terminal. It is then transported to the asphalt plant to be mixed. No agitation is required for this type of RMA to ensure the even distribution of CRM particles in the asphalt cement. This binder type usually contains a maximum of 15 to 25 % crumb rubber.

Terminal blends can be used in dense-graded, open-graded and gap-graded mixes, with dense-graded mixes being the best. They can also be used in chip seal, slurry seal and tack coat applications. (Hicks et al., 2012).

Figure (2.3) shows a photo of high viscosity vs. terminal blend rubberized binders.

Figure (2.3): High viscosity (left) vs. terminal blend (right) rubberized binders

2.3.2.3 Dry Process

The third RMA process involves the addition of the CRM in dry form. The CRM is added to the mix to replace 1-3% of the aggregate as a substitute acting more of an aggregate than an AC.

CRM use in this process does not aim to alter the asphalt cement despite some interactions that occur, such as light absorption of the asphalt into the CRM over time. The sieve size of the CRM aggregate gradations range from slightly larger than 50mm to 0.180mm (Hicks et al., 2012).

2.3.3 Rubber properties & classification:

2.3.3.1 Rubber types & classification:

Rubber is a polymer that can return to its original length, size, or shape after being deformed or stretched. . It is the example of elastomer. There are two types of rubber:

A. Natural rubber

Nature rubber is obtained from rubber trees, such as latex. The latex is coagulated with formic or acetic acid; and then squeezed.

Natural rubber in raw form is a soft, gummy, and sticky mass. It is insoluble in water, dil. Acids and alkalies. However it issoluble in chloroform, benzene, petrol, ether, and carbon disulphide. Natural rubber can absorb large amounts of water; and has low elasticity and tensile strength.

B. Synthetic rubber:

The synthetic rubber is obtained through the process of polymerizing certain organic compounds thatmay have similar properties to rubber and some other desirable properties. Most of them are obtained from butadiene derivatives and contain carbon-carbon double bonds. Some important examples are Neoprene, silicones, styrene, polyurethane, butadiene rubber (SBR) Thiokol, rubber etc. (Rubber Classification., 2017)

2.3.3.2 Rubber properties:

Table 2.6 below lists the most common values of the chemical composition of the vulcanized passenger tire rubber.

Table (2.4): The common values for the chemical composition of tire rubber (Lo Presti., 2013).

Crumb rubber	CR
Specific gravity, g/cm³	1.15
Moisture content, wt%	0.5
Ash content wt%	3.6
Carbon black content, wt%	32.7
Extract content (acetone and chloroform), wt%	7.3
Sulfur content, wt%	1.5

2.3.3.3 Recycled Tire Rubber as engineering material:

The tire is made up of three main component materials: (i) elastomeric compound, (ii) fabric and (iii) steel. The structural skeleton of the tire is made up of the fabric and steel; while the flesh of the tire is made up with the rubber that is the material of the tread, side wall, apexes, liner and shoulder wedge.

Structurally, the main components of a tire are the tread, body, side walls and the beads (Fig. 2.7).

The raised pattern in contact with the road is called the tread. The body gives the tire its shape and supports the tread. The beads hold the tire on the wheel and are metal-wire bundles covered with rubber. The main characteristics of tires include: resistance to mould, mildew, heat and humidity, retardation of bacterial development, resistance to sunlight, ultraviolet rays, some oils, many solvents, acids and other chemicals. Other physical characteristics include non-biodegradability, non-toxicity, weight, shape and elasticity. Many of these characteristics are disadvantageous in the tire's post-consumer life and create collection, storage and/or disposal problems (Lo Presti., 2013). Table 2.7 is list a comparison of passenger car and truck tires in the electric vehicles (EV).

Table (2.5): Comparison of passenger car and truck tires in the EV.

Material (contents)	Car (%)	Truck/buses (%)
Rubber/elastomers	48	43
Carbon black	22	21
Metal	15	27
Textile	5	-
Zinc oxide	1	2
Sulphur	1	1
Additives	8	6

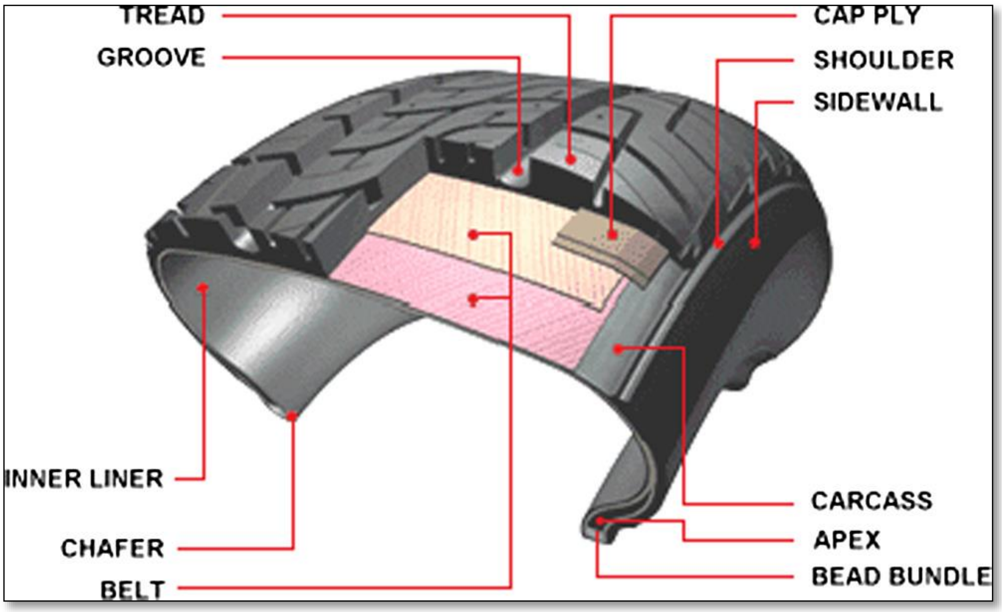

Figure (2.4): Tire structure, adapted from (Lo Presti., 2013).

2.3.3.4 Previous studies

Issa Y. (2016), said that bitumen binder properties affect the properties of pavement performance. Continuous increased consumption, result a large amount of waste rubber materials generated every year. The main objective of this paper is to study the changes in properties of asphalt mixture after adding tires rubber. In this paper, some important things of asphalt mix properties, including stability and flow are investigated. We can prepare the original sample without adding rubber for (4.5%, 5%, and 5.5% bitumen). Other samples have to be prepared by adding rubber to bitumen in wet process with 5%, 10%, and 20% by bitumen weight. The results show that the rubber–asphalt mixture properties are improved in comparison with normal asphalt pavement. It is concluded that the use of tires rubber in asphalt pavement is desirable. The suitable amount of added rubber by bitumen weight was found to be 10%.

Rodriguez-Alloza et al. (2014), He has discussed the technology of warm mix asphalt importance (WMA) as a new research topic in the pavement materials field due to a growing concern of global warming. So, this technology is being incorporated to decrease emissions and improve workability by lowering the production and compaction temperatures of asphalt mixtures without affecting its mechanical properties, the influence of WMA additives on the properties of crumb rubber modified (CRM) binders has not been identified clearly yet. The main objective of this study is to investigate the different types and quantities of WMA effect additives on the high or low temperature properties of a 20% CRM binder. Statistical analysis of variance was applied to determine the significance level of additive content and testing temperature. The results of study indicate that the additives lowering the viscosity of the CRM binders, the stiffness increased at low temperatures, therefore increasing the likelihood the pavement and asphalt binder will crack.

Fouz F. (2014), She studied the possibility of modification of asphalt mixtures used in the city of Lattakia from recycled rubber tires, rubber consuming to improved its performance which research showed that many around the world on the feasibility of their use. The experimental program included the test using bitumen (60-70) and the output of recycled rubber tire damaged caused by tourist vehicles and under the age of 5 years, knowing that she used two different aggregate grading of diameters granulated rubber crumbs and different ratios grains (0.2-0.3-0.4-0.5-5-10-15)% of bitumen. Crumbs according to specific parameters and conducted a series of experiments to determine the properties of recycled rubber modified bitumen and unmodified bituminous mixtures were designed when different ratios from rubber additives and processed the results of experiments using the Excel program. Experiments showed that with the increase in the proportion of rubber the penetration and ductility decreased and softening point rose, showed rubber-modified asphalt mixtures increase in stability and decrease in the flow rate from the mixture of others.

Jaber et al. (2014), He studied in the Islamic university of Gaza the use of recycled rubber tires as partial replacement for coarse aggregate in concrete mixed using locally available waste tires. A total of 10 mixes were prepared with a target strength of 25

Mpa. The specimens were produced with different percentage replacements of the coarse aggregate with 20, 40 and 60% of rubber aggregate using fixed percentage of Forta Ferro (FF) fibers. The results revealed that addition of (FF) fibers with tire rubbers leads to an obvious reduction of slump. The compressive strength loss were 42.75%, 60.31 and 71.73% when the replacement of tire rubber were 20%, 40% and 60% of coarse aggregate respectively. The tensile strength decreased as the percent of tire rubber increased, but with presence of (FF) fibers the tensile strength increased by 25-30%, and when the simsimya coarse aggregates replaced with 20% of rubber the tensile strength decreased by 33%. The impact strength also dropped as the present of rubber increased, but with presence of (FF) fibers, the impact strength improved.

