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إدارة البنية التحتية

The Relationship between Mechanical Properties and Initial Temperature of Compacted Asphalt Mixture of Binder Course

دراسة العلاقة بين الخواص الميكانيكية ودرجة الحرارة الأولية للخليط الأسفلتي عند الدمك للطبقة الرابطة

Prepared by:
Belal Obid Ashour

Supervised by:
Prof. Dr. Eng. Shafik Jendia
Faculty of Engineering – Civil Engineering.

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دراسة العلاقة بين الخواص الميكانيكية ودرجة الحرارة الأولية للخليط الاسفلتي عند الدمك للطبقة الرابطة

The relationship Between Mechanical Properties and Initial temperature of compacted Asphalt mixture of binder course

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Signature: [signature] — التوقيع: [signature]

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The Relationship Between Mechanical Properties and Initial Temperature of compacted Asphalt mixture of Binder Course

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Abstract

Hot Mix Asphalt (HMA) is the most common pavement type in Gaza, Palestine and the quality control of constructed roads with HMA has always been paid great attention by researchers. This study aimed to find the effect of initial temperature of HMA (binder coat) at compaction on asphalt mechanical properties. Practical approach was used as the main procedure to achieve study goals. Laboratory tests were conducted using Marshall test method to determine the Optimum Bitumen Content (OBC), in which asphalt mixes are compacted at different temperatures starting from [80° C, 100° C, 120° C, 140° C, and 160 ° C]. The research indicated that one of the important parameters that has a critical role in changing the mechanical properties of HMA was "compaction temperature". The initial compaction temperature had a positive effect on asphalt density within the golden range 140ºC-160ºC. Moreover, increased temperature made an increase in the stability of asphalt, voids filled with asphalt, plastic flow of asphalt, and asphalt stiffness. As well as it was notable that air voids inherent in the asphalt mix were decreased with the temperature increase through the golden range. This study recommended that site engineers should check the initial compaction temperature for asphalt (quality assurance). Density vs temperature relationship could be used in investigating pavement defects and resolving disputes. This study results could help in establishing local specifications for asphalt pavement. The conclusion of the research offered recommendations for expanding the scope of compaction temperature effect on Asphalt mechanical properties by studying the asphalt wearing coat and by using different bitumen content. The study also offered a recommendation to conduct a similar research using Super Pave Method rather than Marshall method for testing.

Abstract (Arabic)

ملخص البحث

تتنوع طرق الرصف في قطاع غزة من رصفات اسفلتية ورصف بحجر الانترلوك والرصفات الاسمنتية ولكن الرصفات الاسفلتية الساخنة هي الاكثر استخداما، لذلك فان ضبط الجوده للخلطات الاسفلتية المستخدمة في رصف الطرق حظيت باهتمام كبير من قبل الباحثين. هذه الدراسة تهدف لايجاد علاقة بين الخواص الميكانيكية ودرجة الحرارة الاولية للخليط الاسفلتي (الطبقة الرابطة). اعتمدت طريقة البحث على التجارب المخبرية باستخدام طريقة مارشال لتصميم الخلطة الاسفلتية لتحديد محتوي البيتومين الأفضل(OBC) وكذلك لاختبار خصائص الخليط الإسفلتي تم عمل عدة عينات اسفلتية تم تجهيزها تحت درجات حرارة مختلفة عند 80 ºC ، 100ºC ، 120ºC، 140ºC، 160ºC، وبنفس نسب الدمك. وقد أظهرت النتائج ان درجة الحرارة الاولية عند الدمك هي من أهم العوامل التي تؤثر على الخواص الميكانيكة للخلطة الاسفلتية الساخنة، حيث أن درجة الحرارة الاولية عند الدمك تؤثر طرديا على كثافة الخلطة الاسفلتية وقد بينت الدراسة ان أفضل كثافة للخليط الاسفلتي يتم الحصول عليها عند درجة حرارة من 140 ºC الي 160 ºC -الفترة الذهبية لرصف الخليط الاسفلتي في الموقع- بالاضافة الى ذلك فان زيادة درجة الحرارة يصحبها زيادة في ثبات وانسياب الخلطة الاسفلتية وكذلك زيادة متانة الرصف. كذلك أظهرت الدراسة أن زيادة درجة الحرارة تؤدي الى تقليل نسبة الفراغات في الخليط الاسفلتي . توصي الدراسة بالاهتمام بدرجة حرارة الخليط الاسفلتي لضمان جودة الاسفلت اثناء اعمال الرصف وكذلك استخدام العلاقة الخطية بين درجة الحرارة والخواص الميكانيكية للخلطة الاسفلتية في التنبؤ بالخواص الميكانيكية عند درجات حرارة مختلفة، كذلك توصي الدراسة باعتماد النتائج في عمل مواصفات محلية للخلطات الاسفلتية للطبقة الرابطة.

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Abbreviations and Symbols

AASHTO	**American Association of State Highway and Transportation Officials**
AC	**asphalt cement HMA hot-mix asphalt**
ASTM	**American Society of Testing and Materials**
HMA	**Hot Mix Asphalt**
JMF	**job-mix formula**
OBC	**Optimum Bitumen Content**
PWL	**percent of material within specification limits**
QA	**quality assurance**
QC	**quality control**
VFA	**voids filled with asphalt**
VMA	**voids in the mineral aggregate**
ρ_{bit}	**Theoretical maximum density of asphalt mix**
Vb	**Bitumen Volume**
Va	**Air Voids**
SSD	**Saturated surface dry condition**
ρ_{min}	**Density of aggregate in the blend**
ρ_{A}	**Density of compacted mix**

Chapter 1. Introduction

1.1 Background

Asphalt flexible pavement is composed of several layers such as: asphalt wearing course and asphalt binder course, base course, sub base. Asphalt course is the surface course of asphalt pavement structure consists of a mixture of mineral aggregates and bituminous materials placed as the upper course and usually constructed on a base course. The binder course lies between the wearing course and the road base. So, it reduces the stresses which affect the road base and the soil base. The selection of the aggregate mixture depends on the thickness of the layer (Jendia, 2000),

In addition to that role of the binder course, it must also be designed to resist the abrasive forces of traffic, to reduce the amount of surface water penetrating the pavement, to provide a skid-resistance surface, and to provide a smooth and uniform riding surface .The surfacing is traditionally made up of two layers the binder course and the wearing course. The binder course role is generally to ensure an even surface for laying the wearing course (Hunter, 2000).

Asphalt mixes are composite materials that consist of asphalt binder mixed with Filler/fines (together with asphalt called the mastic) and aggregates (Koneru, 2008), The major properties to be incorporated in bituminous paving mixtures are density and stability, durability, flexibility and skid resistance (in the case of wearing surface). Traditional Mix design methods are established to determine the optimum asphalt content that would perform satisfactorily, particularly with respect to density and stability and durability (Asi, 2007).

The main indices related to bituminous paving mixtures are density and stability, durability, Flexibility and skid resistance. Asphalt Mix design is the selection of the components to achieve a desirable balance in these properties for the specific pavement application. Selection of the components and their relative proportions is also influenced by the pavement section in which the mix will be incorporated. Design of asphalt-aggregate mix consists of the following steps:

- Select the type and gradation of the mineral aggregates.
- Select the type and grade of asphalt binder.

- Select the amount of asphalt binder to satisfy the project –specific requirements for mix properties (Wayne-Lee, et al., 2006).

Density is one of the most important parameters in construction of asphalt mixtures. A mixture that is properly designed and compacted will contain enough air voids to prevent rutting due to plastic flow but low enough air voids to prevent permeability of air and water. Since density of an asphalt mixture varies throughout its life the voids must be low enough initially to prevent permeability of air and water and high enough after a few years of traffic to prevent plastic flow (Brown, 1990),

The temperature of the mix during compaction is of high significance for the compaction effort required, with too high mix temperatures the compaction by a roller is supported by the low viscosity of the bitumen. The bitumen acts as a lubricant and reduces the internal friction in the mineral mix, Due to the progressing stiffening of the bitumen caused by cooling, the compaction effort increases considerably under low temperatures. Compaction therefore should, as a general rule be started as soon as possible. Compaction Temperatures between 100° and 140°C have been found most favorable for the conventional bitumen types. Compaction should be completed when the temperature has dropped to between 80° and 100°C (Butcher, 1998).

1.2 Problem statement

In Gaza Strip there's no research in this field on the hot mix asphalt concrete, through that the relationship between mechanical properties and initial temperature of compacted asphalt mixture of binder course, this study will support the effect of initial temperature on the mechanical properties in hot mix asphalt concrete.

1.3 Aim and Objectives

1.3.1 Aim

The aim of this research is to study the relationship between mechanical properties and initial temperature of compacted asphalt mixture of binder course.

1.3.2 Objectives

This research work is intended to achieve the following objectives:

- To investigate the effect of compaction temperature on the mechanical properties of asphalt concrete mixtures.
- To create mathematical relationships between initial compaction temperature and the mechanical properties of asphalt concrete mixtures.

1.4 Importance of the study

- Determining the effect of different temperatures on the density of asphalt mixture.
- Predicting the temperature of the hot mix asphalt concrete based on the determination of asphalt concrete density field samples.
- Identifying other Properties of asphalt mixture at different initial temperature.
- Comparing research results with similar international research result.

1.5 Research Contribution

From the previous studies, it should be noticed that the researchers studied effects of moisture, compaction temperature and gradation types on durability of asphalt concrete mixtures. In this study, it will focus on the study of the relationship between mechanical properties and initial temperature of compacted asphalt mixture of binder course, using Marshal Test.

1.6 Methodology

To achieve the objectives of this study, the following methodology will be applied:

- Reviewing all previous studies regarding the mechanical properties and temperature of the asphalt mixture.
- Studying the asphalt mix design and asphalt specification of binder course like AASHTO T 245-13 and ASTM-D3515-4.
- Studying the specification such as Identifying Optimum Bitumen Content (OBC) using Marshal Mix design procedure. Five percentages of bitumen will be examined to determine the best percentage of bitumen for the aggregates used, which include 4, 4.5, 5, 5.5 and 6% by weight of the mix.
- Implementing the asphalt mixes compacted at different temperatures starting from [80° C, 100° C, 120° C, 140° C, and 160 ° C].
- Analyzing test results.
- Drawing conclusions and recommendations.

The following chart illustrates the proposed methodology:

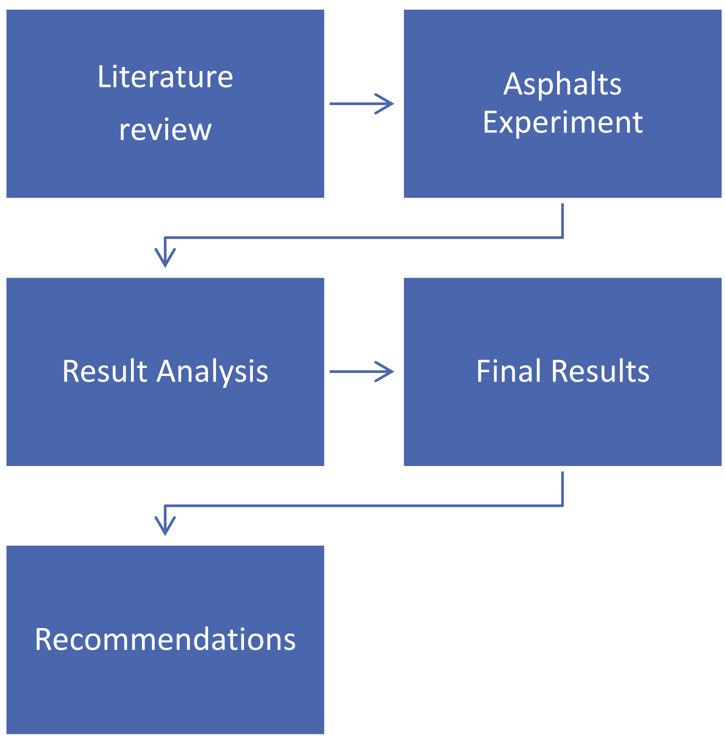

Figure 1.1: Work plan chart

1.7 Thesis Outline

Chapter (1): Introduction

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

Chapter (2): Literature review

Brief introduction related to hot mix asphalt, previous researches.

Chapter (3): Materials and testing program

This chapter handles two topics first is the preliminary evaluation of used materials properties such as aggregates, bitumen. Second is the description of experimental work which has been done to achieve study aims.

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 binder course gradation curve. Second stage, Marshal Test results are analyzed in order to obtain the optimum bitumen content (OBC). The following step discusses study the relationship between mechanical properties and initial temperature of compacted asphalt mixture of binder course.

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 2. Literature Review

2.1 Introduction

One of the most traditional constructed asphalts in Gaza and across the world is "Hot Mix Asphalt". Due to its high durability, solid production, temperature control, moisture and quick provision for traffic crossing, it is being still paid attention by many people. Determination of mechanical properties of HMA samples has vital importance for quality control of constructed roads. The compaction temperature is one of the parameters that can change the HMA mechanical properties. The compaction temperature is one of the major issues in HMA and also on of important criteria in the process of producing good quality of hot mix asphalt. Also, the temperature is a key factor in the control of bitumen viscosity, which affects its ability to coat and provide adequate lubrication for the aggregates and slides with each other (Saedi, 2012).

2.2 Asphalt Layers

The asphalt layers are usually three layers:

a) Asphalt wearing course.

b) Asphalt binder course.

c) Asphalt road base.

The first two layers are forming together a high resistance system for the horizontal and vertical forces and the resultant shear forces especially in the high temperature during the summer season (Jendia, 2000).

2.3 Asphalt course

Asphalt course is the surface course of asphalt pavement structure consists of a mixture of mineral aggregates and bituminous materials placed as the upper course and usually constructed on a base course. The binder course lies between the wearing course and the road base. So, it reduces the stresses which affect the road base and the soil base. The selection of the aggregate mixture depends on the thickness of the layer (Jendia, 2000).

2.4 Hot Mix Asphalts

Hot-Mix Asphalts (HMA) is the most widely used paving material around the world. It's known by many different names: hot mix asphalt, 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 hot mix asphalt. The pavement is a group of layers of specific materials that is positioned on the in-situ soil (Sub Grade). The other layers are (Sub Base, Rock Road Base and Asphalt covering Layers “Binder and Wearing course”).Each layer receives the loads from the above layer, spreads them out, then passes on these loads to the next layer below. Figure (2.1) shows a vertical section of typical asphalt concrete pavement structure.

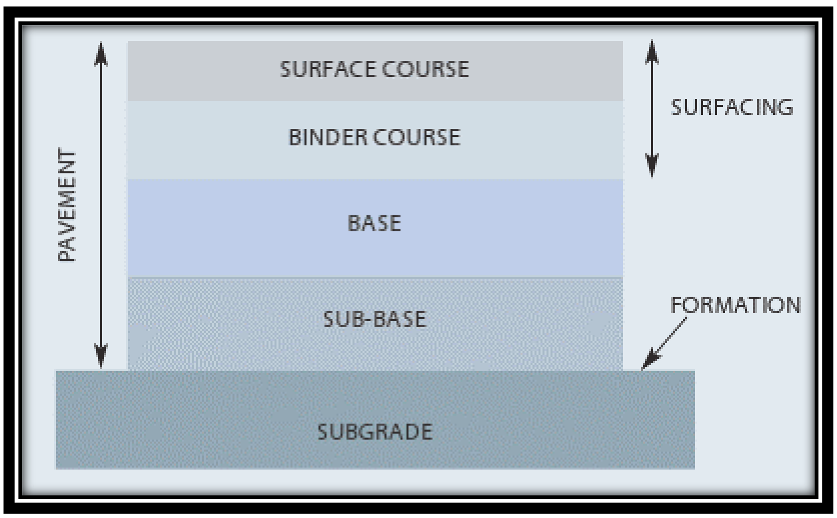

Figure 2.1: Vertical section of asphalt pavement (www.kattenhornsurfacing.co.uk)

2.5 Basic materials in hot mix asphalt

2.5.1 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, 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 0.075mm sieve. Mineral filler is a very fine material with the consistency of flour and is also referred to as mineral dust or rock dust (Transportation research board committee, 2011).

