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إدارة البنى التحتية

Determining the Void Ratio in Hot-Mix Asphalt Pavements Using Different Methods According to EN 12697.

تحديد نسبة الفراغات في الرصفات الإسفلتية الساخنة باستخدام طرق مختلفة حسب الكود الأوروبي 12697

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Determining the Void Ratio in Hot-Mix Asphalt Pavements Using Different Methods According to EN 12697.

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Determining the Void Ratio in Hot-Mix Asphalt Pavements Using Different Methods According to En 12697

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Abstract

Inaccurate air void ratio based on erroneous bulk density can seriously affect the performance of the roadway and its quality. Therefore, several methods were improved to measure bulk density by using different techniques in the developed countries, while the Saturated Surface Dry (SSD) traditional method has been used in Gaza strip as the only method till now. This study aims at providing a better understanding of the effect of the selected bulk density measurement method on the percentage of voids using four methods namely; Dimensional Method, Dry Method, Surface-Saturated Dry Method, and Paraffin Sealing Method. At Laboratory, sixty-nine specimens were prepared, thirty three of them were prepared in the Marshal Design System in order to determine the optimum bitumen content of the three different mix types, and thirty-six of the specimens were taken from mixtures design in order to determine bulk density. In the first mix, the dense asphalt contains 1/2" maximum size limestone aggregate with 5.4% asphalt content. In the second mix, the mastic asphalt contains 3/8" maximum size limestone aggregate with 12.5 % asphalt content. In the third mix, the porous asphalt contains 3/4" maximum size limestone aggregate with 4.2% asphalt content. Laboratory results showed that the SSD method is the best choice for measuring bulk density in dense and mastic mixtures. In addition, there are no differences between SSD and dry methods in mastic mix. The regression analysis demonstrated that there is no correlation among the four methods in porous asphalt. Also, the results showed that the dimensional method is the only method suitable for the determination of bulk density (Gmb) in porous mix despite it always gives underestimated results for Gmb in all asphalt mixes. As a result, the dimensional method can be used as an indicator for the upper limit of voids, while the dry method can be used as an indicator to the lowest limit, regardless the type of mix. Moreover, the study showed that the paraffin sealing method is unsuitable for measuring Gmb because of wide ranged variations and illogical value of voids. The study recommended to use new techniques to determine Gmb in open graded mixtures with more accurate methods rather than traditional ones.

ملخص الدراسة

إن عدم الدقة في تحديد نسبة الفراغات يَرجع في الأساس من الخطأ في تحديد قيمة الكثافة الحجمية وهذا يؤثر على أداء الرصفة وجودتها، ولذا فإن عددًا من الطرق التي تعمل بأليات مختلفة قد تم تطويرها في الدول المتقدمة للحصول على نتائج أكثر دقة للكثافة الحجمية، بينما في قطاع غزة لا زالت الطريقة التقليدية وهى العينة المشبعة بالماء المجففة السطح (SSD) هى الطريقة الوحيدة المستخدمة حتى الآن. هدفت هذه الدراسة لتقديم فهم أعمق لتأثير الطريقة المستخدمة في قياس الكثافة الحجمية على نسبة الفراغات الهوائية في الخليط الاسفلتي من خلال استخدام أربعة طرق وهى : طريقة الأبعاد ، طريقة الغمر بالماء، طريقة العينة المشبعة بالماء والمجفف سطحها، وطريقة التغليف بالشمع. وقد تم تحضير عدد 69 عينة في المختبر؛ 33 عينة تم تحضيرها بالاعتماد على طريقة مارشال لتصميم الخلطات الاسفلتية بغرض تحدد النسبة المثلى من الرابط الاسفلتي لثلاثة أنواع من الخلطات الاسفلتية، بينما 36 عينة تم أخذها من الثلاث خلطات المُصممّة بغرض تحديد الكثافة الحجمية، هذه الخلطات الاسفلتية الثلاثة هى: الخليط الأول: كثيف أقصى حجم حبيبي نصف انش وبنسبة بوتومين 5.4% ، الخليط الثاني: مصمت غير منفذ أقصى حجم حبيبي له 3/8 انش وبنسبة بوتومين 12.5%، والخليط الثالث فراغي أقصى حجم حبيبي له ¾ انش وبنسبة بوتومين 4.2%. النتائج المخبرية أظهرت أن طريقة العينة المشبعة بسطح مجفف (SSD) هى الأنسب لتحديد الكثافة الحجمية في الخلطات الكثيفة والضيقة، كما أن الفروقات بينها وبين طريقة الغمر بالماء متقاربة جدا في الخليط المصمت الخالي من الفراغات ، كما أشار تحليل الارتباط بين الطرق الأربعة الى أن العلاقة بينها معدوم في الخليط المسامي ، بينما طريقة الأبعاد هى الطريقة الوحيدة من بين الطرق الأربعة المناسبة لتحديد الكثافة الحجمية بالرغم من أنها تحدد الكثافة الحجمية أقل من نتائج الطرق الأخرى في كل أنواع الخلطات الاسفلتية. كذلك فان طريقة الأبعاد يمكن استخدامها كمؤشر لفحص الحد الأكبر لنسبة الفراغات داخل الخليط الاسفلتي بينما طريقة الغمر بالماء يمكن استخدامها كمؤشر لفحص الحد الأدنى لنسبة الفراغات بغض النظر عن نوع الخليط الاسفلتي. علاوةً على ذلك فإن طريقة التغليف الشمعي غير مناسبة لقياس الكثافة الحجمية بسبب وجود فروق كبيرة وقيم غير منطقية في القياس .وقد أوصت الدراسة بأن يتم استخدام تقنيات جديدة لتحديد الكثافة الحجمية في الخلطات المفتوحة (المسامية) لأن الطُرق التقليدية لا تعطي الدقة المطلوبة .