Moreno et al. (2013), He analyzed the response of manufactured bituminous mixes with rubber to plastic deformation. therefore, a set of asphalt mixes containing different percentages of crumb rubber modifier (CRM) added by the dry process as well as the wet process were tested. It also compared the performance of a CRM mix to that of a mix made with high-performance polymer-modified bitumen. The mixes were tested with the cyclic triaxial and the wheel-tracking test. Also determining their stiffness modulus at different temperatures due to evaluate bearing capacity. The results obtained showed that for the dosages and percentages of crumb rubber used, the resistance to plastic deformation increased due to the addition of wet-process and dry-process CRM to asphalt mixes with conventional bitumen. Of course, the performance of some CRM mixes was superior to that of the mix with high-performance modified bitumen. stiffness modulus and creep modulus values also increased and improved their resistance to plastic deformations of vehicle traffic loads.

2.4 Summary of Literature Review:

It is thought that adding crumb rubber modifier to the asphalt mixtures has many beneficial properties. The previous studies showed that the properties of rubber–asphalt mixture are improved in comparison with normal asphalt pavement. Adding crumb rubber modifier increases the stability and decreases the flow rate from the mixture of others. It also increased their stiffness modulus and creep modulus values and improved their resistance to plastic deformations caused by vehicle traffic loads.

Chapter 3
Materials and Experimental Program

Chapter 3
Materials and Experimental Program

3.1 Introduction:

The study aims to evaluate the properties of HMA modified with crumb rubber. The process and procedures on how this study was conducted will be explained in detail.

The two topics of this chapter are the evaluation of used materials properties such as aggregates, bitumen and crumb rubber; and the description of how experimental work was conducted to achieve the 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 the Association of Engineers, Gaza and the Consulting Center For Quality & Calibration (CCQC).

There were several stages of laboratory tests, which began with the evaluation of the properties of materials such as aggregates, bitumen, and crumb rubber. Sieve analysis for each type of aggregate was conducted to obtain the grading of aggregate sizes followed by aggregates blending to obtain wearing course gradation curve used to prepare asphalt mix. Then the Marshal Test was conducted for asphalt mixes with different bitumen contents to obtain the optimum bitumen content. The asphalt mixes modified with various percentages of crumb rubber are prepared based on the optimum bitumen content. The Marshal Test was used to evaluate the properties of these modified mixes. Finally, laboratory test results were obtained and analyzed. Figure (3.1) shows the flow chart of the laboratory testing procedure.

3.3 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 the main and the local sources of these materials.

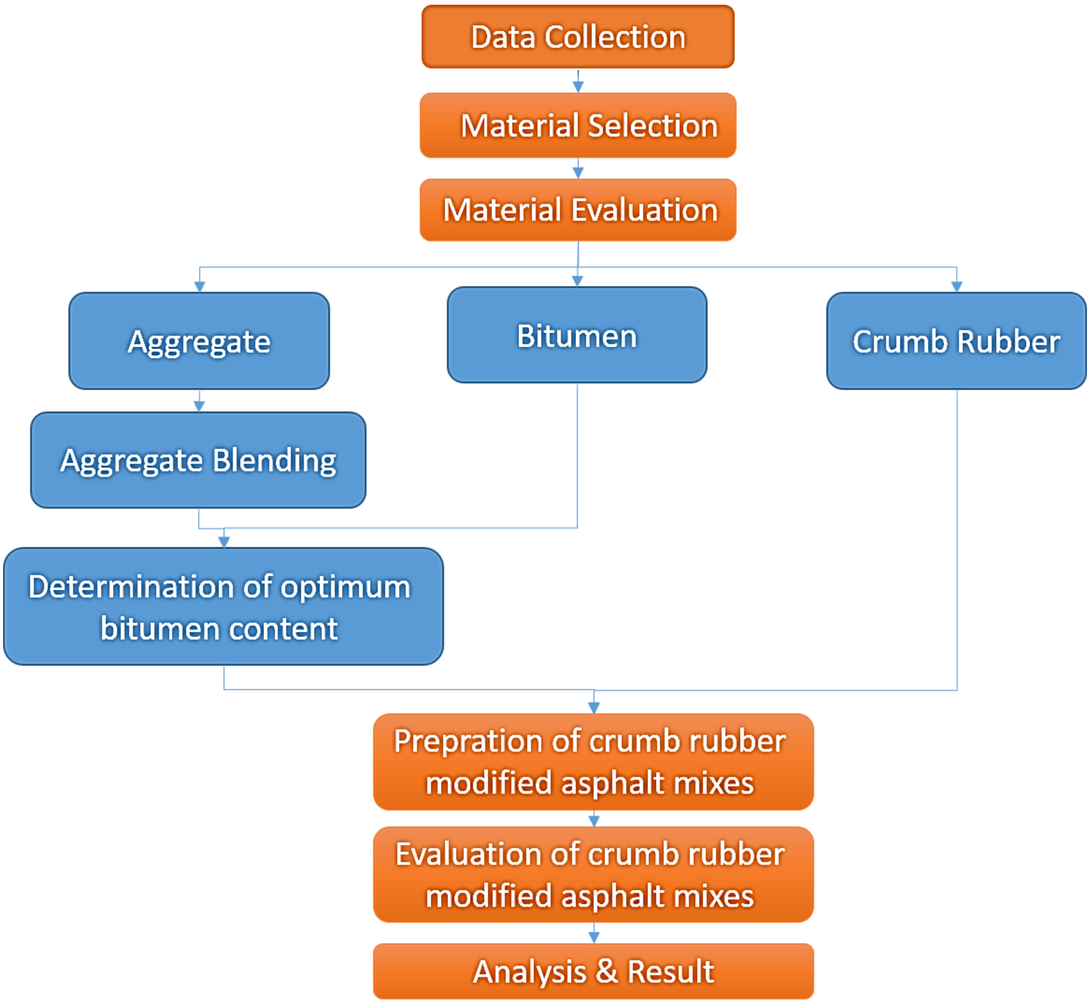

Figure (3.1): Flow chart of laboratory testing procedure

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
Crumb rubber	Local company	Local company

3.4 Number of samples required:

First Stage:

Four percentages of bitumen will be used to find the optimum percentage of bitumen for the aggregates used, which include 4.5, 5, 5.5 and 6% by total weight of the mix with 3 samples for each percentage, total samples 12.

Second Stage:

Three samples will be made using the OBC for determining the mechanical properties at different percentages of crumb rubber (0, 10%, 15%, 20%, 25%, 30%) by weight of bitumen, as aggregate the total number of samples will be 18.

Total number of samples required for the two stages = 30 samples.

3.5 Materials properties

3.5.1 Bitumen properties

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

a) Bitumen penetration test

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

Table (3.2): Bitumen penetration test results

Test	Unit	Result	Requirements	Specification
Penetration	1/10 mm	61	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) shows ductility test results 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) shows the softening point test results for bitumen samples.

Table (3.4): Bitumen softening point results

Test	Unit	Result	Requirements	Specification
Softening point	° C	48.90	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	286	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	1.01	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	61	60-70
Ductility (cm)	ASTM D113-86	+150	Min 100
Softening point (°C)	ASTMD36-2002	48.9	(48 – 56)
Flash point (°C)	ASTM D92-12b	286	Min 230° C
Specific gravity (g/ml)	ASTM D 3289-03	1.01	0.97-1.06

3.5.2 Crumb Rubber:

Table (3.8) shows the physical property of Crumb Rubber. The mix design was prepared using different percentages of crumb rubber (0, 10%, 15%, 20%, 25%, 30%) by weight of bitumen, as aggregate**.** The average size of the crumb rubber is 5.00 mm according to the Sieve analysis.

Table (3.8): Crumb Rubber properties

Property	Detail
Specific gravity, g/cm³	1.15
Carbon black content, wt%	32.7
Average size (mm)	5.00

Figure (3.4): Used Crumb Rubber

3.5.3 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, a number of 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	g/cm^3	2.553	2.619
Dry Specific Gravity	g/cm^3	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	g/cm^3	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%

3.5.4 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

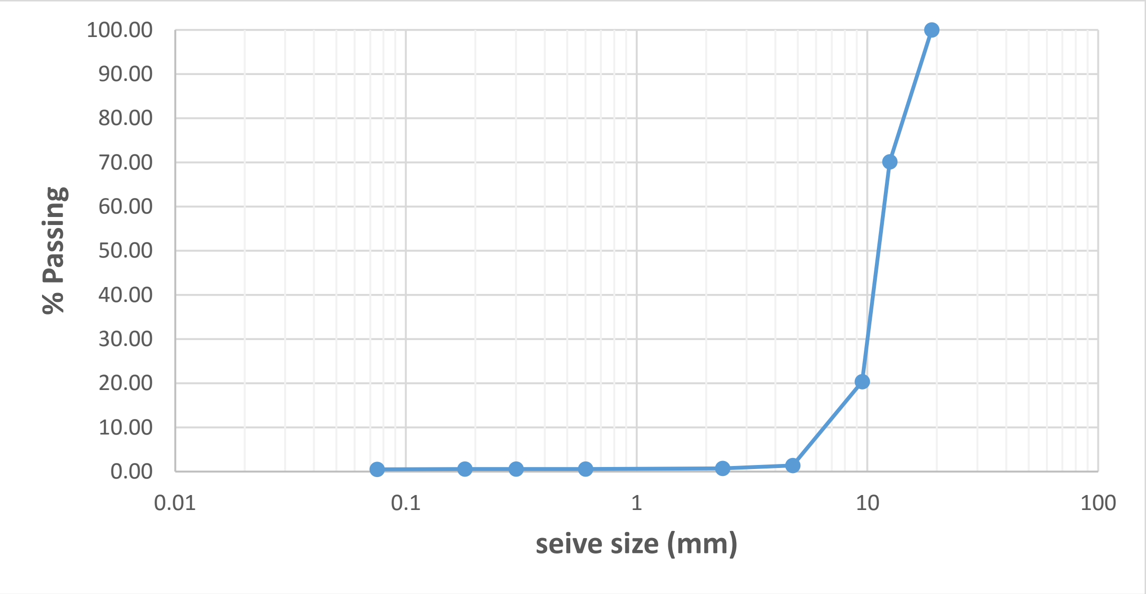

Figure (3.6): Gradation curve (Adasia 0/ 12.5)