2.5.2 Coarse aggregate

Gravels are often dredged from rivers and are sometimes mined from deposits. Because of the rounded particle size, gravels are not suitable for use in HMA mixtures unless they are well crushed. Poorly crushed gravels will not interlock when used in HMA, and the resulting mixture will have poor strength and rut resistance. Crushed stone is coarse aggregate that is mined and processed by mechanical crushing. It tends to be a very angular material and, depending on its other properties, can be well suited for use in HMA pavements. One potential problem with crushed stone is that the particles sometimes will tend to be flat, elongated, or both, which can cause problems in HMA mixtures. Ideally, the particles in crushed stone aggregate should be cubicle and highly angular.

2.5.3 Fine aggregate

The fine aggregate, or sand, used in HMA can be natural sand, manufactured sand, or a mixture of both types. Natural sand is dredged from rivers or mined from deposits and is then processed by sieving to produce a fine aggregate having the desired particle size distribution. Manufactured sand is produced by crushing quarried stone and, like natural sand, sieving to produce the desired gradation. The particles in manufactured sands tend to be more angular than those in natural sand and often will produce HMA mixtures having greater strength and rut resistance compared to those made with natural sand. However, this is not always true, and care is needed when selecting fine aggregate.

2.5.4 Asphalt binder (bitumen)

Asphalt binders have been used in road construction for centuries. Although there are natural deposits of asphalt, most asphalts used today is produced through refining crude oil. Asphalt is a strong cement that is very adhesive and highly waterproof. It is also highly resistant to most acids, alkalis, and salts (Tabash, 2013).

2.5.5 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 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

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

Property	Definition	Examples of Mix Variables Which have Influence
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.

2.6 Asphalt Compaction

Compaction is the most important factor in the performance of an HMA pavement. Adequate compaction of the mix increases fatigue life, decreases permanent deformation (rutting), reduces oxidation or aging, decreases moisture damage, increases strength and stability, and decreases low-temperature cracking. An HMA mixture with all the desirable mix design characteristics will perform poorly under traffic if it has not been compacted to the proper density level. Indeed, a properly compacted mix with marginal properties will often outperform a mix with desirable properties that has been inadequately compacted. Four primary factors affect the ability of the compaction equipment to densify an asphalt mixture: properties of the materials in the mixture, environmental variables, conditions at the laydown site, and type of compaction equipment used (AASHTO, 2000).

2.7 Effect of compaction temperature on asphalt pavement

Jiménez, *et al*, (2014), discussed the effect of compaction temperature and procedure on the design of asphalt mixtures using Marshall and gyratory compactors .Temperature was observed to have more effect on mechanical properties than on compact ability with both procedures. In the case of SGC the difference in compact ability of specimens between 80 C and 160 C is about 1–2% while modulus reduction is between 25% and 30%. In the case of Marshall Compactor a higher variation in density reduction was appreciated, between 3% and 5%, when passing from 80 ° C to 160 ° C, and a modulus loss of 30–35% (Pérez-Jiménez, et al., 2014).

Saedi, (2012), argued that Hot Mix Asphalt (HMA) is one of the most common constructed asphalts in Iran and the quality control of constructed roads with HMA have been always paid due attention by researchers. The quality control of constructed roads with this method is being usually carried out by measuring volumetric parameters of HMA marshal samples. One of the important parameters that has a critical role in changing these volumetric parameters is “compaction temperature”; which as a result of its changing, volumetric parameters of Marshall Samples and subsequently constructed asphalt is encountered with variations. In this study, considering the necessity of preservation of the compaction temperature, the effect of various temperatures on Hot Mix Asphalt (HMA) samples properties has been evaluated. As well, to evaluate the effect of this parameter on different grading, two different grading (Top coat index grading and binder index grading) have been used and samples were compacted at 5 various temperatures (Saedi, 2012).

Saedi, (2012), concluded the following:

- Increasing compaction temperature makes density to be increased, but there is a limitation for this increase and afterwards density will be decreased. (145 °C) (See Figure 2.2).

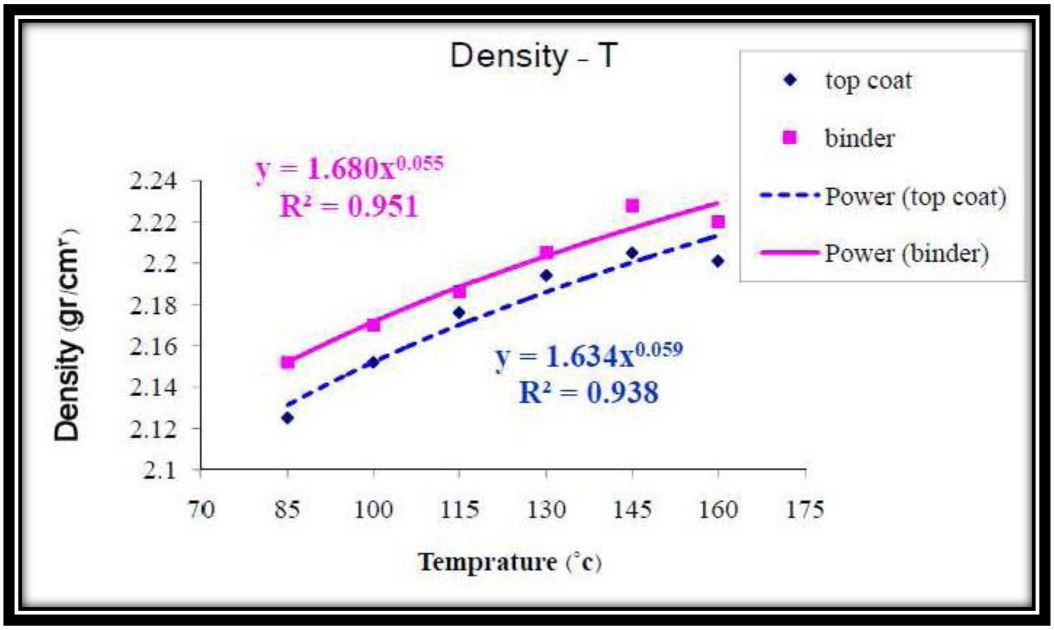

Figure 2.2: Density versus compaction temperature (Saedi, 2012)

- Considering the mentioned minimum and maximum for Va and VFA in MS2 and other references, the amount of authorized temperature parallel with them can be achieved (See Figure 2.3, 2.4).

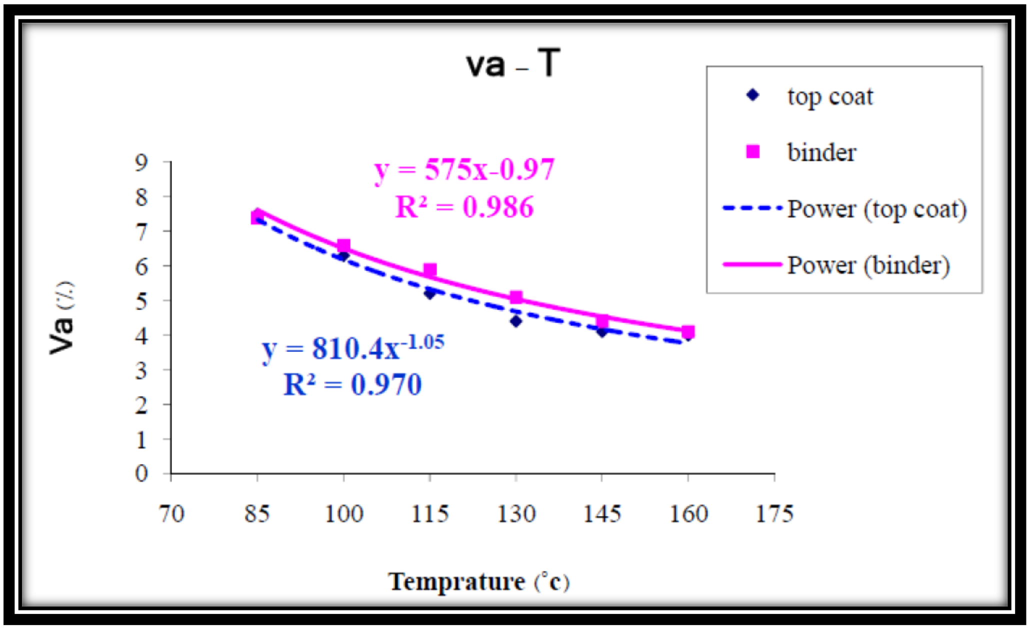

Figure 2.3: Air voids versus compaction temperature (Saedi, 2012)

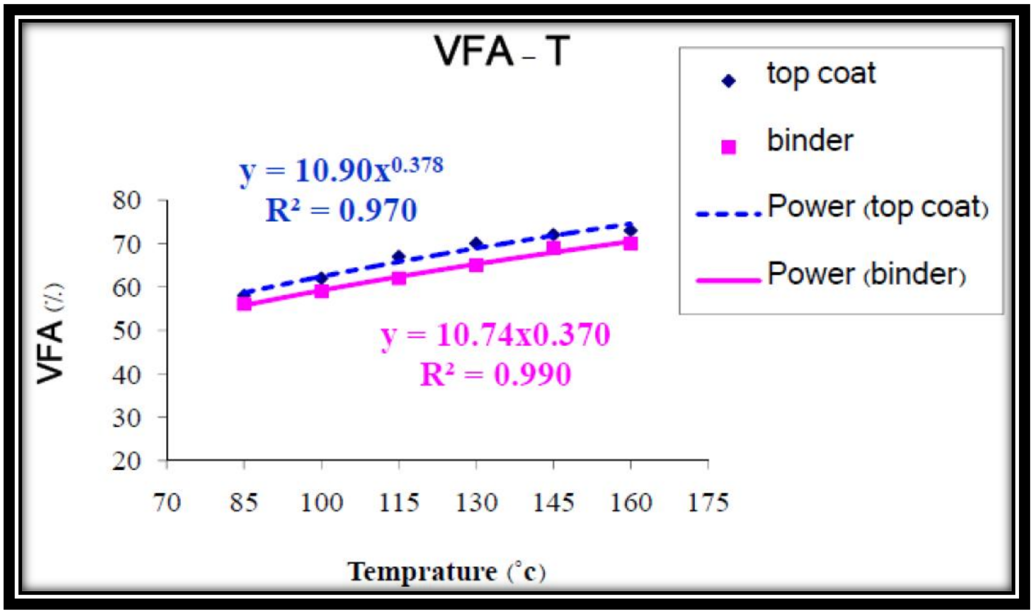

Figure 2.4: VFA versus compaction temperature (Saedi, 2012)

- Increasing the temperature makes stability to be increased, but the maximum rate of increase in this investigation is being occurred over the distance of 115°C - 130°C and 130°C - 145°C (See Figure 2.5).

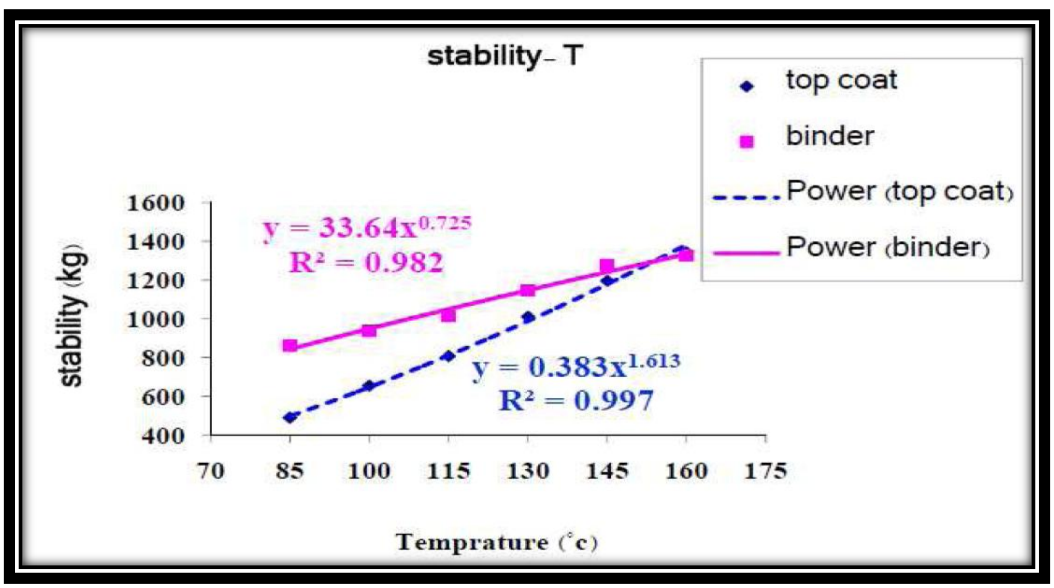

Figure 2.5: Stability versus compaction temperature (Saedi, 2012)

There can be found a best temperature for each mix design asphalt, which its Marshall sample has got best performance. (The temperature is about 145°C.).

Another study was conducted by (Al-Shalout, et al., 2007), who noticed that unit weight increases with the increase of compaction temperature. This is true for all mixtures containing different types of gradations. The increase in unit weight of asphalt concrete mixtures with the increase temperature was noticed in all grading because temperature decreased viscosity and made compaction easy (See Figure 2.6).

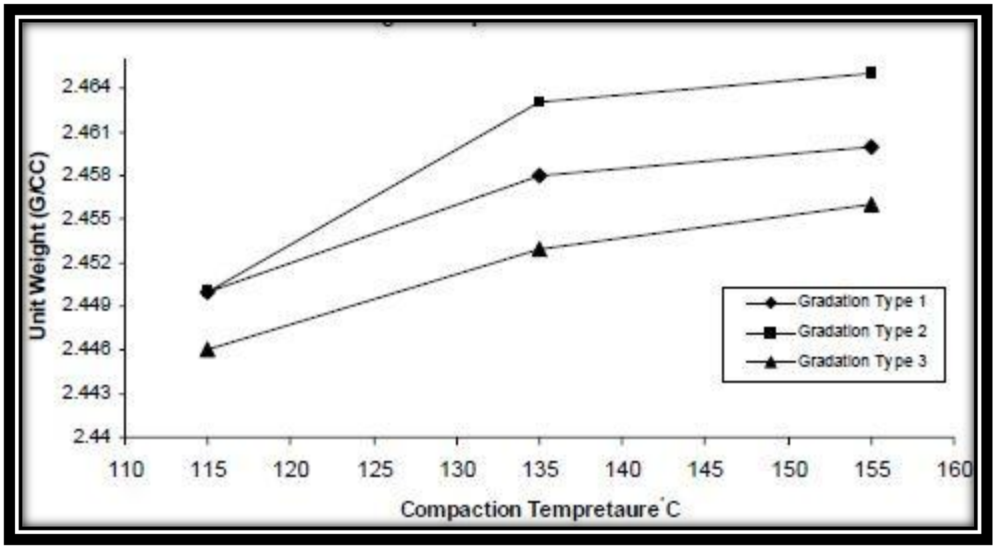

Figure 2.6: Relationship of compaction temperature versus unit weight of asphalt concrete mixture (Al-Shalout, et al., 2007)

Where noted Al-Shalout, *et al.*, (2007), the percent air voids decreases with increasing compaction temperature. This is also true for all mixes containing different types of gradations. The decrease in percent air voids with the increase in compaction temperature is due to lubricating effect of asphalt concrete keeping viscosity of the binder suitable for compaction. Gradation type 3 which is close to the coarse side exhibited highest value of percent air voids, while gradation type 1 and 2 which are close to the finer gradation and are in the middle of the gradation envelope exhibited the lowest values and they were very close to each other because there was so enough fines to fill the voids (See Figure 2.7).