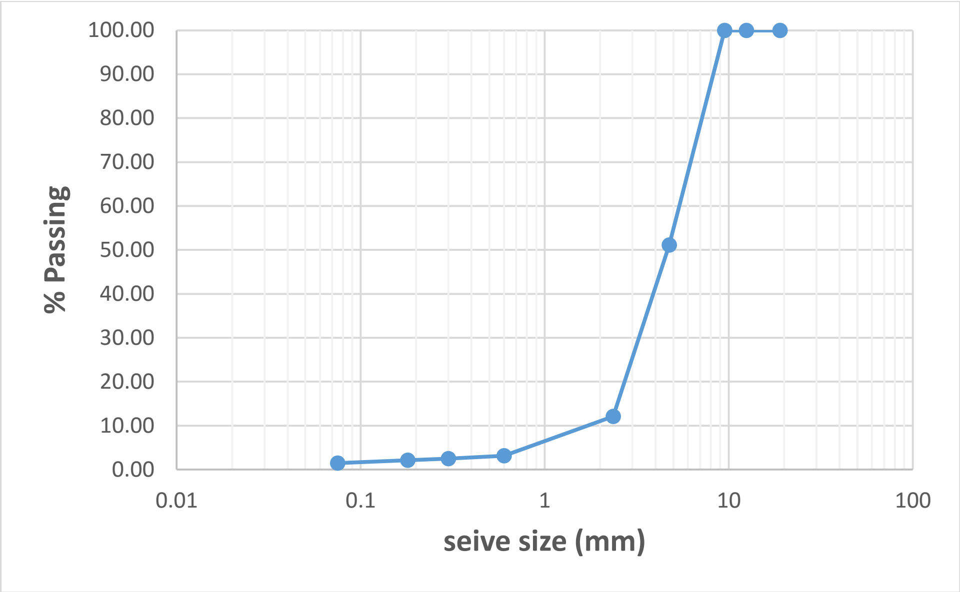

Figure (3.7): Gradation curve (Simsimia 0/ 9.5)

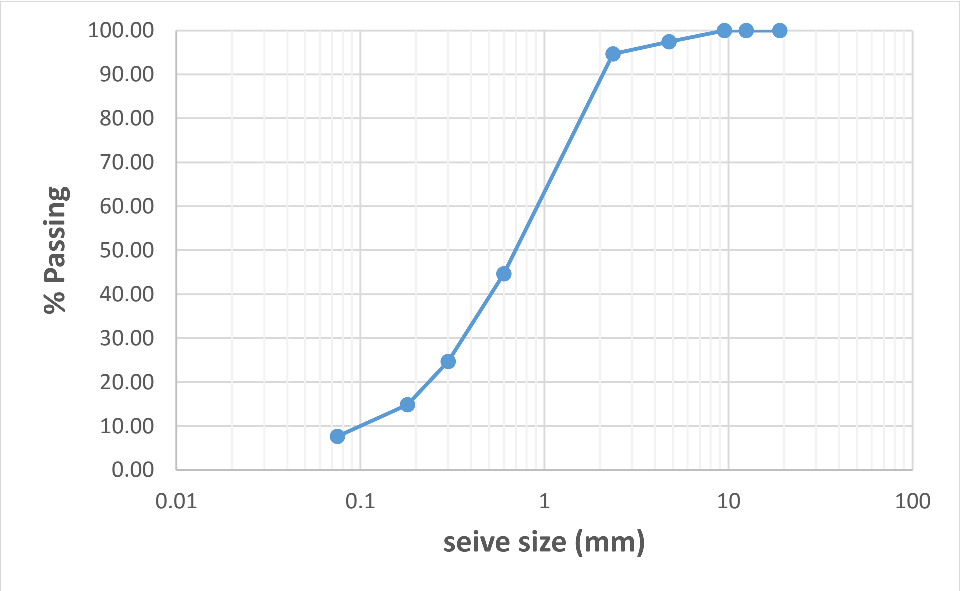

Figure (3.8): Gradation curve (Trabia 0/ 4.75)

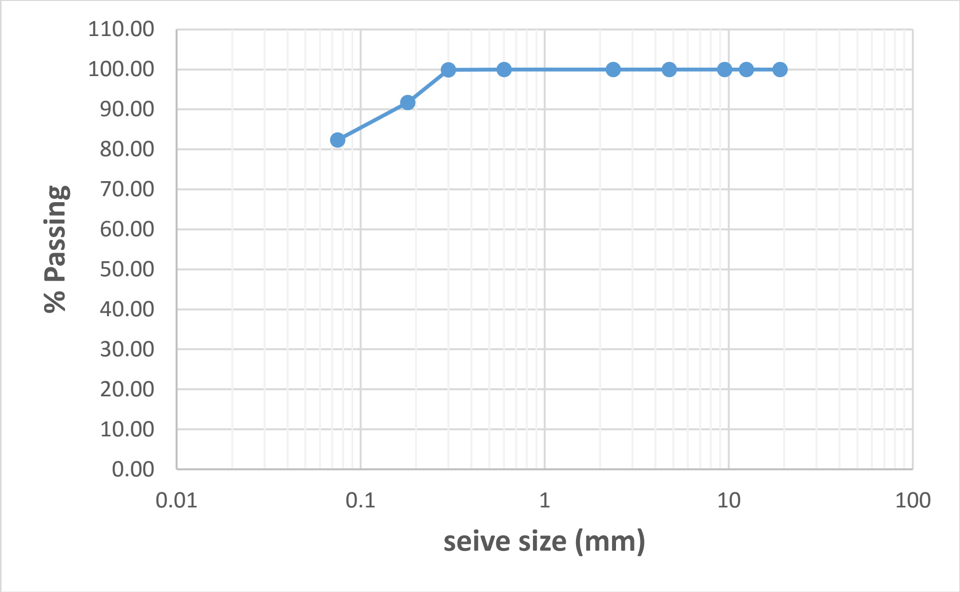

Figure (3.9): Gradation curve (Filler)

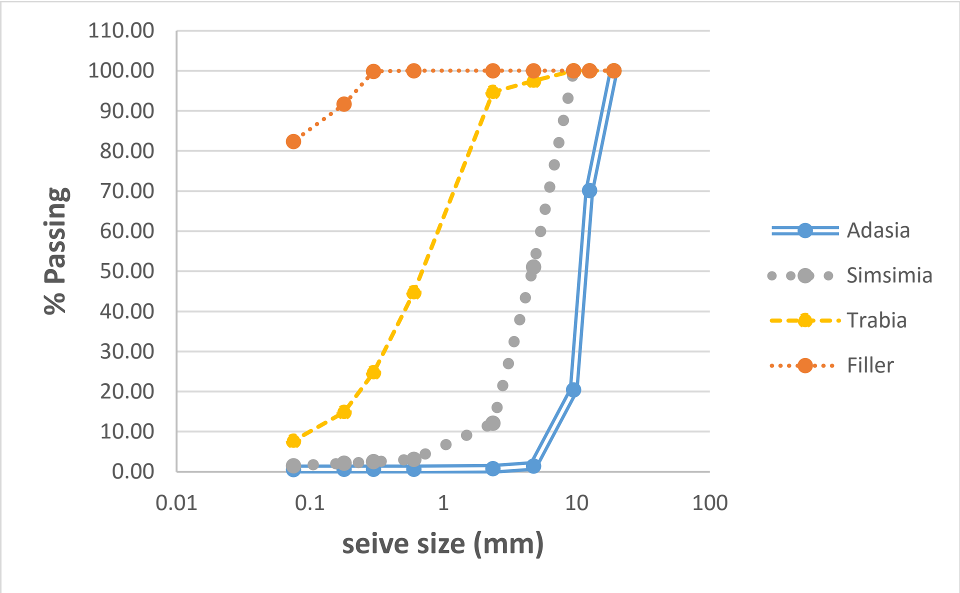

Figure (3.10): Aggregates gradation curves

3.6 Testing program

3.6.1 Blending of aggregates

Asphalt mix with an aggregate blend that meets gradation specifications for a particular asphalt mix is achieved through combining two or more aggregates of different gradations.