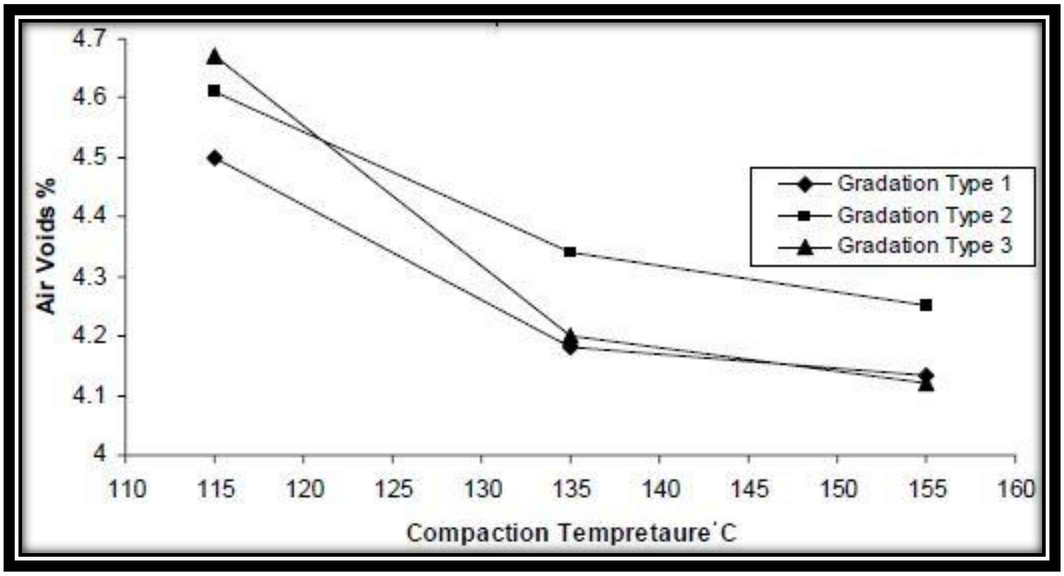

Figure 2.7: Relationship of compaction temperature versus percent air voids in asphalt concrete mixture (Al-Shalout, et al., 2007)

The relationships of compaction temperature versus percent V.M.A. It is noticed that the percent V.M.A decreases with the increase of compaction temperature. It was noticed that the initial decrease of percent V.M.A with the increase of compaction temperature is due to lubricating effect of binder, which increase the workability of the mix and improves the compaction and, consequently decreases the percent air voids and percent V.M.A (See Figure 2.7).

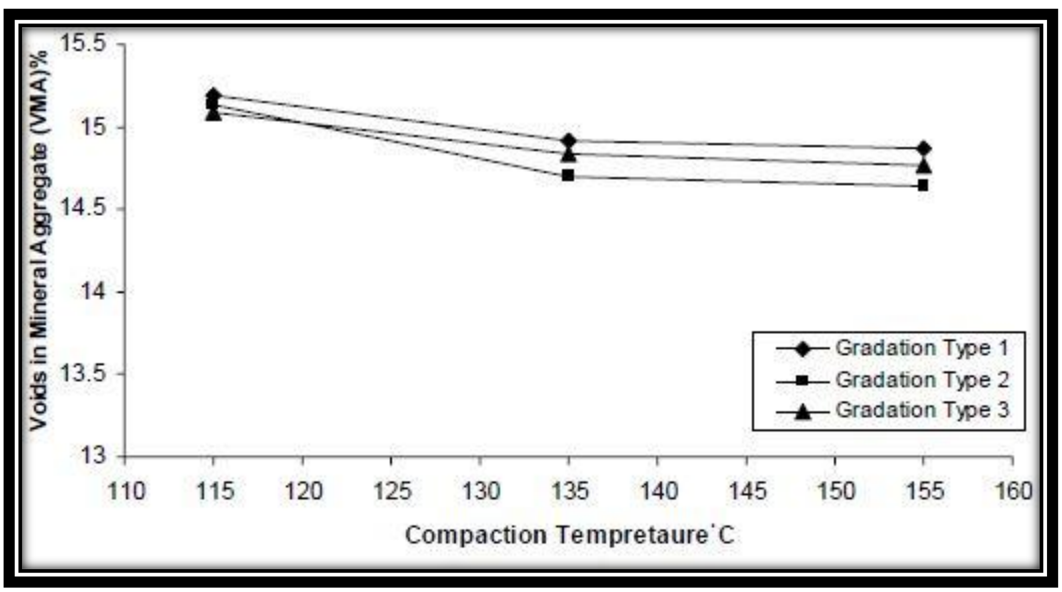

Figure 2.8: Relationship of compaction temperature versus percent voids in mineral aggregates (V.M.A) % (Al-Shalout, et al., 2007)

Brown and Cross, (1991), investigated the relationships between the measured density of the mixture obtained in the mix design, during quality control of the mixture (laboratory compaction of field produced mix), after initial compaction (cores obtained after construction and before traffic), the final or ultimate density obtained from pavement cores after densification by traffic and the density of re-compacted samples. Primary concern is the relationship between density after traffic, mix design density and density of laboratory compacted samples during construction. Eighteen different pavements were sampled from six states. Thirteen of the pavements were experiencing premature rutting and five of the pavements were performing satisfactorily. Construction history including mix design data, quality control and/or quality assurance data, traffic data and laboratory data of the physical properties of the pavement cores were analyzed from each site. The results show that in-place air void contents below 3% greatly increase the probability of coming early rutting and the in-place unit weights of the pavements after traffic usually exceed the mix design unit weight resulting in low air voids and hence premature rutting (Brown & Cross, 1991).

Jendia, and Jarada, (2006), in their study concluded that the time available for asphalt compaction (TAC) and the traffic opening time (TOT) are highly affected by the mix temperature, this study conducted in Gaza did not deal the effect of temperature on the density of the hot mix asphaltic concrete. The field study covered the collection of data for the cooling time of the HMA binder layers. It aimed at providing data for verification of the laboratory test results. A test program was designed in order to provide the necessary data. It involved measuring layer temperature in ongoing paving projects. The testing field sites were selected with properties similar to large extent to the laboratory tests (Jendia & Jarada, 2006).

Chapter 3. Material and testing program

3.1 Introduction

The major purpose of this thesis is to investigate the effect of compaction temperature on the mechanical properties of asphalt concrete mixtures. 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 used material properties such as aggregates, bitumen. Second, is to describe how experimental work has been carried out to achieve study objectives.

3.2 Laboratory testing process

This thesis depends on laboratory testing as the main procedure to achieve study goals. All the testing is conducted using equipment and devices existing in the Consulting Center for Quality and Calibration Material and soil Lab.

Laboratory tests are divided into a number of stages, which start with assessment of the properties of used materials as aggregates, bitumen. Sieve analysis is carried out for each aggregate type to obtain the grading of aggregate sizes followed by aggregates blending to obtain binder course gradation curve used to prepare asphalt mix, Therefore; 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. Marshal Test will be used to evaluate the properties of these modified mixes. Finally, laboratory tests 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.

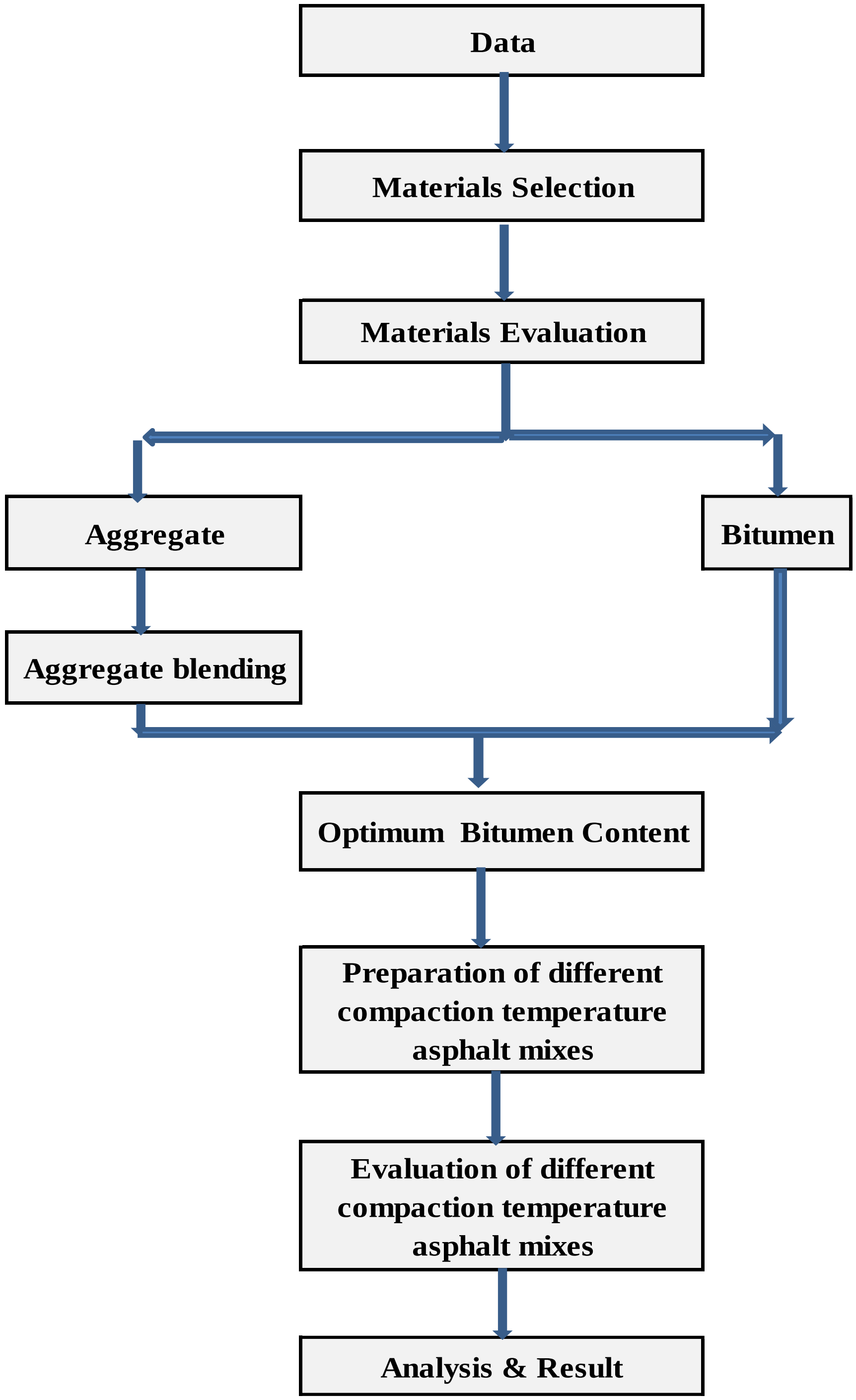

Figure 3.1 : Flow chart of laboratory testing procedure

Table 3.1: Main and local sources of used materials

Material	Source	
	Main	**Local**
Aggregates	Crushed rocks (Occupied Palestinian Territories)	Al-Amal factory
Bitumen	Occupied Palestinian Territories	Al-Amal factory

3.2.2 Number of samples required

First Stage:

Five percentages of bitumen will be examined to determine the best percentage of bitumen for the aggregates used, which include 4, 4.5, 5, 5.5 and 6% by weight of the mix with 5 samples for each percentage, total samples 25.

Second Stage:

Three samples will be made using the OBC for determining the mechanical properties at different temperatures starting from [80° C, 100° C, 120° C, 140° C, and 160 ° C], total samples 15.

Total number of samples required for two stage = approximately 40 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 number of laboratory tests have been performed such as: specific gravity, ductility, flash point, fire point, softening point and penetration.

3.2.3.1.1 Bitumen penetration test

Penetration: A measure of hardness and consistency. A sample is brought to a specified temperature and tested by allowing a loaded needle to penetrate it. The depth of penetration is measured.

O Test specification: ASTM D5/D5M -13, BS-EN 12591-2009, PS 166-1-1998.

O Container dimension: 75 mm x 55mm

O Test results are listed in Table (3.2) & Figure (3.2) shows penetration test

Setup for a bitumen sample.

Table 3.2: Bitumen penetration test results

Test	Unit	Result	Requirements	Specification
Penetration	1/10 mm	62	60-70	ASTM D5/D5M -13 BS-EN 12591-2009 PS 166-1-1998

Figure 3.2 :Penetration test for a bitumen sample

3.2.3.1.2 Ductility test

Ductility: A measure of an asphalt cement's adhesive qualities. The distance a briquette of asphalt cement is stretched before it breaks is measured.

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

Table 3.3: Bitumen ductility test results

Test	Unit	Result	Requirements	Specification
Ductility	cm	148	Min 100	ASTM D113-86

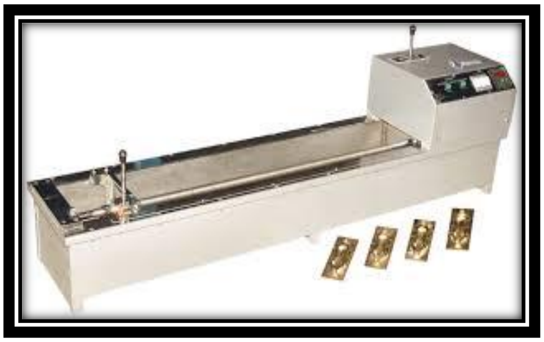

Figure 3.3 :Ductility test for a bitumen sample

3.2.3.1.3 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.

O Test specification: ASTMD36-2002

O Test results are listed in Table (3.4).

Table 3.4: Bitumen softening point results

Test	Unit	Result	Requirements	Specification
Softening point	° C	48.10	Min 44	ASTMD36-2002

3.2.3.1.4 Flash point tests

Flash Point: The temperature to which asphalt cement may safely be heated without the danger of instantaneous flash in the presence of an open flame (asphalt cement gives off vapors that can ignite).

O Test specification: ASTM D92-12b

O Test results is listed in Table (3.5)

O 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.

Table 3.5: Bitumen flash point test results

Test	Unit	Result	Requirements	Specification
Flash point	° C	261	Min 230 C°	ASTM D92-12b BS-EN 12591-2009 PS 166-1-1998

3.2.3.1.5 Density test

O Test specification: ASTM D 3289-08BS

O 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 3289-08 BS-EN 12591-2009

3.2.3.1.6 Solubility test

Solubility in Trichloroethylene: Determines the bitumen content (purity) of asphalt cement by measuring the insoluble left after dissolving a sample in trichloroethylene.

O Test specification: ASTM D 2042-09

O Test results is listed in Table (3.6)

Table 3.7: Bitumen solubility test results

Test	Unit	Result	Requirements	Specification
Solubility	%	99.2	Min 99.0%	ASTM D 2042-09 BS-EN 12591-2009 PS 166-1-1998

3.2.3.1.7 Viscosity test

Viscosity: A measure of the flow characteristics (consistency). Viscosity is a fluid's resistance to flow ("fluid friction"). Viscosity is measured in a capillary tube viscometer.