The mathematical trial method, in accordance with ASTM specifications, are used to get the proper gradation within allowable limits for the available aggregate materials (0/12.5), (0/9.5), (0/4.75) and filler. This is done by suggesting different trial proportions for aggregate materials from whole gradation. The percentage of each aggregate size is calculated and compared to specification limits. No further adjustment is made if the calculated gradation is within the allowable limits. However the calculations must be repeated if an adjustment in the proportions must be made. 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).

3.6.2 Marshal test

The optimum bitumen content to be added to specific aggregate blend is done utilizing the Marshal Method for asphalt mix content. This results in a mix that meets the desired strength and durability properties. 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 approximately were prepared using four different bitumen contents (from 4.5 - 6% with 0.5 % incremental). Three samples were used to prepare asphalt mixture for each bitumen content to have an average value of Marshal Stability, bulk density and flow. Figure (3.11) shows Marshal Specimens for different bitumen percentages.

Various bitumen contents determine the Marshal properties of an asphalt mix. These properties include stability, flow, density, air voids in total mix, and voids filled with bitumen percentage. The following graphs are then 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

3.6.3 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) % =

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

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

Chapter 4
Results and Data Analysis

Chapter 4
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 crumb rubber on the mechanical properties of asphalt mix and identify the optimum percent of crumb rubber to be added to hot mix asphalt.

Laboratory work results are presented in this chapter in three stages. First, handle 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 third step is to study the effect of adding different percentages of Crumb Rubber on asphalt mix properties which are (10, 15, 20, 25, 30%) by weight of bitumen as aggregate of asphalt mix. Marshal test results for modified asphalt mixes are analyzed and finally the optimum Crumb Rubber 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 (0/12.5)	22.0 %
Simsimia Aggregate (0/9.5)	30.0 %
Fine Aggregate (0/4.75)	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

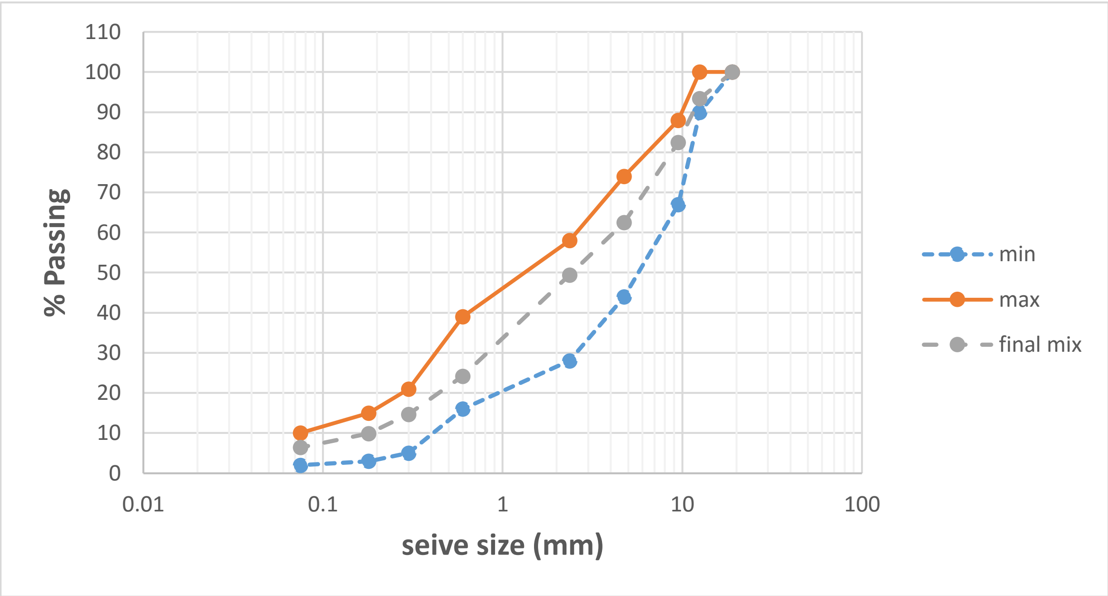

Figure (4.1): Gradation of final aggregates mix with ASTM specification range

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 four 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). The stability results for various bitumen contents are shown in Figure (4.2). 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.

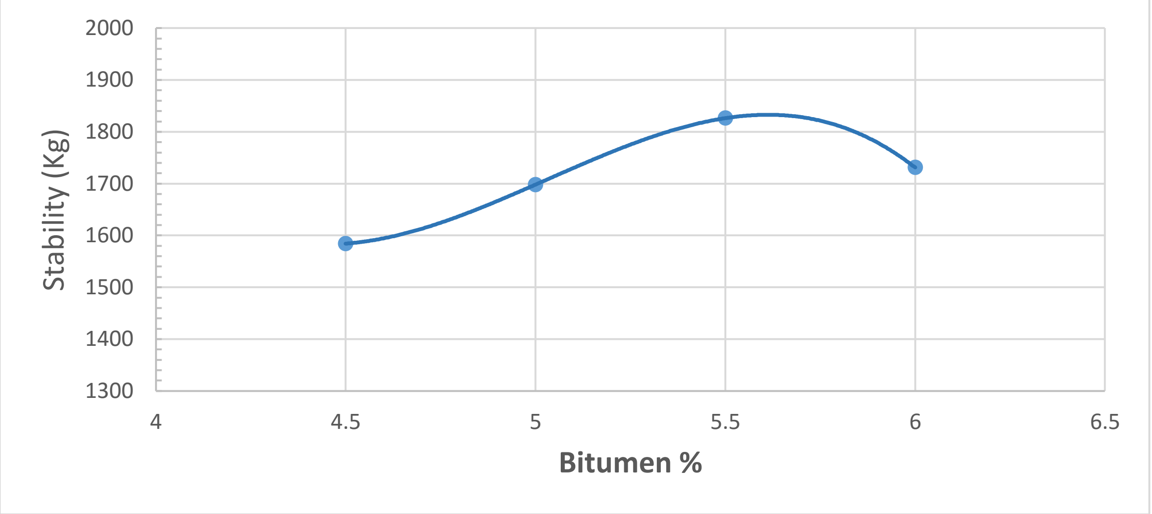

Figure (4.2): Stability vs. bitumen content

4.3.2 Flow – bitumen content relationship

The total amount of deformation at maximum load is called the Flow (Jendia, 2000). Figure (4.3) displays the Flow results for different bitumen contents. Maximum bitumen content of 6.0% is the peak of Flow of asphalt mix; with the Flow increasing gradually before this peak.

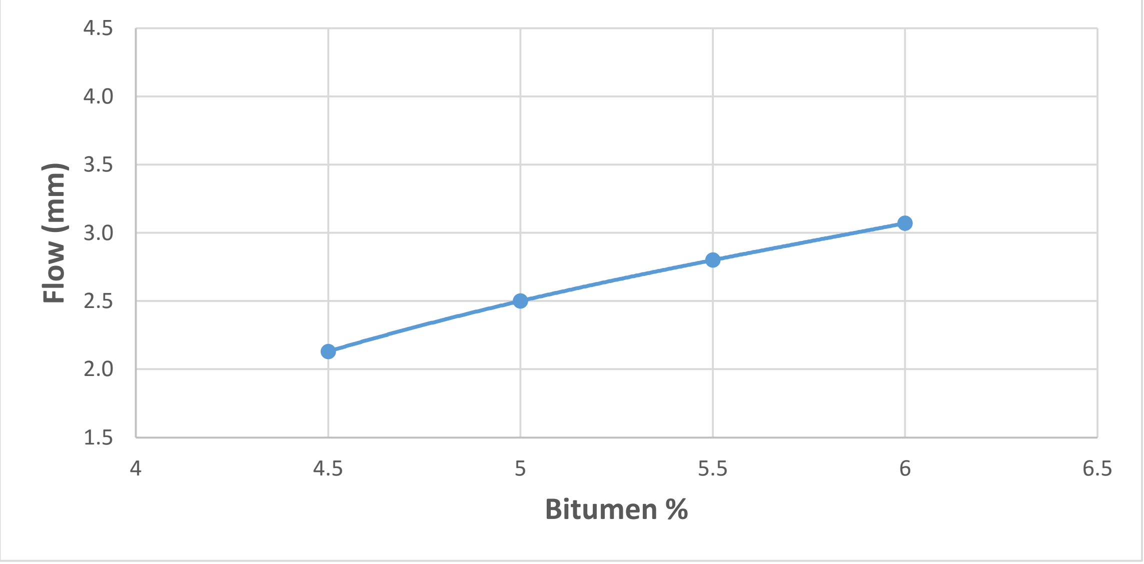

Figure (4.3): Flow vs. bitumen content

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 are represented. 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.

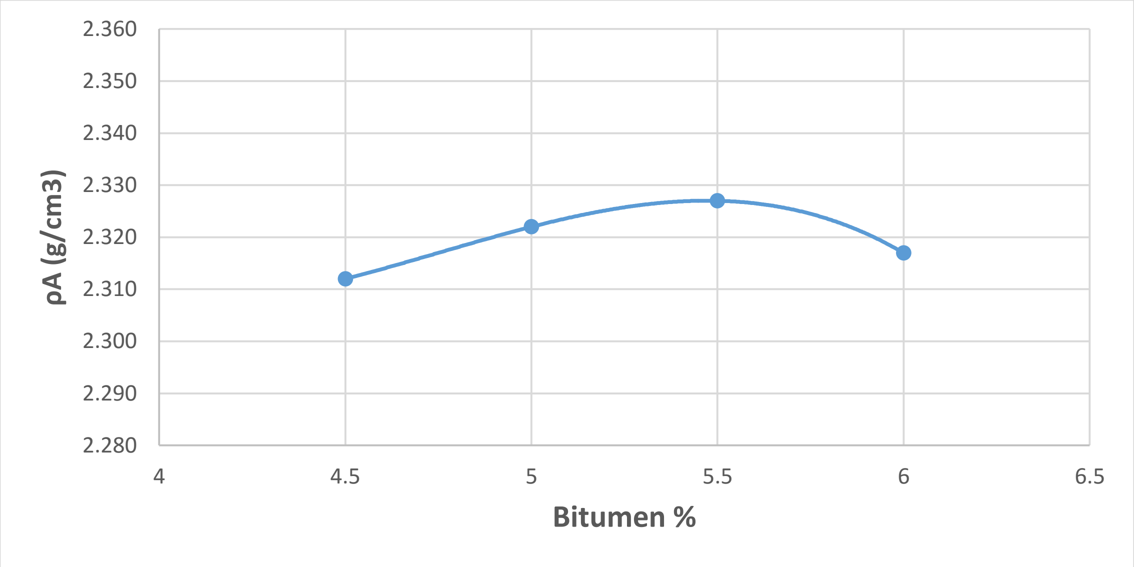

Figure (4.4): Bulk density vs. bitumen content

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 are represented. 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.

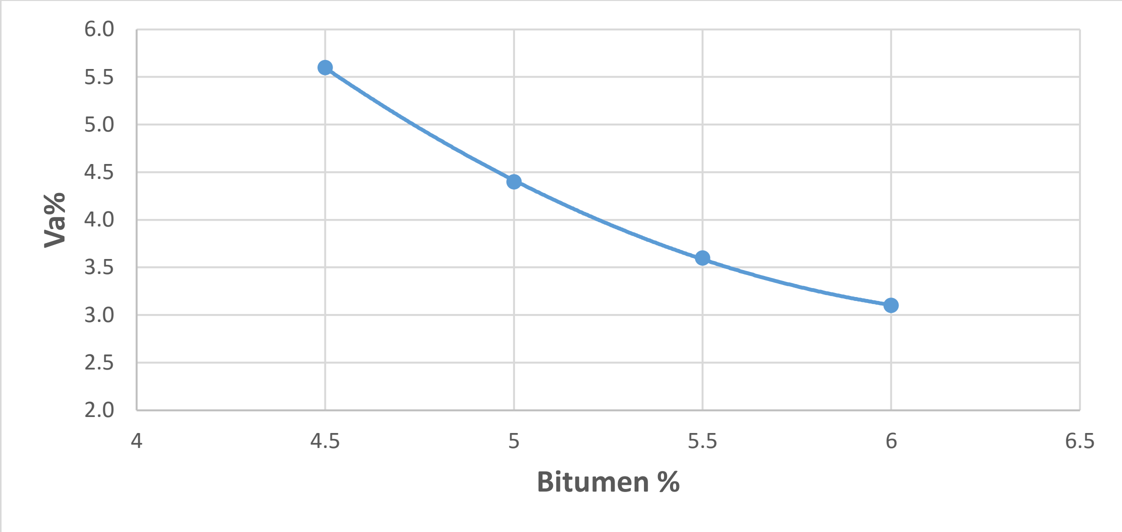

Figure (4.5): Mix air voids proportion vs. bitumen content

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 are represented. 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.

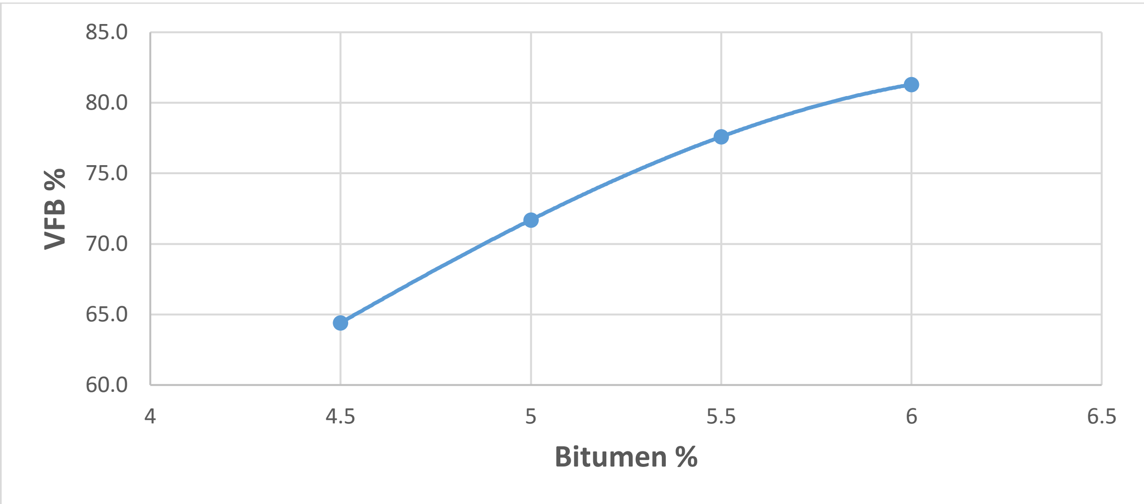

Figure (4.6): Voids filled bitumen proportion vs. bitumen content

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

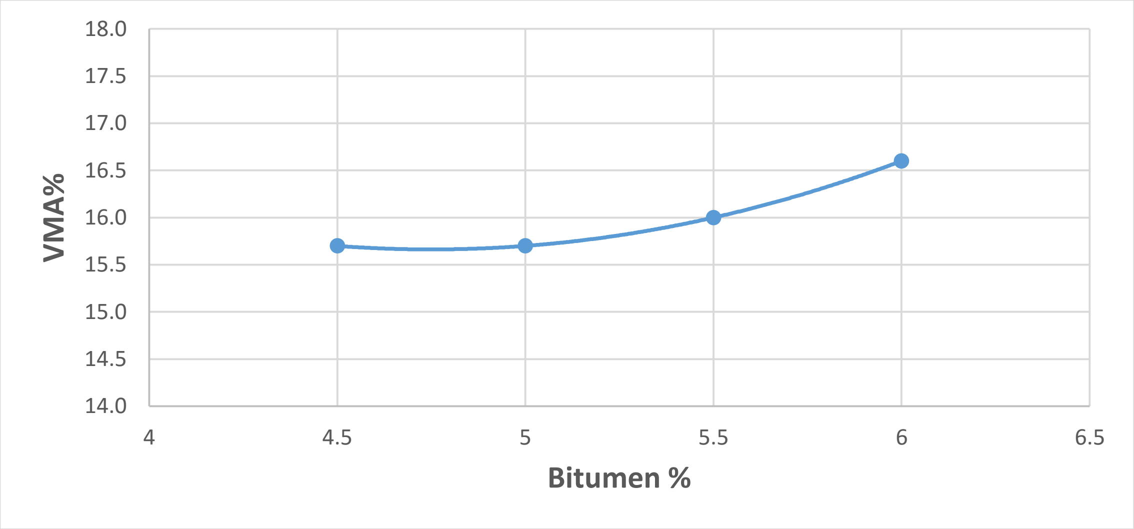

Figure (4.7): Voids of mineral aggregates proportion vs. bitumen content

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	g/cm^3	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 Crumb Rubber 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 Crumb Rubber is shown in Table (4.5).

Table (4.5): Mechanical properties of asphalt mix without addition of Crumb Rubber

Bitumen %(by total weight)	**Sample No.**	**Stability (Kg)**	**Flow (mm)**	**ρA (g/cm3)**	**Va (%)**	**(VMA) (%)**	**(VFB) (%)**	**Stiffness (Kg/mm)**
5.4	1	1723.6	2.7	2.323	5	17.2	70.7	638.4
	2	1715.9	2.8	2.322	5.1	17.3	70.5	612.8
	3	1721.0	2.8	2.323	5.1	17.2	70.6	614.7
	Average	**1720.2**	**2.8**	**2.323**	**5.1**	**17.2**	**70.6**	**621.9**

4.4.2 Phase (II): Asphalt mix with Crumb Rubber

According to procedure previously illustrated in Chapter (3), 18 samples were prepared at OBC to evaluate the effect of adding Crumb Rubber to asphalt mixture samples by considering 5 proportions of Crumb Rubber (10, 15, 20, 25, and 30% by weight of bitumen as aggregate. Table (4.6) shows the mechanical properties of asphalt mix using different percentages of Crumb Rubber at the OBC. Further details are presented in Appendix (D).