O Test specification: ASTM D3381/D3381M-13

O Test results is listed in Table (3.6)

Table 3.8: Bitumen viscosity test results

Test	Unit	Result	Requirements	Specification
Viscosity	135 ° C	385	Min. 300	ASTM D3381/D3381M-13 , ASTM D 2170-01a

3.2.3.1.6 Summary of bitumen properties

Table (3.9) display a various bitumen properties and compared with ASTM specifications limits.

Table 3.9: Summary of bitumen properties

Test	Unit	Result	Requirements	Specification
Penetration	1/10 mm	62	60-70	ASTM D5/D5M -13 , BS - EN 12591-2009, PS 166-1-1998
Ductility	cm	148	Min 100	ASTM D113-86
Softening point	° C	48.10	44	ASTMD36-2002
Flash point	° C	261	Min 230 ° C	ASTM D92-12b, BS - EN 12591-2009, PS 166-1-1998
Density	g/ml	1.02	0.97-1.06	ASTM D 3289, BS - EN 12591-2009
Solubility	%	99.2	Min 99.0%	ASTM D 2042-09 BS EN 12591-2009 PS 166-1-1998
Viscosity	135 ° C	385	Min. 300	ASTM D3381/D3381M-13 , ASTM D 2170-01a

3.2.3.2 Aggregates properties

Aggregates used in asphalt mix can be divided as shown in Table (3.10) and

Table 3.10: Used aggregates types

	Type of aggregate	Particle size (mm)
Coarse	Folia	0/ 19.0
	Adasia	0/ 12.5
	Simsimia	0/ 9.50
Fine	Trabia	0/4.75
	Sand	0/0.6

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

- Sieve Analysis(ASTM C136)
- Specific gravity test (ASTM C127).
- Water absorption (ASTM C128)
- Flakiness (ASTM D4791)
- Elongation (ASTM D4791)

- Abrasion Loss (ASTM C 131)
- Clay Lumps (ASTM C142/C142M)
- Sand Equivalent (AASHTO T 176)

Table 3.11: Specific Gravity Test of aggregates

		Folia	Adasia	Simsimia
S.S.D Weight	g	2880.0	2968.0	**1598.0**
Weight in Water	g	1745.8	1808.3	**970.6**
Volume of Solids	cm^3	1134.2	1159.7	**627.4**
Specific Gravity		2.539	2.559	**2.547**
Dry Specific Gravity		2.481	2.504	**2.458**

Table 3.12: Water Absorption Test of Aggregates

		Folia	Adasia	Simsimia
S.S.D Weight	g	2880.0	2968.0	**1598.0**
Oven Dry Weight	g	2815.5	2905	**1544**
Water Absorption	%	2.3	2.2	**3.5**

Table 3.13: Specific Gravity Test of Sand & Filler

		Fine	Filler
Dry Weight	g	481.4	**320.6**
Pycnometer + water	g	1070.7	**1070.7**
Pycnometer + water +Sample	g	1364.8	**1265.9**
Specific Gravity		2.622	**2.608**

Table 3.14: Aggregates Quality Test Results

Aggregate Type	**Folia Aggregate**	**Adasia Aggregate**	**Simsimia Aggregate**	**Fine Aggregate**
Test Name				
Flakiness Index	14	16	15	*
Elongation Index	18	19	23	*
Abrasion Loss (500 Cycles) %	24.9	23.9	19.4	*
Ratio of 100/500 Loss %	0.17	0.19	0.15	*
Aggregates Crushing Value %	22.8	22.2	21.4	*
Soundness Loss (MgSO4) %	2.7	2.4	3.6	4.1
Clay Lumps %	0.2	0.1	0.6	0.8
Sand Equivalent %	*	*	*	73

3.2.3.2.1 Sieve analysis

According to specification (ASTM C136), show aggregates sieve analysis result.

Table 3.15: Folia Aggregate sieve analysis

Dry Wt. Before Sieving:	3169 g				
Sieve No.	**Sieve Opening Size (mm)**	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	**% Passing**
1"	25.00	0.0	0.00	0.0	**100.00**
3/4"	19.00	53.0	1.67	1.7	**98.33**
1/2"	12.50	2902.0	91.57	93.2	**6.75**
3/8"	9.50	191.0	6.03	99.3	**0.73**
#4	4.75	13.0	0.41	99.7	**0.32**
#8	2.36	0.0	0.00	99.7	**0.32**
#20	0.850	0.0	0.00	99.7	**0.32**
#50	0.300	0.0	0.00	99.7	**0.32**
#80	0.180	0.5	0.02	99.7	**0.30**
#200	0.075	1.0	0.03	99.7	**0.27**
pan	0.000	8.5	0.27	100.0	**0.00**

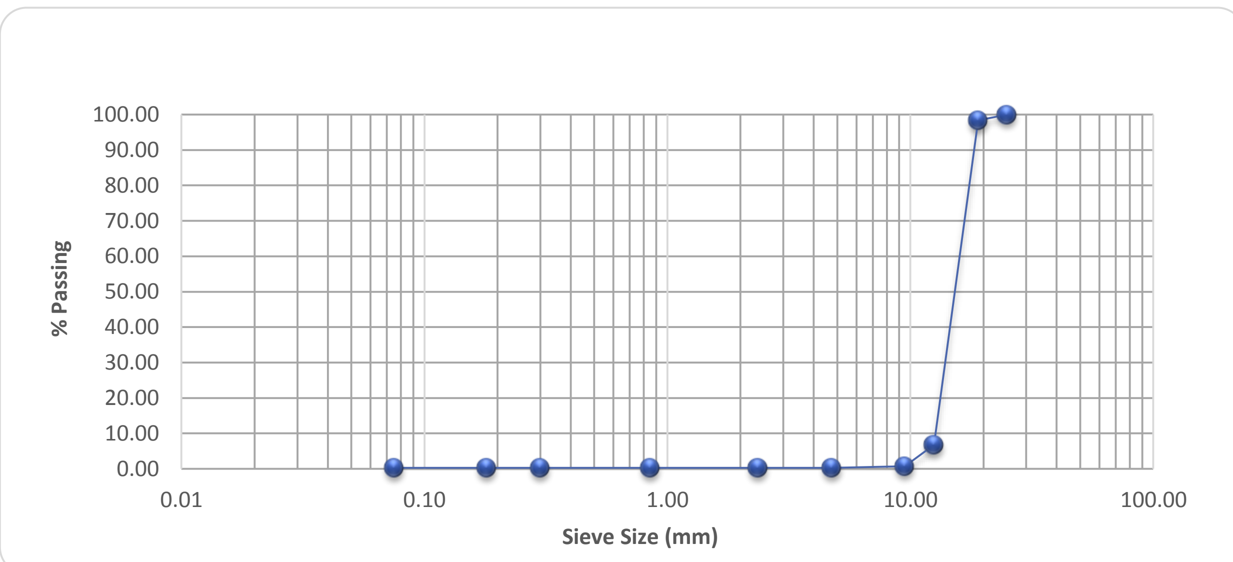

Figure 3.4: Gradation curve - (Folia 0/19mm) for aggregate

Table 3.16: Adasia Aggregate sieve analysis

Dry Wt. Before Sieving:	1966 g				
Sieve No.	**Sieve Opening Size (mm)**	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	**% Passing**
1"	25.00	0.0	0.00	0.0	**100.00**
3/4"	19.00	0.0	0.00	0.0	**100.00**
1/2"	12.50	351.0	17.85	17.9	**82.15**
3/8"	9.50	1206.0	61.34	79.2	**20.80**
#4	4.75	392.0	19.94	99.1	**0.86**
#8	2.36	5.9	0.30	99.4	**0.56**
#20	0.850	4.3	0.22	99.7	**0.35**
#50	0.300	0.6	0.03	99.7	**0.32**
#80	0.180	2.3	0.12	99.8	**0.20**
#200	0.075	1.9	0.10	99.9	**0.10**
pan	0.000	2.0	0.10	100.0	**0.00**

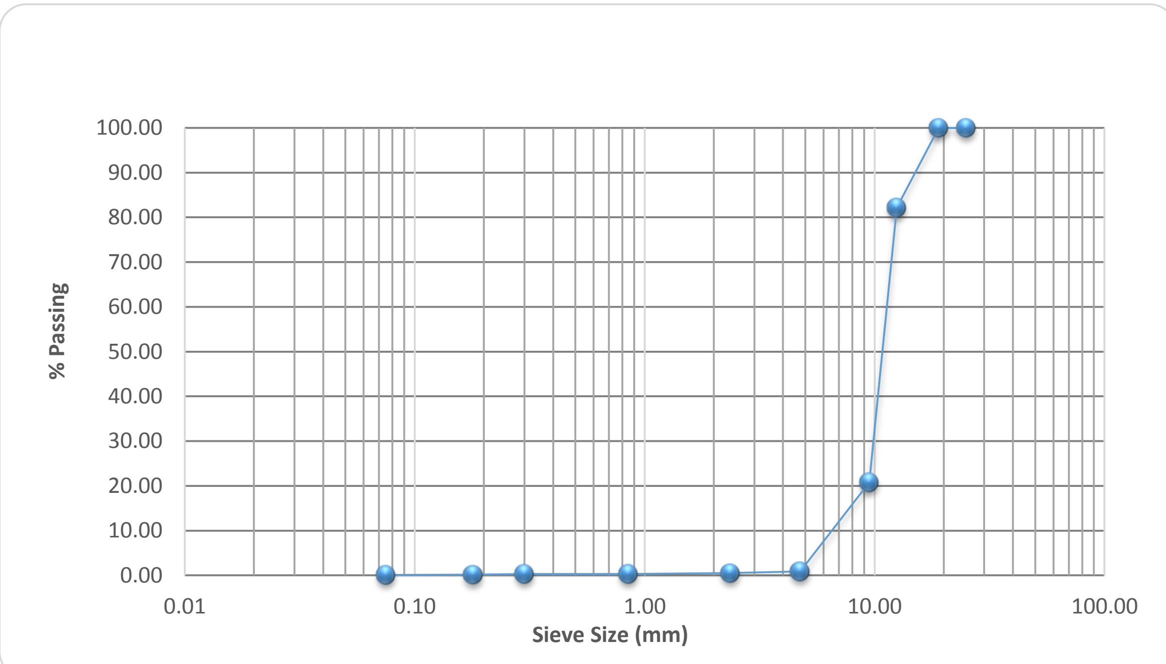

Figure 3.5: Gradation curve - (Adasia 0/12.5 mm)

Table 3.17: Simsimia Aggregate sieve analysis

Dry Wt. Before Sieving:	1458 g				
Sieve No.	**Sieve Opening Size (mm)**	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	% Passing
1"	25.00	0.0	0.00	0.0	**100.00**
3/4"	19.00	0.0	0.00	0.0	**100.00**
1/2"	12.50	0.0	0.00	0.0	**100.00**
3/8"	9.50	13.0	0.89	0.9	**99.11**
#4	4.75	667.0	45.75	46.6	**53.36**
#8	2.36	644.0	44.17	90.8	**9.19**
#20	0.850	126.0	8.64	99.5	**0.55**
#50	0.300	0.6	0.04	99.5	**0.51**
#80	0.180	0.0	0.00	99.5	**0.51**
#200	0.075	3.4	0.23	99.7	**0.27**
pan	0.000	4.0	0.27	100.0	**0.00**

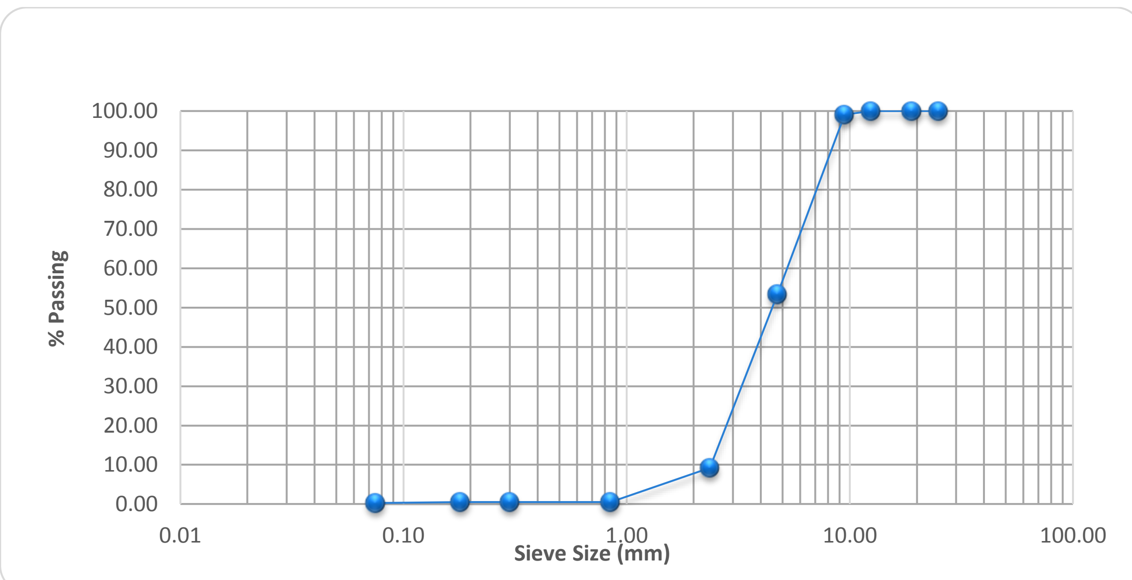

Figure 3.6: Gradation curve - (Sismimia 0/9.5 mm)

Table 3.18: Fine Aggregate sieve analysis

Dry Wt. Before Sieving:	889.6 g				
Sieve No.	**Sieve Opening Size (mm)**	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	% Passing
1"	25.00	0.0	0.00	0.0	**100.00**
3/4"	19.00	0.0	0.00	0.0	**100.00**
1/2"	12.50	0.0	0.00	0.0	**100.00**
3/8"	9.50	2.6	0.29	0.3	**99.71**
#4	4.75	46.9	5.27	5.6	**94.44**
#8	2.36	106.8	12.01	17.6	**82.43**
#20	0.850	390.0	43.84	61.4	**38.59**
#50	0.300	218.0	24.51	85.9	**14.08**
#80	0.180	45.8	5.15	91.1	**8.94**
#200	0.075	32.3	3.63	94.7	**5.31**
pan	0.000	47.2	5.31	100.0	**0.00**

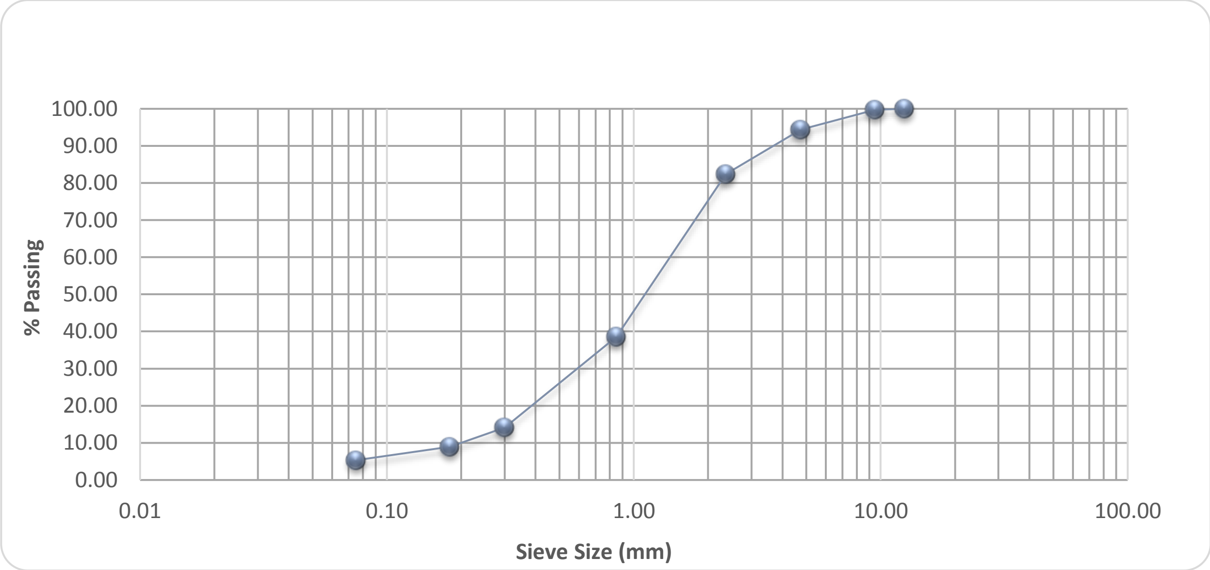

Figure 3.7: Gradation curve - (Fine 0/4.75mm)