Table (4.6): Mechanical properties of asphalt mix with Crumb Rubber

% Crumb Rubber of bitumen content	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
10	1	1634.4	3	2.319	5.5	17.6	68.9	544.8
	2	1652.3	2.9	2.32	5.5	17.6	69	569.7
	3	1642.1	3	2.319	5.5	17.6	68.9	547.4
	Average	**1642.9**	**3**	**2.319**	**5.5**	**17.6**	**68.9**	**554**
15	1	1494.1	3.2	2.314	4.6	16.7	72.7	466.9
	2	15.4.3	3.3	2.318	4.4	16.5	73.5	455.9
	3	1499.2	3.3	2.314	4.5	16.7	72.8	454.3
	Average	**1499.2**	**3.3**	**2.315**	**4.5**	**16.6**	**73**	**459**
20	1	1435.4	3.4	2.306	4.2	16.4	73.7	422.2
	2	1453.3	3.6	2.308	4.2	16.3	74.1	403.7
	3	1463.5	3.5	2.308	4.2	16.3	74.2	418.1
	Average	**1450.7**	**3.5**	**2.307**	**4.2**	**16.3**	**74**	**414.7**
25	1	1218	3.8	2.289	4	16	75.2	320
	2	1228.2	3.8	2.289	4	16	75	323.2
	3	1212.8	3.9	2.29	4	16	75.2	311
	Average	**1219.7**	**3.8**	**2.289**	**4**	**16**	**75.1**	**318.2**
30	1	1053.9	4.1	2.277	3.4	15.3	78	257
	2	1038.5	4.3	2.274	3.5	15.4	77.5	241.5
	3	1046.2	4.2	2.274	3.5	15.4	77.4	249.1
	Average	**1046.2**	**4.2**	**2.275**	**3.4**	**15.4**	**77.6**	**249.2**

4.4.3 Stability – Crumb Rubber content relationship

Generally, the stability of modified asphalt mixes is lower than the conventional asphalt mix (1720.2 kg). The maximum stability value is found nearly (1642.9 kg) at Crumb Rubber content around (10%). Figure (4.8) shows that the stability of modified asphalt mix decreases as the Crumb Rubber content increases.

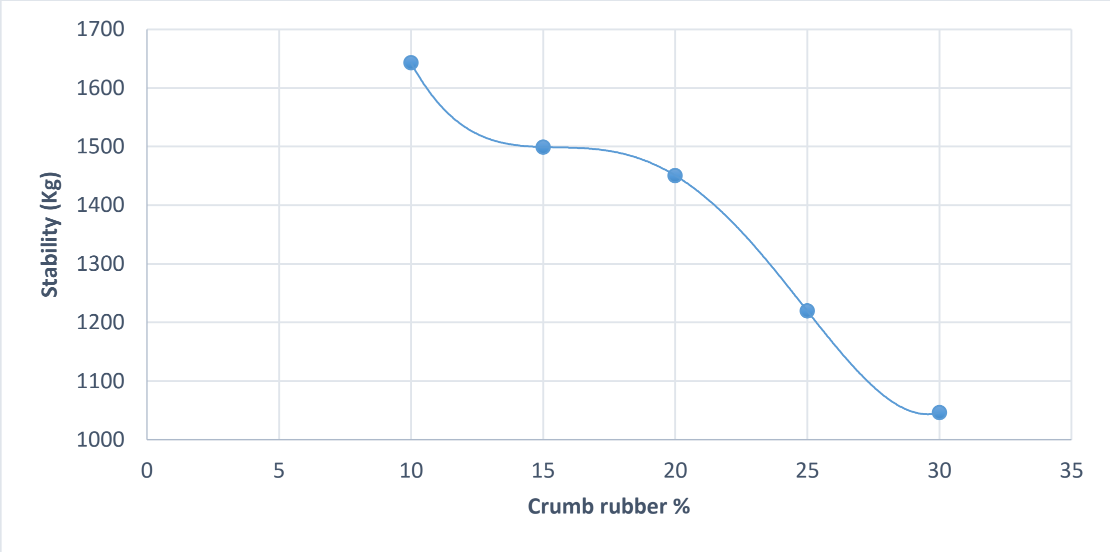

Figure (4.8): Asphalt mix Stability – Crumb Rubber content relationship

4.4.4 Flow – Crumb Rubber content relationship

Generally, the flow of modified asphalt mix is higher than the conventional asphalt mix (3.0 mm). Figure (4.9) shows that the flow increases continuously as the Crumb Rubber modifier content increase. The flow value extends from (2.9mm) till it reach (4.3mm) at Crumb Rubber content (30%).

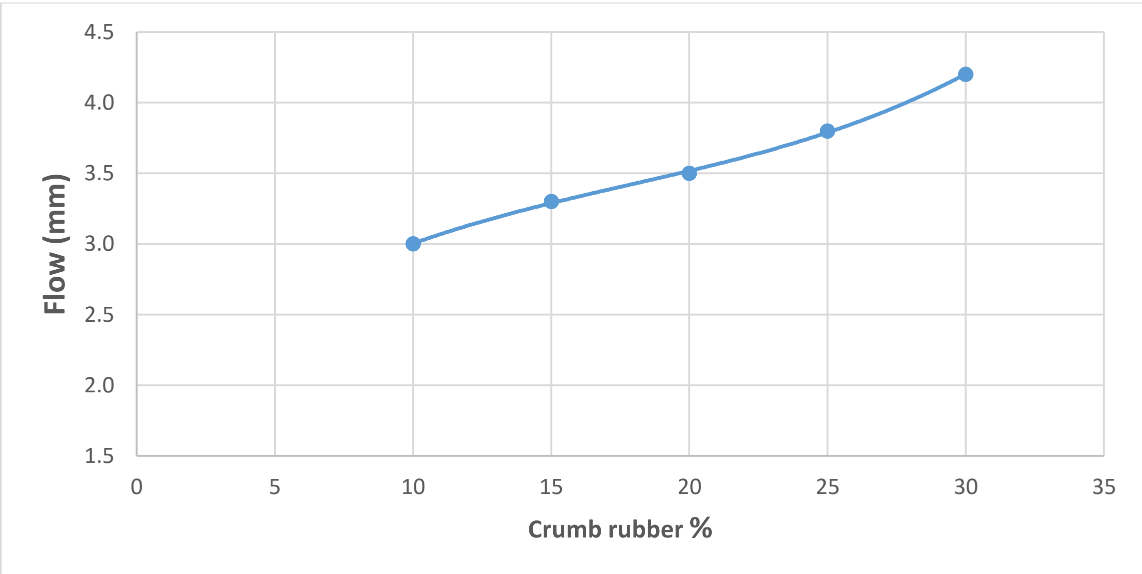

Figure (4.9): Asphalt mix flow – Crumb Rubber content relationship

4.4.5 Bulk density – Crumb Rubber content relationship

The bulk density of crumb rubber 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 Crumb Rubber content increase. The maximum bulk density is (2.319 g/cm3) at Crumb Rubber content (10%) and the minimum bulk density is (2.275 g/cm3) at Crumb Rubber content (30%). This decrease of bulk density can be explained to be as a result of the low density of added Crumb. Figure (4.10) show the curve which represents asphalt mix bulk density – Crumb Rubber content relationship.

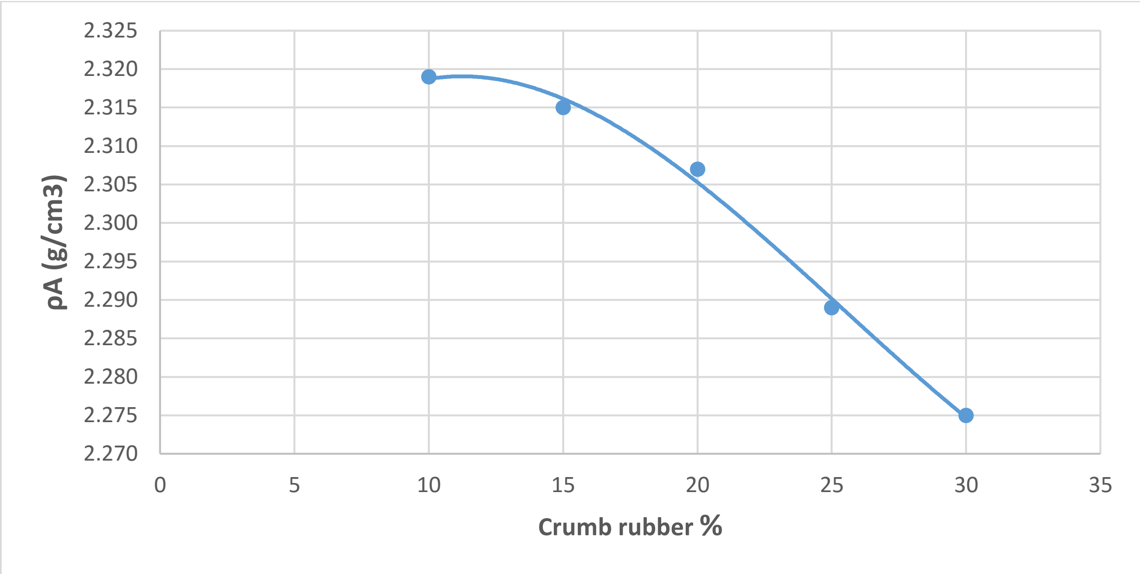

Figure (4.10): Asphalt mix bulk density – Crumb Rubber content relationship

4.4.6 Air voids (Va) – Crumb Rubber content relationship

In general, the air voids proportion of modified asphalt mixes is higher than conventional asphalt mix (5.1 %). Va % of modified asphalt mixes decreases gradually as the Crumb Rubber content increase till it reaches the lowest Va% value at 30% Crumb Rubber content. Generally modified asphalt mixes have Va% content within specifications range. Figure (4.11) shows the curve which represents asphalt mix air voids – Crumb Rubber content relationship.