Table 3.19: Filler Aggregate sieve analysis

Dry Wt. Before Sieving:	522.4 g				
Sieve No.	**Sieve Opening Size (mm)**	**Weight Retained (gm)**	**% Retained**	**Cumulative % Retained**	% Passing
1"	25.00	0.0	0.00	0.0	**100.00**
3/4"	19.00	0.0	0.00	0.0	**100.00**
1/2"	12.50	0.0	0.00	0.0	**100.00**
3/8"	9.50	0.0	0.00	0.0	**100.00**
#4	4.75	0.0	0.00	0.0	**100.00**
#8	2.36	0.0	0.00	0.0	**100.00**
#20	0.850	0.0	0.00	0.0	**100.00**
#50	0.300	25.1	4.80	4.8	**95.20**
#80	0.180	30.8	5.90	10.7	**89.30**
#200	0.075	61.7	11.81	22.5	**77.49**
pan	0.000	404.8	77.49	100.0	**0.00**
					100.00

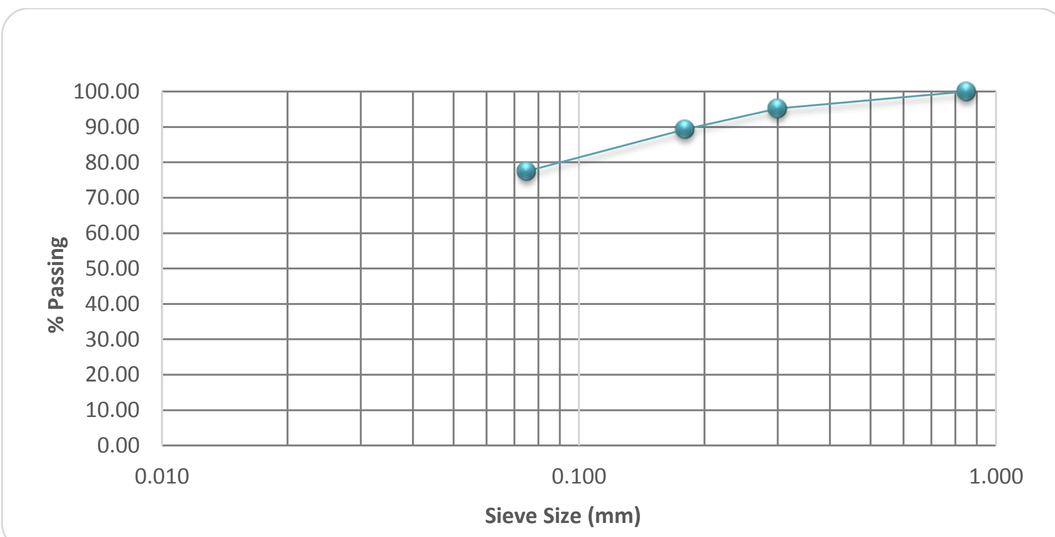

Figure 3.8: Gradation curve - (Filler 0/0.3 mm)

3.2.1 Blending of aggregates

Asphalt mix needs the combining of two or more aggregates, having different gradations, to produce an aggregate blend that meets gradation specifications for a particular asphalt mix. Existing aggregate materials integrated with the purpose to get the proper gradation within the acceptable limits according to ASTM specifications using mathematical trial method. This manner 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 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 offered in Chapter (4) and in additional detail in Appendix (A).

3.2.2 Marshal test

Marshall Method for designing hot asphalt mixtures is used to determine the optimum bitumen content (OBC) 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 15 samples each of 1200 gm in weight were prepared using five different bitumen contents (from 4 - 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 (Tabash, 2013). Figure (3.9) 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. The following graphs are then plotted:

Steps for Marshal Method (AASHTO , 2013):

1) Preparation of test specimens.
2) Bulk specific gravity determination. Bitumen Content;
3) Stability and flow test determination. Bitumen Content;
4) Density and voids determination (Va) vs. Bitumen Content;

5) Voids Filled with Bitumen (VFB) vs. Bitumen Content These graphs are utilized to obtain optimum bitumen content.

Figure 3.9: Marshal specimens for different bitumen percentages

3.2.3 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 consist of:

- Bitumen content at the highest stability (% mb)Stability
- Bitumen content at the highest value of bulk density (% mb)bulk density
- 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) % =

$$\frac{(\%mb)_{stability} + (\%mb)_{bulk\ density} + (\%mb)_{v_a}}{3}$$

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

3.3 Preparation of asphalt mix at different temperatures.

Implementing the asphalt mixes compacted at different temperatures starting from [80° C, 100° C, 120° C, 140° C, and 160 ° C].

Figure 3.10: Preparation of asphalt mix at 160 C°

Figure 3.11: Asphalt compaction temperature at 80C° and 160C°

Chapter 4. Results and data analysis

4.1 Introduction

Results of laboratory work have been obtained and analyzed with the purpose of achieving study objectives which include studying the relationship between the density and the initial temperature of the asphalt binder course.

Laboratory work results are presented in this chapter in three stages. First, handle the results of blending aggregates to obtain asphalt binder course gradation curve. Second stage, Marshal Test is carried out with different percentages of bitumen which are (4.0, 4.5, 5.0, 5.5 and 6.0%) and the results are analyzed with the purpose of obtaining the optimum bitumen content (OBC). Later than identify OBC, the next step is to study the relationship between the density and the initial temperature of the asphalt binder course.

4.2 First Stage

4.2.1 Blending of aggregates

The final ratio of each aggregate material in asphalt binder course is shown in Table (4.1). The proposed aggregates gradation curve is found to be satisfying ASTM specification for asphalt binder 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
Folia Aggregate	8.0 %
Adasia Aggregate	29.0 %
Simsimia Aggregate	15.0 %
Fine Aggregate	43.0 %
Filler	5.0 %
Total	100.0 %

Table 4.2: Mix gradations of aggregates

Sieve No.	Folia Aggregate	Adasia Aggregate	Simsimia Aggregate	Fine Aggregate	Filler
1"	100.0	100.0	100.0	100.0	100.0
3/4"	98.3	100.0	100.0	100.0	100.0
1/2"	6.8	82.1	100.0	100.0	100.0
3/8"	0.7	20.8	99.1	99.7	100.0
#4	0.3	0.9	53.4	94.4	100.0
#8	0.3	0.6	9.2	82.4	100.0
#20	0.3	0.3	0.5	38.6	100.0
#50	0.3	0.3	0.5	14.1	95.2
#80	0.3	0.2	0.5	8.9	89.3
#200	0.3	0.1	0.3	5.3	77.5

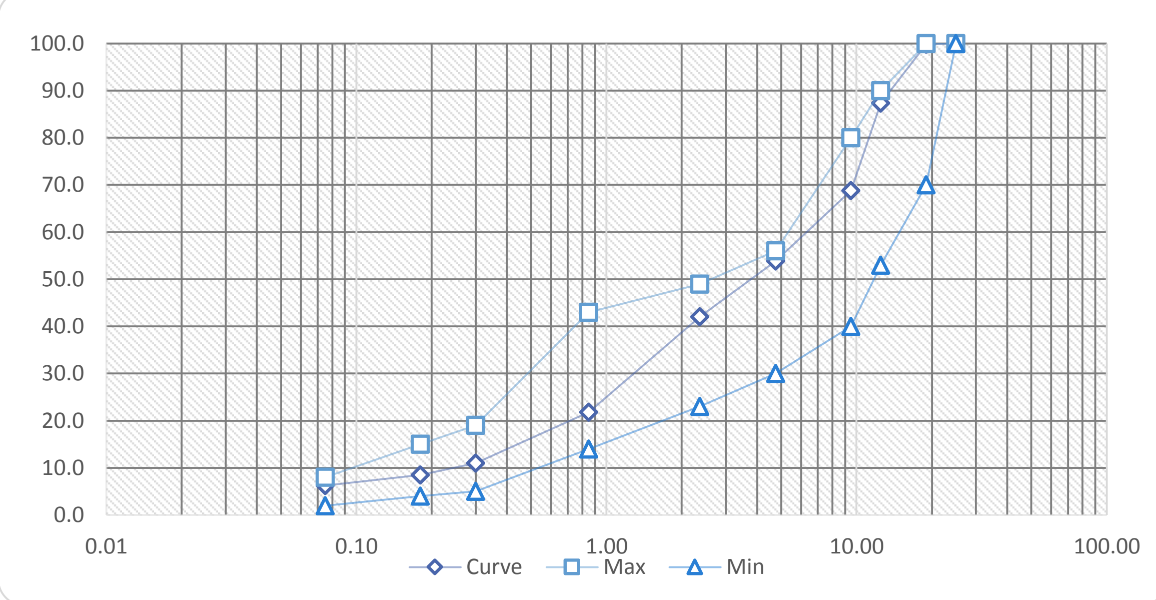

Figure 4.1: Job Mix Gradation with Palestinian Specification PS 171/1998

Table 4.3: Gradation of proposed mix with Palestinian Specification PS 171/1998

Sieve No.	Sieve Opening (mm)	Passing %	Min	Max
1"	25.0	100	100	100
3/4"	19.0	99.9	70	100
1/2"	12.5	87.4	53	90
3/8"	9.5	68.8	40	80
#4	4.75	53.9	30	56
#8	2.36	42.0	23	49
#20	0.850	21.8	14	43
#50	0.300	11.0	5	19
#80	0.180	8.5	4	15
#200	0.075	6.2	2	8

4.2.2 Optimum bitumen content

As indicated in Chapter (3). A number of 15 samples each of 1200 gm approximate in weight were prepared using five different bitumen contents (from 4 - 6% with 0.5 % incremental) with the purpose to obtain the optimum bitumen content (OBC) for one job mix. Table (4.4) and Figures (4.2 –4.7) show summary of Marshal Test results. Further details are offered in Appendix (D).

Table 4.4: 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	1	1194.9	2.30	2.273	6.7	15.6	56.7	519.5
	2	1130.3	2.30	2.268	6.9	15.7	56.0	491.4
	3	1126.2	2.20	2.270	6.9	15.7	56.3	511.9
	Average	**1150.5**	**2.27**	**2.271**	**6.8**	**15.7**	**56.3**	**507.6**
4.5	1	1194.9	2.60	2.295	5.20	15.20	66.0	459.6
	2	1167.6	2.60	2.293	5.30	15.30	65.6	449.1
	3	1227.2	2.80	2.294	5.20	15.20	65.8	438.3
	Average	**1196.5**	**2.67**	**2.294**	**5.20**	**15.20**	**65.8**	**449.0**
5	1	1420.9	2.90	2.307	4.00	15.20	73.6	490.0

Bitumen %(by total weight)	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
	2	1513.8	3.00	2.306	4.00	15.20	73.5	504.6
	3	1485.5	3.10	2.308	3.90	15.20	74.0	479.2
	Average	**1473.4**	**3.00**	**2.307**	**4.00**	**15.20**	**73.7**	**491.3**
5.5	1	1291.7	3.50	2.293	3.90	16.10	75.9	369.1
	2	1259.4	3.60	2.295	3.80	16.10	76.3	349.8
	3	1345.6	3.50	2.294	3.90	16.10	76.0	384.4
	Average	**1298.9**	**3.53**	**2.294**	**3.90**	**16.10**	**76.0**	**367.8**
6	1	1065.7	3.90	2.269	4.20	17.50	75.7	273.3
	2	1130.3	3.80	2.271	4.20	17.40	76.0	297.4
	3	1063.7	4.00	2.271	4.20	17.40	76.1	265.9
	Average	**1086.5**	**3.90**	**2.270**	**4.20**	**17.4**	**75.9**	**278.9**

4.2.3 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 are represented. Stability of asphalt mix increases as the bitumen content increase till it reaches the peak at bitumen content 5.0% then it started to drop gradually at higher bitumen content.

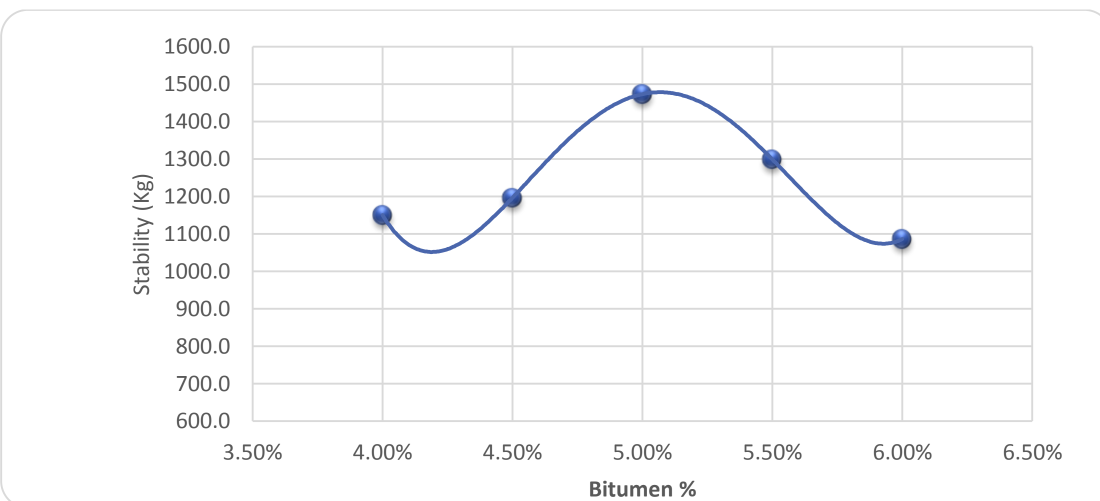

Figure 4.2: Stability vs. bitumen content

4.2.4 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 are represented. Flow of asphalt mix increases as the bitumen content increase till it reaches the peak at the max bitumen content 6 %.

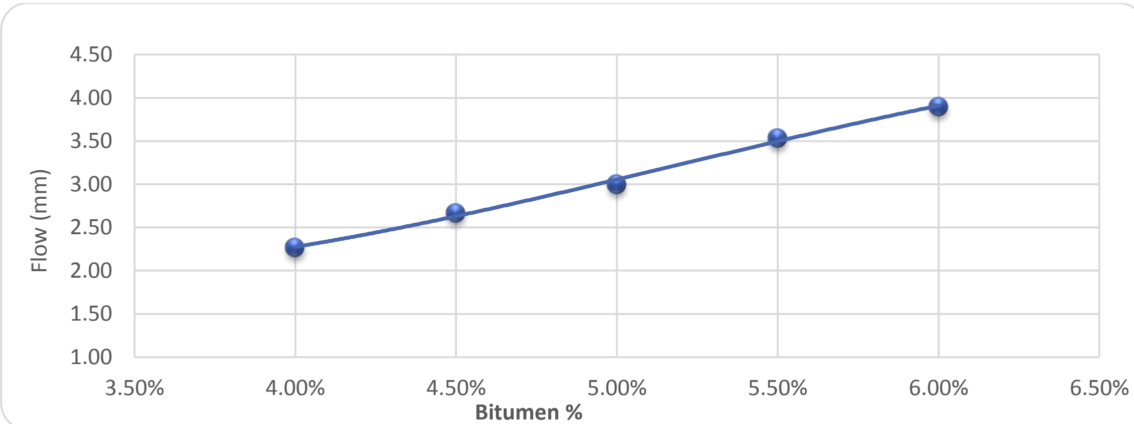

Figure 4.3: Flow vs. bitumen content

4.2.5 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 (2.307g/cm3) at bitumen content 5.0 % then it started to decline gradually at higher bitumen content.

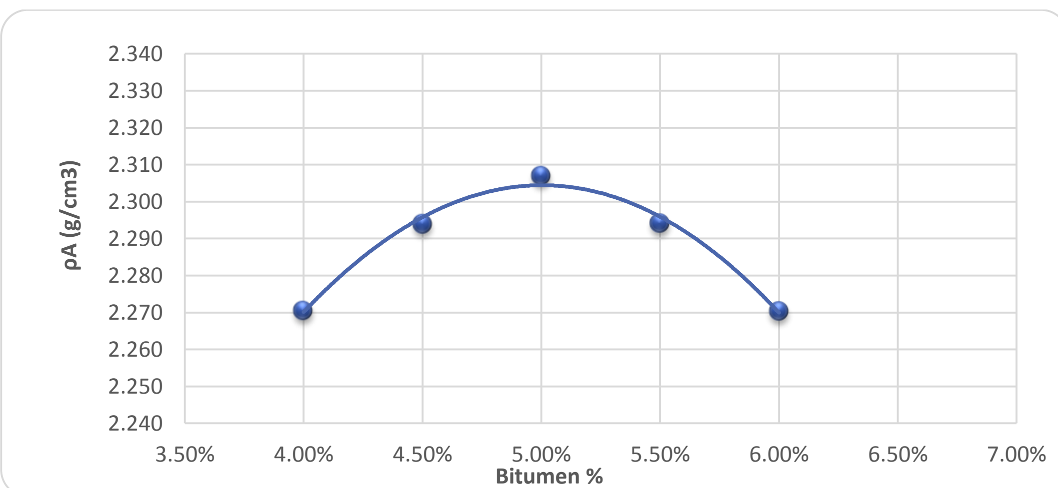

Figure 4.4: Bulk density vs. bitumen content

4.2.6 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%), (Va %) decrease steadily as bitumen content increase due to the increase of voids percentage filled with bitumen in the asphalt mix.

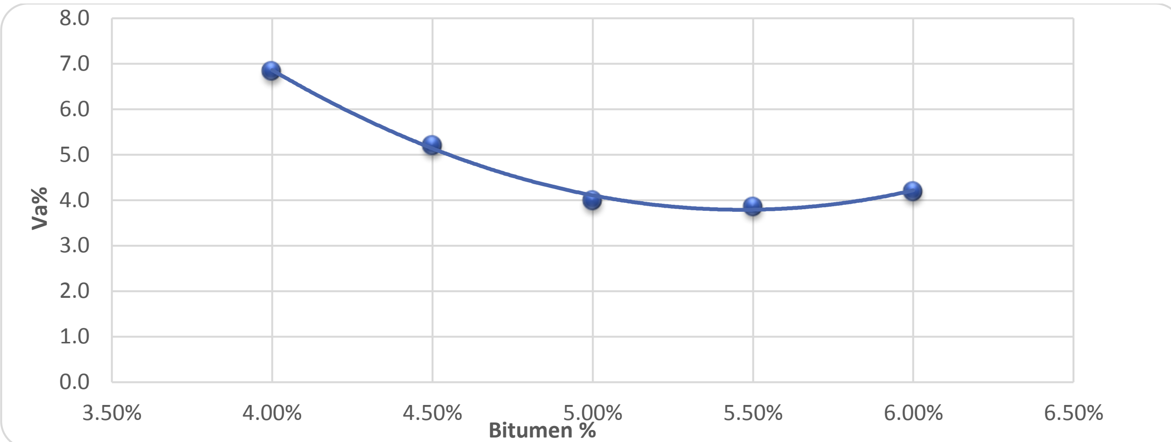

Figure 4.5: Mix air voids proportion vs. bitumen content

4.2.7 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%), VFB% increase steadily as bitumen content increase due to the increase of voids percentage filled with bitumen in the asphalt mix.

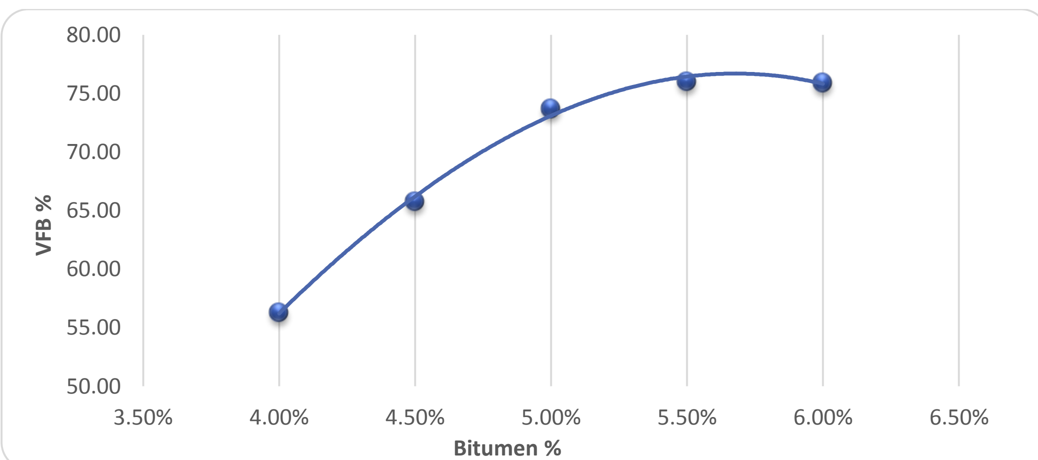

Figure 4.6: Voids filled bitumen proportion vs. bitumen content

4.2.8 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.

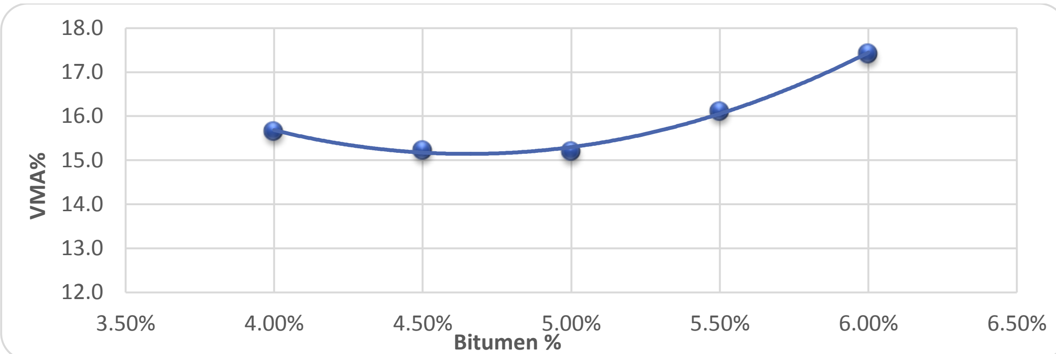

Figure 4.7: Voids of mineral aggregates proportion vs. bitumen content

4.2.9 Determination of optimum bitumen content (OBC)

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

- Bitumen content at the highest stability (% mb) Stability = 5.05 %
- Bitumen content at the highest value of bulk density (% mb) bulk density =5.00%
- Bitumen content at the median of allowed percentages of air voids (%mb) Va = 5.05%
- Optimum bitumen content (OBC) = $\frac{(5.05+5.00+5.05)}{3} \cong 5.00$

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

Table 4.5: Recommended to select the optimum asphalt bitumen content (MPWH, 1998)

	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	%	13.5	***
Stiffness	Kg/mm	400.0	***

According to Asphalt Institute, it is recommended to select the optimum asphalt bitumen content (OBC), corresponding to required air voids content. Then determining the properties at this optimum asphalt binder content by referring to the curves. Then a narrow range is determined, comparing each of these values against specified values and if all are within specification, then the preceding optimum asphalt binder content is satisfactory. Otherwise, if any of these properties is outside the specification range the mixture should be redesigned. The following combined grading is considered as a mix grading and the corresponding tolerance of production can be used as stated in (Palestinian Standard, 1998) for Highways and bridge Constructions.

4.3 Effect of Compaction Temperatures on Hot Mix Asphalt (HMA) Properties

4.3.1 Density versus compaction temperature

Figure. 4.8 shows that density of binder is being increased with increasing compaction temperature. According to (Saedi, 2012), the increased density is as a result of asphalt cement viscosity due to temperature increase and subsequently, the condition of aggregates location beside each other is in a denser condition. The results indicated that the highest density of binder layer (2.337 g/cm3) is being occurred at the temperature of 160 °C. High correlation of binder layer indicated the significant relationship between density and compaction temperature (index R2 = 0.9232).

Moreover, it was observed that asphalt samples compacted at temperature from (140 °C to 160 °C) has higher densities than those compacted at lower temperatures (less than 120 °C). With R2=0.9306, the relationship between initial temperature vs asphalt density could be fitted by the equation:

$$D = 0.0021T + 2.0124$$ (D: density in g/cm3, T: temperature in °C).

This equation could be used by site engineers to predict the asphalt density before paving and laboratory results.

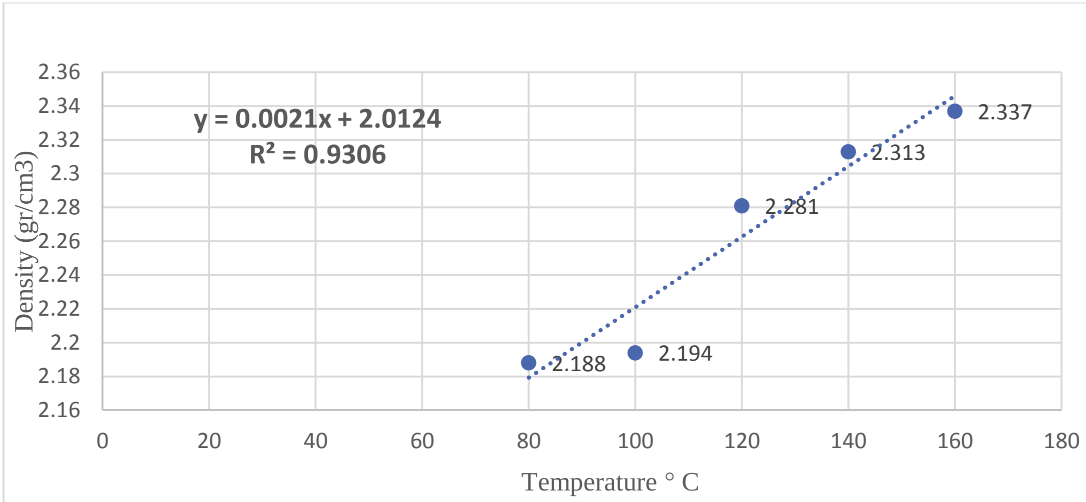

Figure 4.8: Density versus compaction temperature.

4.3.2 Stability versus compaction temperature

As shown in Figure 4.9, stability of binder layer mix design is being increased with the increase of the compaction temperature. However, the increase increments is being decreased as the temperature increase. This figure also indicated the strong relationship between stability and compaction temperature with R^2 = 0.9708.

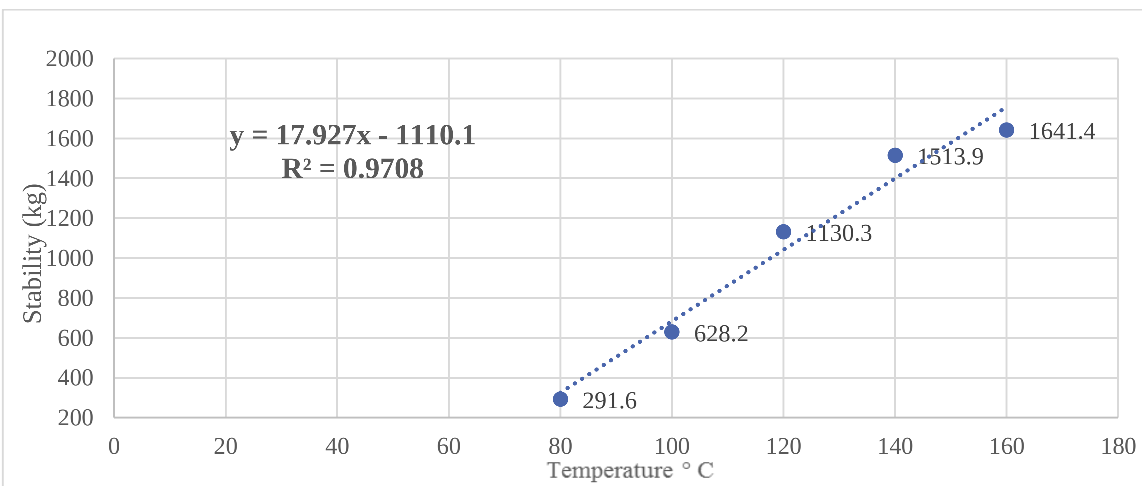

Figure 4.9: Stability versus compaction temperature

4.3.3 Air voids versus compaction temperature

According to figure 4.10, Percent air voids (Va) of binder aggregate is being decreased as the compaction temperature increase. Saedi, (2012) aruged that the higher compaction temperature is behind of the asphalt cement viscosity and more asphalt cement dispersion on the asphalt surface, as well it makes a thin film of bitumen becomes enough for covering the coarse aggregates. The figure also displayed the strong relationship between air voids and compaction temperature with $R^2 = 0.9321$.

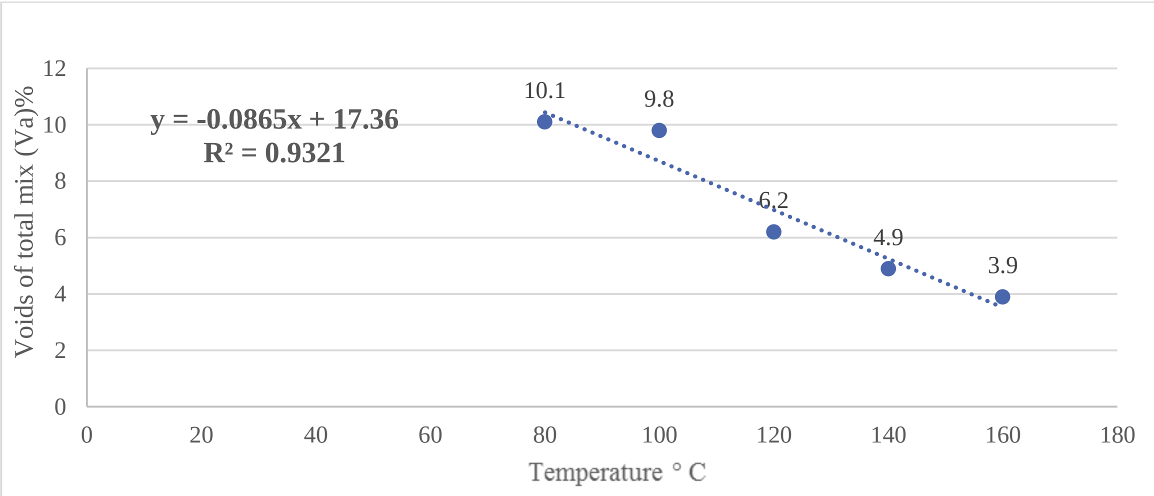

Figure 4.10: Air voids versus compaction temperature

4.3.4 Voids Filled with Bitumen (VFB) versus compaction temperature

Fig. 4.11 showed that VFB is being increased with the increase of compaction temperature. A strong relationship between VFB and compaction temperature indicated was adapted with $R^2 = 0.9445$. According to AASHTO, (2000), and Palestinian Specification PS 171/1998 for Highways and bridge Constructions, the authorized limitations for the VFB of the binder layer are in the range between 130 °C (VFA = 60) to 165 °C (VFA = 75).