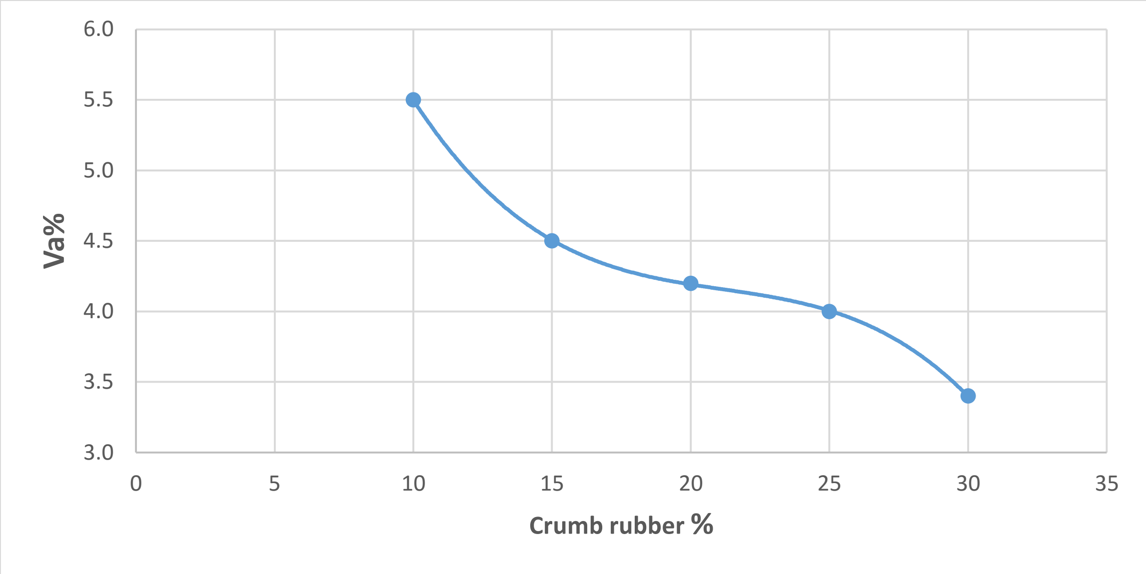

Figure (4.11): Asphalt mix air voids – Crumb Rubber content relationship

4.4.7 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 Crumb Rubber content increase, it reaches (15.4%) at Crumb Rubber content (30%). Figure (4.12) show the curve which represents asphalt mix VMA% – Crumb Rubber content relationship.

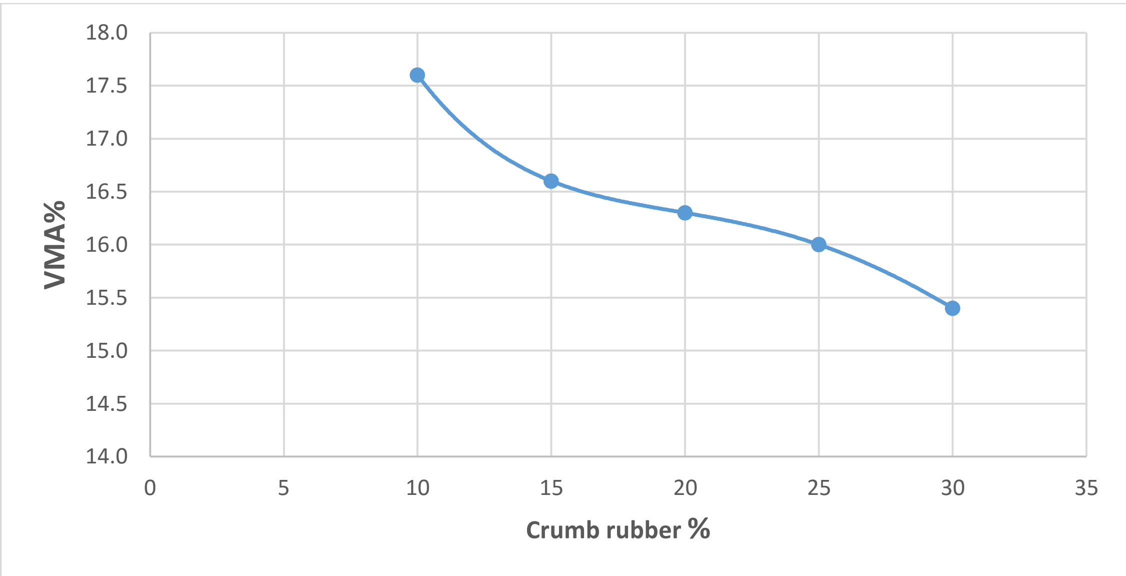

Figure (4.12): Asphalt mix voids of mineral aggregates (VMA) – Crumb Rubber content relationship

4.4.8 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 Crumb Rubber percentages which satisfy these three controls. The Crumb Rubber percentages which satisfy controls are summarized in Table (4.7).

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

Property	Crumb Rubber (By Weight of Bitumen)
Maximum stability	10 %
Maximum bulk density	10 %
Va % within the allowed range of specifications	30 %

The Optimum Crumb Rubber content is the average of the previous three Crumb Rubber contents.

Optimum Crumb Rubber content (by weight of bitumen) = $\frac{10+10+30}{3}$ **~ = 17%**

4.4.9 Evaluation of Crumb Rubber modified asphalt mix:

The mechanical properties of Crumb Rubber modified asphalt mix at the optimum Crumb Rubber content (17 % by weight of bitumen as aggregate) is shown in Table (4.8).

Table (4.8): Properties of Crumb Rubber modified asphalt mix with MPWH specification range

Property	Units	(0.17 %) modified asphalt mix	Min Specified	Max Specified
Stability	Kg	1500	900	***
Flow	mm	3.4	2.0	4.0
Bulk Specific Gravity	g/cm^3	2.313	2.300	***
Va	%	4.3	3.0	5.0
VFB	%	73.5	60.0	75.0
VMA	%	16.4	14.0	***
Stiffness	Kg/mm	441.2	500.0	***

It's clearly shown that adding Crumb Rubber to the asphalt mix (17 % by weight of bitumen as aggregate) meet the local and international standards requirements as shown in table (4.8).

Chapter 5

Conclusions and Recommendations

Conclusions and Recommendations

6.1 Conclusions

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

a. Crumb Rubber can be conveniently used as a modifier for asphalt mixes.
b. The optimum amount of Crumb Rubber to be added as a modifier of asphalt mix was found to be (17 %) by weight of bitumen.
c. Asphalt mix modified with Crumb Rubber meets the local and international standards requirements.
d. Asphalt mix modified with Crumb Rubber exhibits higher flow value when the Crumb Rubber percentage increased. However, the stiffness of the modified mix decreased .

6.2 Recommendations

a. It is recommended to use Crumb Rubber content at 17% by weight of bitumen to improve performance of asphalt mix.
b. It is recommended to use Crumb Rubber in the streets which do not have high loads.
c. It is required to establish a local Palestinian specification for the usage of Crumb Rubber, fibers and modifiers in asphalt mixes.
d. Encourage factories to use crumb rubber in asphalt mixtures

6.3 Future studies

a. Further researches are recommended to conduct this study using different bitumen types.
b. Further researches are recommended to conduct this study using Super Pave Method rather than Marshall.

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Appendices

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

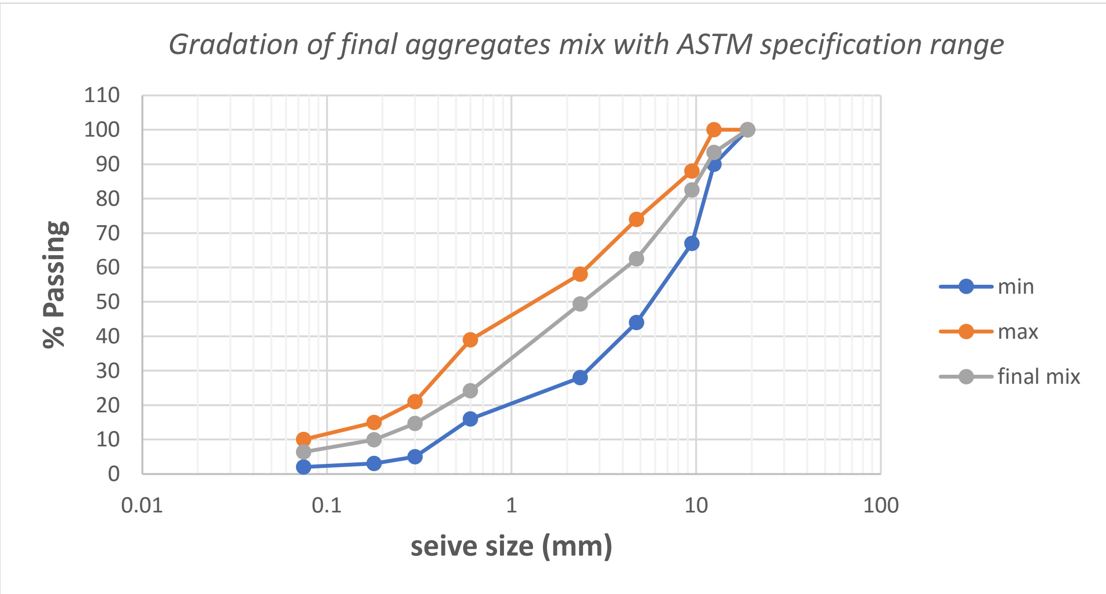

Figure 8A.1: Job Mix Gradation

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): Calculations of physical properties of aggregates