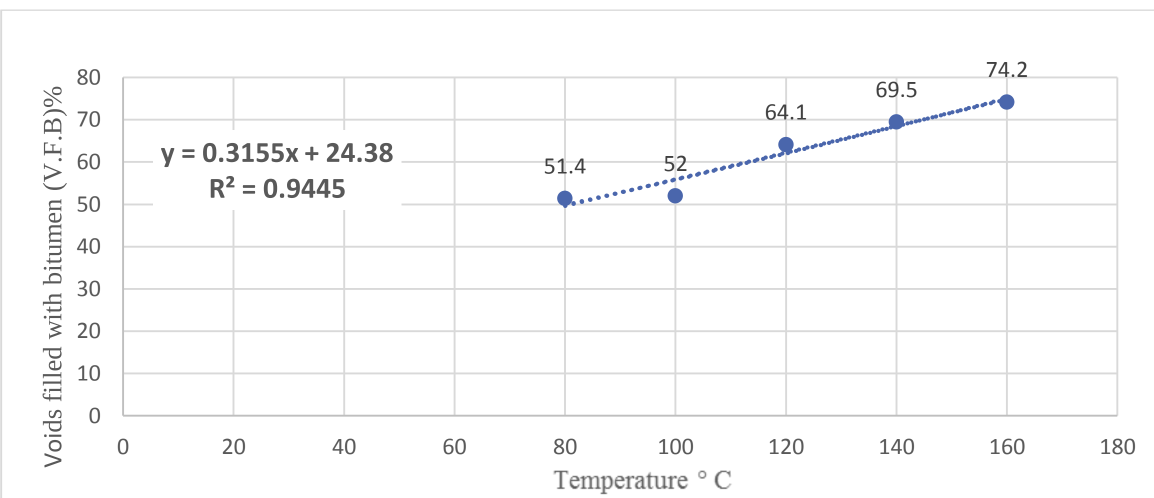

Figure 4.11: Voids filled with bitumen versus compaction temperature

4.3.5 Plastic flow versus compaction temperature

The quantity of Marshall Flow binder layers is being simultaneously increased with the increase of compaction temperature. The fig. 4.12 revealed a strong relationship between flow and compaction temperature (R^2 = 0.9641). According to the mentioned minimum and maximum authorized quantity for flow (2-4 mm), all of the attained flow quantities for binder layer are in the authorized limitation.

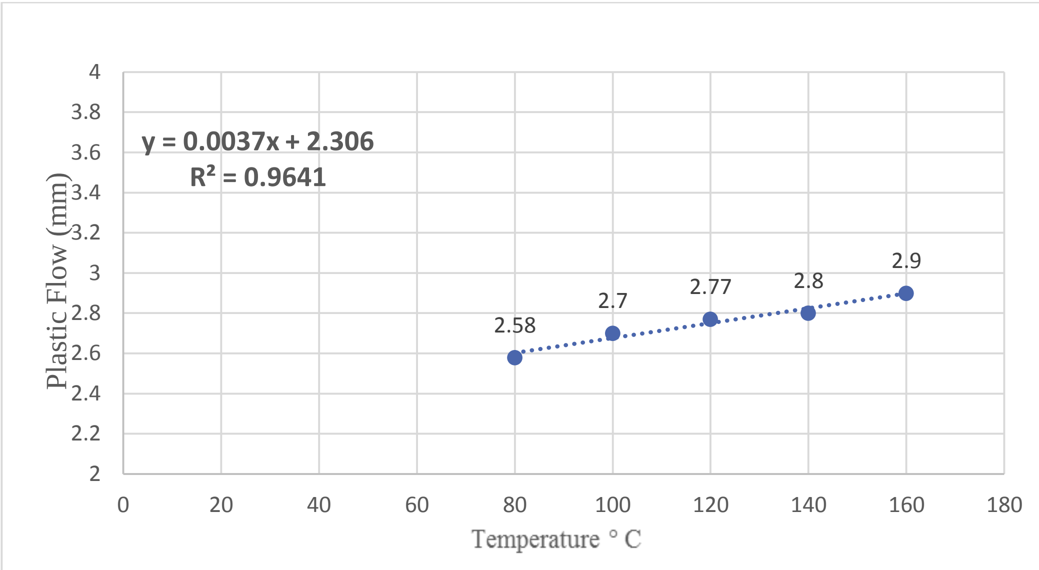

Figure 4.12: Plastic flow versus compaction temperature

4.3.6 Stiffness versus compaction temperature

The graph of stiffness versus compaction temperature showed that the stiffness is being increase as the compaction temperature increase between 80°C and 160°C. The fig. 4.13 illustrated a refined relationship between stiffness and compaction temperature (R^2 = 0.9655).

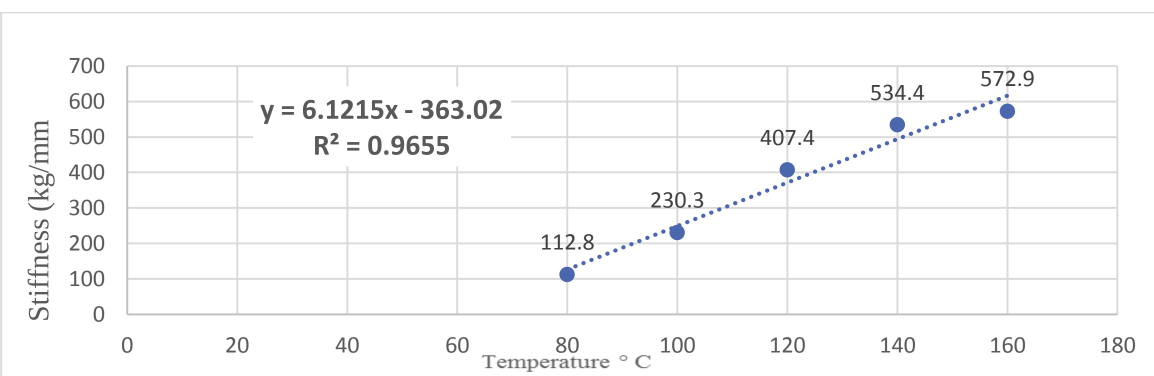

Figure 4.13: Stiffness versus compaction temperature

Chapter 5. Conclusions and Recommendations

5.1 Conclusion

- This research indicated that the initial temperature of the compacted asphalt mixture has significant impression on the asphalt density which in turn affects the other mechanical properties. It was obvious that from high correlation value (R^2 over 0.90) in the generated figures, we could realize that there was a strong relation between mechanical properties of HMA and compaction temperature. So, observing the compaction temperature during the performing of hot mix asphalt, can help to assure asphalt quality as per specifications. As well as this relationship could help to predict the reasons behind asphalt paving defects.
- Within the specified initial temperature at compaction (130C° – 165 C°) by (AASHTO, 2000), increasing compaction temperature made density to be increased. Moreover, it was observed that asphalt samples compacted at temperature within the mentioned range significantly has higher densities than those compacted at lower temperatures (less than 120 C°). With R^2=0.9306, the relationship between initial temperature vs asphalt density could be fitted by the equation:

  D = 0.0021T + 2.0124 (D: density in g/cm3, T: temperature in °C).
- Increasing the temperature made stability to be increased, but the maximum rate of increase in this investigation is being occurred over the distance of 100°C - 120°C. Converged values of stability were obtained over the distance of 140°C - 160°C.
- There is an inverse relationship between the initial temperature and air voids in total mix (Va), considering the mentioned minimum and maximum for Va and VFB in (AASHTO, 2000) and other references, the amount of specified temperature parallel with them can be achieved.
- Increasing the temperature made plastic flow of asphalt to be increased which resulted in increased asphalt stiffness.
- There could be found a golden range of temperature for each mix design asphalt, which its Marshall sample has got best performance. (For this investigation, the temperature range was 140°C - 160°C).

5.2 Recommendations

- It is recommended for site engineers to ensure initial compaction temperature for asphalt within the golden range (140°C - 160°C) since it achieves the best densities and other mechanical properties of HMA.
- It is recommended that the density temperature relationship would be used in investigating pavement defects and resolving disputes.
- It is required to establish local specifications for Palestine.
- It is recommended to execute governmental monitoring on local asphalt factories to ensure initial temperatures as per specifications.

5.3 Future studies

- Further researches are recommended to study the effect of initial temperature on the mechanical properties for asphalt wearing layer.
- Further researches are recommended to conduct this study using different bitumen percentages and bitumen types.
- 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 binder course aggregate mix

Aggregate mix	**Suggested percentages for binder course aggregate mix**										**Suggested percents for final agg. Mix**
	0.075	0.18	0.3	0.85	2.36	4.75	9.5	12.5	19	25	
Filler	77.49	11.81	5.90	4.80	0.00	0.00	0.00	0.00	0.00	0.00	**5**
	3.87	0.59	0.30	0.24	0.00	0.00	0.00	0.00	0.00	0.00	
Fine (0/4.75)	5.31	3.63	5.14	24.51	43.84	12.01	5.27	0.29	0.00	0.00	**43**
	2.28	1.56	2.21	10.54	18.85	5.16	2.27	0.12	0.00	0.00	
Sand (0/6.0)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0**
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Simsimia (0/9.5)	0.27	0.24	0.00	0.04	8.64	44.17	45.75	0.89	0.00	0.00	**15**
	0.04	0.04	0.00	0.01	1.30	6.63	6.86	0.13	0.00	0.00	
Adasia (0/12.5)	0.10	0.10	0.12	0.03	0.21	0.30	19.94	61.35	17.85	0.00	**29**
	0.03	0.03	0.03	0.01	0.06	0.09	5.78	17.79	5.18	0.00	
Folia (0/19)	0.27	0.03	0.02	0.00	0.00	0.00	0.41	6.02	91.58	1.67	**8**
	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.48	7.33	0.13	
Sum	6.25	2.22	2.54	10.79	20.21	11.88	14.94	18.53	12.50	0.13	**100**
∑% passing	6.2	8.5	11.0	21.8	42.0	53.9	68.8	87.4	99.9	100	
Sieve size (mm)	0.075	0.15	0.3	0.85	2.36	4.75	9.5	12.5	19	25	
Binder0/ 19 (min)	2	4	5	14	23	30	40	53	70	100	**Palestinian Specification PS 171/1998**
(max)	8	15	19	43	49	56	80	90	100	100	

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

Aggregate Type	% by Total Weight of Aggregates
Folia Aggregate	8.0 %
Adasia Aggregate	29.0 %
Simsimia Aggregate	15.0 %
Fine Aggregate	43.0 %
Filler	5.0 %
Total	100.0 %

Table A.3: Mix gradations of aggregates

Sieve No.	Folia Aggregate	Adasia Aggregate	Simsimia Aggregate	Fine Aggregate	Filler
1"	100.0	100.0	100.0	100.0	100.0
3/4"	98.3	100.0	100.0	100.0	100.0
1/2"	6.8	82.1	100.0	100.0	100.0
3/8"	0.7	20.8	99.1	99.7	100.0
#4	0.3	0.9	53.4	94.4	100.0
#8	0.3	0.6	9.2	82.4	100.0
#20	0.3	0.3	0.5	38.6	100.0
#50	0.3	0.3	0.5	14.1	95.2
#80	0.3	0.2	0.5	8.9	89.3
#200	0.3	0.1	0.3	5.3	77.5

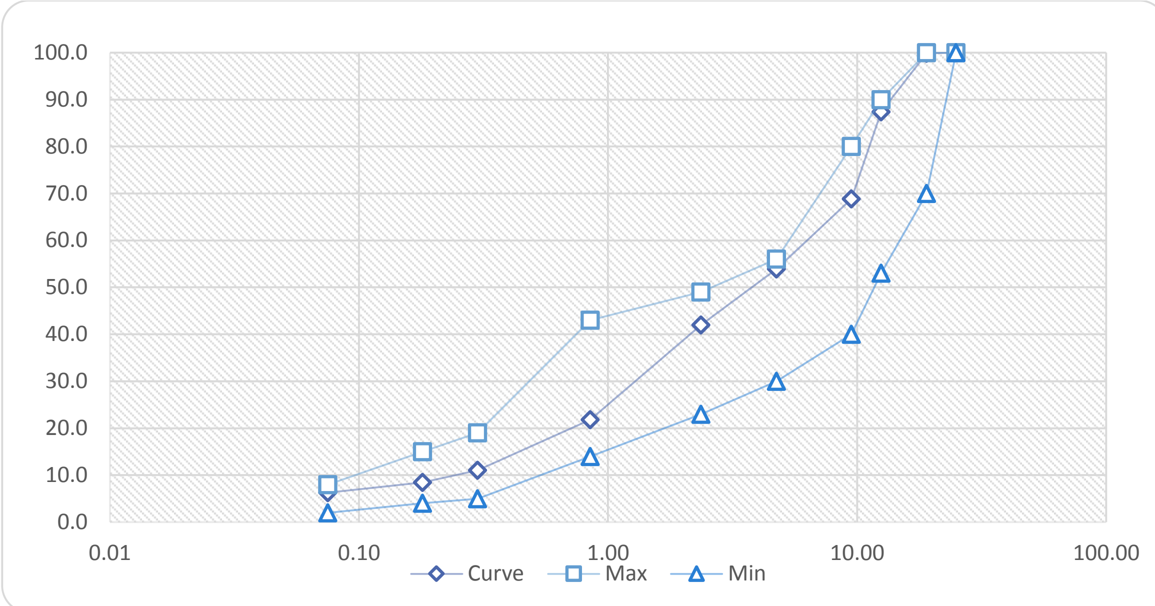

Figure A.1: Job Mix Gradation

Table A.4: Gradation of proposed mix with Palestinian Specification PS 171/1998

Sieve No.	Sieve Opening (mm)	Passing %	Min	Max
1"	25.0	100	100	100
3/4"	19.0	99.9	70	100
1/2"	12.5	87.4	53	90
3/8"	9.5	68.8	40	80
#4	4.75	53.9	30	56
#8	2.36	42.0	23	49
#20	0.850	21.8	14	43
#50	0.300	11.0	5	19
#80	0.180	8.5	4	15
#200	0.075	6.2	2	8

Appendix B

Appendix (B)
Calculations of physical properties of aggregates

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

- **Coarse aggregate (Folia)**

A= Weight of oven-dry sample in air, grams = 2815.5 gr

B=weight of saturated - surface -dry sample in air = 2880 gr

C= weight of saturated sample in water = 1745.8 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{2815.5}{2880-1745.8}$=2.481
- SSD S.G =$\frac{B}{B-C} = \frac{2880}{2880-1745.8}$ =2.539
- Apparent S.G =$\frac{A}{A-C} = \frac{2815.5}{2815.5-1745.8}$ =2.632
- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.481+2.632}{2} = 2.556$
- Absorption = $\frac{2880-2815.5}{2815.5} * 100 = 2.3\%$
- **Coarse aggregate (Adasia)**