1- <u>**Specific gravity and absorption** (ASTM C128-12)</u>

- **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- Pycnometer method

- **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

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

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

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 C8.4: 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**
$\rho_{bitumen}$		**1.03**
ρ_{mix}	**bitumen %**	**Max density**
	4.5	**2.445**
	5.0	**2.428**
	5.5	**2.410**
	6.0	**2.393**

Appendix (D):
Crumb Rubber Modified asphalt mix tests results

Marshal tests results

Conventional mix

Crumb Rubber = 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)	1197.5	1171.5	1195	**1188**
Weight in water (g)	683.5	668.5	681.5	**678**
Weight in air (S.S.D) (g)	1199	1173	1196	**1189**
Volume (cm3)	515.5	504.5	514.5	**511.5**
Bulk dry specific gravity	2.323	2.322	2.323	**2.323**
Max specific gravity	2.446	2.446	2.446	**2.446**
Marshal stability reading (×5 div)	670	667	669	**669**
Stability correction factor	1.00	1.00	1.00	**1.00**
Corrected stability (kg)	1723.6	1715.9	1721.0	**1720.2**
Plastic Flow (mm)	2.70	2.80	2.80	**2.80**
Stiffness (kg/mm)	638.4	612.8	614.7	**621.9**
Air voids content in total mix Va (%)	5.0	5.1	5.1	**5.1**
Voids of mineral agg. (V.M.A) %	17.2	17.3	17.2	**17.2**
Voids filled with bitumen (V.F.B) %	70.7%	70.5%	70.6%	**70.6%**

Marshal tests results

Crumb Rubber = 10 % (By weight of bitumen as aggregate**)**

- 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)	1194.5	1190	1191	**1192**
Weight in water (g)	681.5	678.5	679	**680**
Weight in air (S.S.D) (g)	1196.5	1191.5	1192.5	**1194**
Volume (cm3)	515	513	513.5	**513.5**
Bulk dry specific gravity	2.319	2.320	2.319	**2.319**
Max specific gravity	2.454	2.454	2.454	**2.454**
Marshal stability reading (×5 div)	535	642	638	**638**
Stability correction factor	1.00	1.00	1.00	**1.00**
Corrected stability (kg)	1634.4	1652.3	1642.1	**1642.9**
Plastic Flow (mm)	3.0	2.9	3.0	**3.0**
Stiffness (kg/mm)	544.8	569.7	547.4	**554.0**
Air voids content in total mix Va (%)	5.5	5.5	5.5	**5.5**
Voids of mineral agg. (V.M.A) %	17.6	17.6	17.6	**17.6**
Voids filled with bitumen (V.F.B) %	68.9%	69.0%	68.9%	**68.9%**

Marshal tests results
Crumb Rubber = 15 % (By weight of bitumen as aggregate**)**

- 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)	1180	1181	1181.5	**1181**
Weight in water (g)	671	672.5	672	**672**
Weight in air (S.S.D) (g)	1181	1182	1182.5	**1182**
Volume (cm3)	510	509.5	510.5	**510**
Bulk dry specific gravity	2.314	2.318	2.314	**2.315**
Max specific gravity	2.454	2.454	2.454	**2.454**
Marshal stability reading (×5 div)	580	584	582	**582**
Stability correction factor	1.00	1.00	1.00	**1.00**
Corrected stability (kg)	1494.1	1504.3	1499.2	**1499.2**
Plastic Flow (mm)	3.2	3.3	3.3	**3.3**
Stiffness (kg/mm)	466.9	455.9	454.3	**459**
Air voids content in total mix Va (%)	4.6	4.4	4.5	**4.5**
Voids of mineral agg. (V.M.A) %	16.7	16.5	16.7	**16.6**
Voids filled with bitumen (V.F.B) %	72.7%	73.5%	72.8%	**73%**

Marshal tests results

Crumb Rubber = 20 % (By weight of bitumen as aggregate**)**

- 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)	1169	1165.5	1171.5	**1169**
Weight in water (g)	663	662	665	**663**
Weight in air (S.S.D) (g)	1170	1167	1172.5	**1170**
Volume (cm3)	507	505	507.5	**506.5**
Bulk dry specific gravity	2.306	2.308	2.308	**2.307**
Max specific gravity	2.410	2.410	2.410	**2.410**
Marshal stability reading (×5 div)	557	564	568	**563**
Stability correction factor	1.00	1.00	1.00	**1.00**
Corrected stability (kg)	1435.4	1453.3	1463.5	**1450.7**
Plastic Flow (mm)	3.4	3.6	3.5	**3.5**
Stiffness (kg/mm)	422.2	403.7	418.1	**414.7**
Air voids content in total mix Va (%)	4.3	4.2	4.2	**4.2**
Voids of mineral agg. (V.M.A) %	16.4	16.3	16.3	**16.3**
Voids filled with bitumen (V.F.B) %	73.7%	74.1%	74.2%	**74%**

Marshal tests results

Crumb Rubber = 25 % (By weight of bitumen as aggregate**)**

- 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)	1166.5	1177.5	1170	**1171**
Weight in water (g)	658	664	660	**661**
Weight in air (S.S.D) (g)	1167.5	1178.5	1171	**1172**
Volume (cm3)	509.5	514.5	511	**511.7**
Bulk dry specific gravity	2.289	2.289	2.290	**2.289**
Max specific gravity	2.384	2.384	2.384	**2.384**
Marshal stability reading (×5 div)	472	476	470	**473**
Stability correction factor	1.00	1.00	1.00	**1.00**
Corrected stability (kg)	1218	1228.2	1212.8	**1219.7**
Plastic Flow (mm)	3.8	3.8	3.8	**3.8**
Stiffness (kg/mm)	320.5	323.2	311	**318.2**
Air voids content in total mix Va (%)	4.0	4.0	4.0	**4.0**
Voids of mineral agg. (V.M.A) %	16.0	16.0	16.0	**16.0**
Voids filled with bitumen (V.F.B) %	75.2%	75%	75.2%	**75.1%**

Marshal tests results

Crumb Rubber = 30 % (By weight of bitumen as aggregate**)**

- 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)	1185	1189.5	1188	**1188**
Weight in water (g)	666	668.5	666.5	**667**
Weight in air (S.S.D) (g)	1186.5	1191.5	1189	**1189**
Volume (cm3)	520.5	523	522.5	**522**
Bulk dry specific gravity	2.277	2.274	2.274	**2.275**
Max specific gravity	2.356	2.356	2.356	**2.356**
Marshal stability reading (×5 div)	408	402	405	**405**
Stability correction factor	1.00	1.00	1.00	**1.00**
Corrected stability (kg)	1053.9	1038.5	1046.2	**1046.2**
Plastic Flow (mm)	4.1	4.3	4.2	**4.2**
Stiffness (kg/mm)	257	241.5	249.1	**249.2**
Air voids content in total mix Va (%)	3.4	3.5	3.5	**3.4**
Voids of mineral agg. (V.M.A) %	15.3	15.4	15.4	**15.4**
Voids filled with bitumen (V.F.B) %	78%	77.5%	77%	**77.6%**

Appendix (E): Photos

Figure E.1: Used Crumb Rubber

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

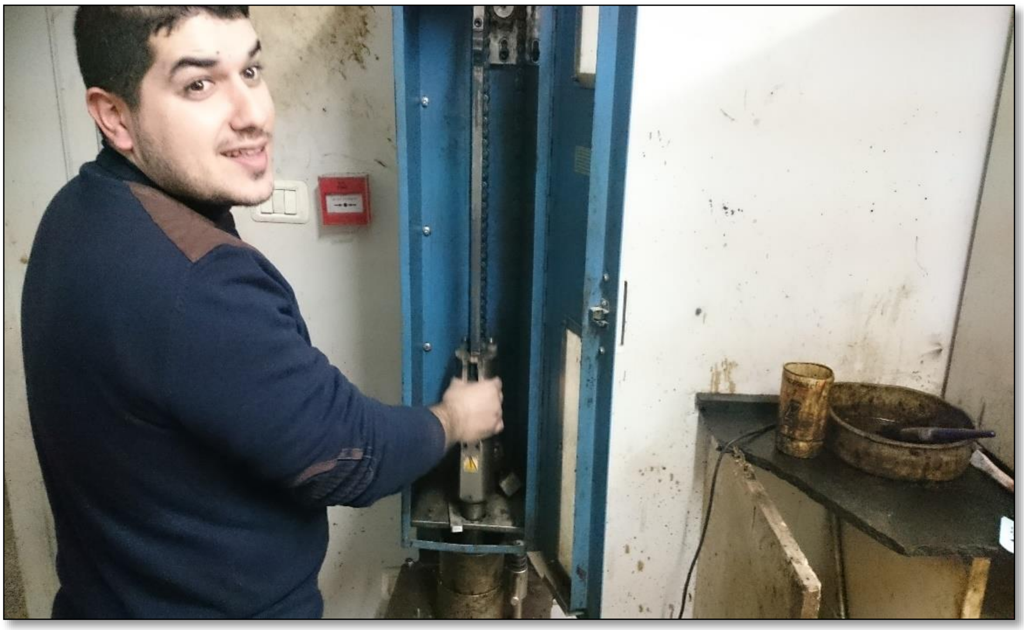

Figure E.7: Asphalt mix during compaction

Figure E.8: Aggregate types