A= Weight of oven-dry sample in air, grams = 2905 gr

B=weight of saturated - surface -dry sample in air = 2968 gr

C= weight of saturated sample in water = 1808.3 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{2905}{2968-1808.3}$=2.504
- SSD S.G =$\frac{B}{B-C} = \frac{2968}{2968-1808.3}$ =2.559
- Apparent S.G =$\frac{A}{A-C} = \frac{2905}{2905-1808.3}$ =2.648
- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.504+2.648}{2} = 2.576$
- Absorption = $\frac{2968-2905}{2905} * 100 = 2.2\%$
- **Coarse Aggregate (Simsimia)**

A= Weight of oven-dry sample in air, grams = 1544 gr

B=weight of saturated - surface -dry sample in air = 1598 gr

C= weight of saturated sample in water = 970.6 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{1544}{1598-970.6}$=2.458
- SSD S.G =$\frac{B}{B-C} = \frac{1598}{1598-970.6}$ =2.547
- Apparent S.G =$\frac{A}{A-C} = \frac{1544}{1544-970.6}$ =2.698

- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.458+2.698}{2} = 2.578$
- Absorption = $\frac{1598-1544}{1544} * 100 = 3.5\%$

2- <u>Pycnometer method</u>

- **Fine Aggregate**

(W_{P+W}) = Weight of Pycnometer filled with water = 1070.7 gr

(W_S) = Weight of the Fine sample dry = 481.4 gr

(W_{S+P+W}) =Weight of Pycnometer filled with water and the Fine sample= 1364.8 gr

- Specific Gravity = $\frac{481.4*1.02}{(481.4)-(1364.8-1070.7}$= 2.622

- **Filler**

(W_{P+W}) = Weight of Pycnometer filled with water = 1070.7 gr

(W_S) = Weight of the Fine sample dry = 320.6 gr

(W_{S+P+W}) =Weight of Pycnometer filled with water and the Fine sample = 1265.9 gr

- Specific Gravity = $\frac{320.6*1.02}{(320.6)-(1265.9-1070.7}$=2.608

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 4.0% bitumen content

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1211.5	1207.7	1223.9	1214.4
Weight in water (g)	692.2	689.8	698.3	693.4
Weight in air(S.S.D) (g)	1225.2	1222.2	1237.4	1228.3
Volume (cm3)	533.0	532.4	539.1	534.8
Bulk dry specific gravity	2.273	2.268	2.270	2.271
Max specific gravity	2.437	2.437	2.437	2.437
Marshal stability reading (×5 div)	37.0	35.0	36.0	36.0
Stability correction factor	0.96	0.96	0.93	0.95
Corrected stability (kg)	1194.9	1130.3	1126.2	1150.5
Plastic Flow (mm)	2.30	2.30	2.20	2.27
Stiffness (kg/mm)	519.5	491.4	511.9	507.6
Air voids content in total mix Va (%)	6.7	6.9	6.9	6.8
Voids of mineral agg. (V.M.A)%	15.6	15.7	15.7	15.7
Voids filled with bitumen (V.F.B)%	56.7%	56.0%	56.3%	56.3%

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

Table C.2: Marshal Test results for 4.5% bitumen content

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1215.5	1265.2	1200.7	1227.1
Weight in water (g)	690.9	719.4	682.6	697.6
Weight in air(S.S.D) (g)	1220.5	1271.2	1206.0	1232.6
Volume (cm3)	529.6	551.8	523.4	534.9
Bulk dry specific gravity	2.295	2.293	2.294	2.294
Max specific gravity	2.420	2.420	2.420	2.420
Marshal stability reading (×5 div)	37.0	39.0	38.0	38.0
Stability correction factor	0.96	0.89	0.96	0.94
Corrected stability (kg)	1194.9	1167.6	1227.2	1196.5
Plastic Flow (mm)	2.60	2.60	2.80	2.67
Stiffness (kg/mm)	459.6	449.1	438.3	449.0
Air voids content in total mix Va (%)	5.2	5.3	5.2	5.2
Voids of mineral agg. (V.M.A)%	15.2	15.3	15.2	15.2
Voids filled with bitumen (V.F.B)%	66.0%	65.6%	65.8%	65.8%

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

Table C.3: Marshal Test results for 5.0% bitumen content

Description	Sample No.			Average
	1	2	3	
Weight in air (g)	1223.9	1188.9	1210.2	1207.7
Weight in water (g)	696.8	676.8	689.6	687.7
Weight in air(S.S.D) (g)	1227.4	1192.3	1213.9	1211.2
Volume (cm3)	530.6	515.5	524.3	523.5
Bulk dry specific gravity	2.307	2.306	2.308	2.307
Max specific gravity	2.403	2.403	2.403	2.403
Marshal stability reading (×5 div)	44.0	45.0	46.0	45.0
Stability correction factor	0.96	1.00	0.96	0.97
Corrected stability (kg)	1420.9	1513.8	1485.5	1473.4
Plastic Flow (mm)	2.90	3.00	3.10	3.00
Stiffness (kg/mm)	490.0	504.6	479.2	491.3
Air voids content in total mix Va (%)	4.0	4.0	3.9	4.0
Voids of mineral agg. (V.M.A)%	15.2	15.2	15.2	15.2
Voids filled with bitumen (V.F.B)%	73.6%	73.5%	74.0%	73.7%

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

Table C.4: Marshal Test results for 5.5% bitumen content

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1205.2	1205.7	1180.6	1197.2
Weight in water (g)	680.9	682.8	667.5	677.1
Weight in air(S.S.D) (g)	1206.4	1208.1	1182.2	1198.9
Volume (cm3)	525.5	525.3	514.7	521.8
Bulk dry specific gravity	2.293	2.295	2.294	2.294
Max specific gravity	2.386	2.386	2.386	2.386
Marshal stability reading (×5 div)	40.0	39.0	40.0	39.7
Stability correction factor	0.96	0.96	1.00	0.97
Corrected stability (kg)	1291.7	1259.4	1345.6	1298.9
Plastic Flow (mm)	3.50	3.60	3.50	3.53
Stiffness (kg/mm)	369.1	349.8	384.4	367.8
Air voids content in total mix Va (%)	3.9	3.8	3.9	3.9
Voids of mineral agg. (V.M.A)%	16.1	16.1	16.1	16.1
Voids filled with bitumen (V.F.B)%	75.9%	76.3%	76.0%	76.0%

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

Table C.5: Marshal Test results for 6.0% bitumen content

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1215.2	1209.3	1219.9	1214.8
Weight in water (g)	679.9	677.9	683.6	680.5
Weight in air(S.S.D) (g)	1215.4	1210.5	1220.7	1215.5
Volume (cm3)	535.5	532.6	537.1	535.1
Bulk dry specific gravity	2.269	2.271	2.271	2.270
Max specific gravity	2.370	2.370	2.370	2.370
Marshal stability reading (×5 div)	33.0	35.0	34.0	34.0
Stability correction factor	0.96	0.96	0.93	0.95
Corrected stability (kg)	1065.7	1130.3	1063.7	1086.5
Plastic Flow (mm)	3.90	3.80	4.00	3.90
Stiffness (kg/mm)	273.3	297.4	265.9	278.9
Air voids content in total mix Va (%)	4.2	4.2	4.2	4.2
Voids of mineral agg. (V.M.A)%	17.5	17.4	17.4	17.4
Voids filled with bitumen (V.F.B)%	75.7%	76.0%	76.1%	75.9%

Table C.6: Calculations of the Max. Theoretical density

	%	S.G
Folia Aggregate	8.0%	2.539
Adasia Aggregate	29.0%	2.559
Simsimia Aggregate	15.0%	2.547
Fine Aggregate	43.0%	2.622
Filler	5.0%	2.608
G_{sb}		2.585
$p_{bitumen}$		1.03
p_{mix}	bitumen %	Max density
	4.0	2.437
	4.5	2.420
	5.0	2.403
	5.5	2.386
	6.0	2.370

Appendix D

Appendix (D)
Asphalt mix at different temperatures tests results

Marshal tests results

- No. of blows on each side : 75 blow
- Mixing temp : 80° C
- Bitumen = 5 % (By total weight)
- 3/4" binder course mix

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1215.1	1217.9	1212.7	1215.2
Weight in water (g)	671.5	677.1	675.4	674.7
Weight in air(S.S.D) (g)	1226.5	1233.3	1230.5	1230.1
Volume (cm3)	555.0	556.2	555.1	555.4
Bulk dry specific gravity	2.189	2.190	2.185	2.188
Max specific gravity	2.433	2.433	2.433	2.433
Marshal stability reading (×5 div)	38	37	39	38.0
Stability correction factor	0.89	0.89	0.89	0.89
Corrected stability (kg)	291.5	276.3	307.1	291.6
Plastic Flow (mm)	2.6	2.5	2.65	2.58
Stiffness (kg/mm)	112.1	110.5	115.9	112.8
Air voids content in total mix Va (%)	10.0	10.0	10.2	10.1
Voids of mineral agg. (V.M.A)%	20.6	20.6	20.8	20.7
Voids filled with bitumen (V.F.B)%	51.5%	51.6%	51.0%	51.4%

- No. of blows on each side : 75 blow
- Mixing temp : 100° C
- Bitumen = 5 % (By total weight)
- 3/4" binder course mix

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1200.3	1229.9	1206.8	1212.3
Weight in water (g)	669.9	692.7	669.5	677.4
Weight in air(S.S.D) (g)	1218.1	1252.3	1219.7	1230.0
Volume (cm3)	548.2	559.6	550.2	552.7
Bulk dry specific gravity	2.190	2.198	2.193	2.194
Max specific gravity	2.433	2.433	2.433	2.433
Marshal stability reading (×5 div)	56	56	55	55.7
Stability correction factor	0.89	0.89	0.89	0.89
Corrected stability (kg)	635.7	635.7	613.1	628.2
Plastic Flow (mm)	2.9	2.6	2.7	2.7
Stiffness (kg/mm)	219.2	244.5	227.1	230.3
Air voids content in total mix Va (%)	10.0	9.7	9.8	9.8
Voids of mineral agg. (V.M.A)%	20.6	20.3	20.5	20.5
Voids filled with bitumen (V.F.B)%	51.5%	52.5%	52.0%	52.0%

- No. of blows on each side : 75 blow
- Mixing temp : 120° C
- Bitumen = 5 % (By total weight)
- 3/4" binder course mix

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1154.5	1197.1	1181.8	1177.8
Weight in water (g)	653.7	676.6	674.1	668.1
Weight in air(S.S.D) (g)	1161.9	1200.6	1190.7	1184.4
Volume (cm3)	508.2	524.0	516.6	516.3
Bulk dry specific gravity	2.272	2.285	2.288	2.281
Max specific gravity	2.433	2.433	2.433	2.433
Marshal stability reading (×5 div)	70	70	71	70.3
Stability correction factor	1.04	0.96	1	1.00
Corrected stability (kg)	1164.2	1074.7	1151.9	1130.3
Plastic Flow (mm)	2.82	2.7	2.8	2.77
Stiffness (kg/mm)	412.9	398.0	411.4	407.4
Air voids content in total mix Va (%)	6.6	6.1	6.0	6.2
Voids of mineral agg. (V.M.A)%	17.6	17.2	17.1	17.3
Voids filled with bitumen (V.F.B)%	62.5%	64.6%	65.1%	64.1%

- No. of blows on each side : 75 blow
- Mixing temp : 140° C
- Bitumen = 5 % (By total weight)
- 3/4" binder course mix

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1192.2	1208.1	1201.8	1200.7
Weight in water (g)	681.5	688.4	690.2	686.7
Weight in air(S.S.D) (g)	1197.8	1210.5	1209.3	1205.9
Volume (cm3)	516.3	522.1	519.1	519.2
Bulk dry specific gravity	2.309	2.314	2.315	2.313
Max specific gravity	2.433	2.433	2.433	2.433
Marshal stability reading (×5 div)	81	81	82	81.3
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1501.4	1501.4	1538.9	1513.9
Plastic Flow (mm)	2.8	2.8	2.9	2.8
Stiffness (kg/mm)	536.2	536.2	530.7	534.4
Air voids content in total mix Va(%)	5.1	4.9	4.8	4.9
Voids of mineral agg. (V.M.A)%	16.3	16.1	16.1	16.2
Voids filled with bitumen (V.F.B)%	68.8%	69.7%	69.9%	69.5%

- No. of blows on each side : 75 blow
- Mixing temp : 160° C
- Bitumen = 5 % (By total weight)
- 3/4" binder course mix

Description	Sample No.			Average
	1	**2**	**3**	
Weight in air (g)	1203.2	1208.0	1209.6	1206.9
Weight in water (g)	690.6	692.6	694.6	692.6
Weight in air(S.S.D) (g)	1205.0	1209.8	1212.4	1209.1
Volume (cm3)	514.4	517.2	517.8	516.5
Bulk dry specific gravity	2.339	2.336	2.336	2.337
Max specific gravity	2.433	2.433	2.433	2.433
Marshal stability reading (×5 div)	83	85	86	84.7
Stability correction factor	1	1	1	1.00
Corrected stability (kg)	1576.8	1654.0	1693.3	1641.4
Plastic Flow (mm)	2.7	2.9	3	2.9
Stiffness (kg/mm)	584.0	570.4	564.4	572.9
Air voids content in total mix Va(%)	3.9	4.0	4.0	3.9
Voids of mineral agg. (V.M.A)%	15.2	15.3	15.3	15.3
Voids filled with bitumen (V.F.B)%	74.7%	74.0%	74.1%	74.2%

Appendix E

Appendix (E)
Photos

Figure E.1: Used aggregate type

Figure E.2: Aggregates preparing for specific gravity and water absorption

Figure E.3: Marshal Samples Weighting in SSD

Figure E.4: Removing Marshal Samples after compaction

Figure E.5: Asphalt mix preparing in the mold

Figure E.6: Removing Marshal Samples after compaction

Figure E.7: The division of asphalt mix samples

Figure E.8: Heating process for Marshal Samples

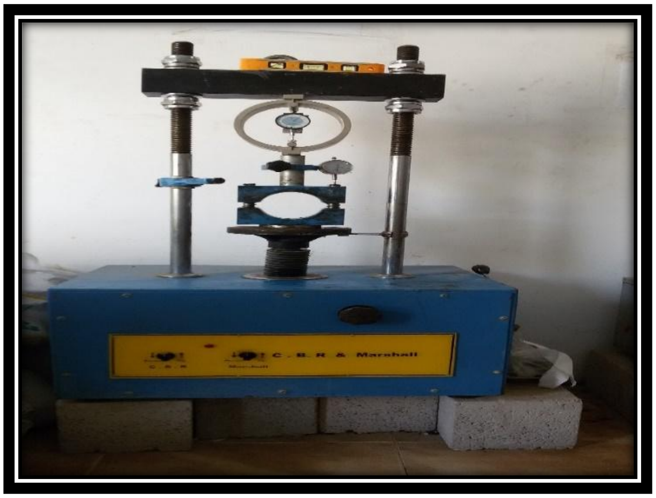

Figure E.9: Testing Marshall Samples for stability and flow

Figure E.10: Asphalt mix during compaction

Figure E.11: Measuring the theoritical density using pycnometer

Figure E.12: Asphalt mixture samples in oven