بسم الله الرحمن الرحيم

وَمَن يَتَوَكَّلْ عَلَى اللَّهِ فَهُوَ حَسْبُهُ ۚ إِنَّ اللَّهَ بَالِغُ أَمْرِهِ ۚ قَدْ جَعَلَ اللَّهُ لِكُلِّ شَيْءٍ قَدْرًا

صدق الله العظيم ،،

Dedication

I dedicate this work to my Father and my Mother who encouraged me to follow up my studies, who taught me when I was a child, who gave me their time, love, and attention.

I also dedicate this thesis to my brothers, sisters, uncle Dr. Bassem , and to my wife.

Finally, many thanks go to my best friends for their help.

Acknowledgment

At the beginning, I thank ALLAH for giving me the strength and health to let this work see the light. I thank my supervisor Prof. Dr. Shafik Jendia for his time, consideration, suggestions, ideas and advice during this thesis.

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List of Abbreviations

AC	Asphalt Concrete
HMA	Hot Mix Asphalt
DA	Dense Asphalt
MA	Mastic Asphalt
PA	Purse Asphalt
SMA	Stone Mastic Asphalt
Gmb	Bulk Specific Gravity
TMD/ Gmm	Theoretical Maximum Density
AASHTO	American Association of State Transportation and Highway Officials
VTM	Void in Total Mix
EN	European Standard
ASTM	American Society for Testing and Materials
NMAS	Nominal Maximum Aggregate Size
VFBD	Voids free bulk density
OGFC	Open-Graded Friction Course
NCHRP	National Cooperative Highway Research Program
NAPA	National Asphalt Pavement Association
FHWA	Federal Highway Administration
VFB	Voids Filled Bitumen
VMA	Voids Mineral Aggregates
OBC	Optimum Bitumen Content

Chapter 1

Introduction

1. Introduction

1.1 Background

Density is one of the most important parameters used in calculations to determine the quality and quantity of asphalt in design and construction stages. A mixture that is properly designed and compacted will contain enough air voids to prevent rutting due to plastic flow but low enough to prevent permeability of air and water. Since the 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 & Cross, 1989).

There are three primary methods of specifying density: percent of control strip, percent of laboratory density, and percent of theoretical maximum density. All three methods can be used to obtain satisfactory compaction if used correctly. The initial in-place air voids must be below approximately eight percent and the final in-place air voids must be above approximately three percent. The initial in-place air voids are determined by comparing bulk density to theoretical maximum density (TMD) and the final in-place air voids are estimated by comparing the bulk density of laboratory compacted sampler to the TMD (TXDOT, 2016).

The two methods that have been used to measure bulk density of asphalt mixture are physical measurements of cores and nuclear gage. The nuclear gage is fast and non-destructive but is not as accurate as the core method. (Palmer, 1989)

1.2 Problem Statement

All basic volumetric calculations of compacted HMA specimens depend on the correct measurement of the bulk density. So, this study focuses on measuring an accurate bulk density by using four methods that including the saturated surface dry (SSD) method which is the only one used in Gaza, and also the widely common used in general. The following statements illustrates the problem:

1. There are some methods available to obtain the asphalt density, and each one of these methods uses a slightly different way to determine specimen volume, which may result in different density values.
2. There is a difficulty in specifying the void ratio especially in the Open Graded Friction Courses (OGFC) mixtures, because of large interconnected air voids

which reach the surface, and this reason lead to an error when using SSD method.

3. Some new methods and techniques were developed to determine the bulk density, but, what about the accuracy and confidence of the traditional methods result, this is an essential question in the study.
4. Some recent researches focus on using porous and mastic asphalt, this issue requires providing an accurate estimation result when measuring the bulk density, and taking into consideration gradation of the mixture.

1.3 Study Objectives

This study aims at comparing the methods of specifying bulk density of asphalt mixtures, and also to discuss the following points in particular:

- Investigate and evaluate the current methods used for determining HMA bulk density.
- Determine the possible reasons that produce the variability in bulk density and void ratio results.
- Studying the effects of air void content requirements in design stage on the best method of measuring bulk density.
- Comparing between the SSD method and the other three methods in measuring bulk density depending on the void ratio in HMA.
- Implementing regression analysis to provide predicted void ratio values of the three methods according to SSD void ratio measurement.
- Provide recommendations for changes in the current methods in order to improve the accuracy and minimize the variability in HMA density determination.

1.4 Study Methodology

In the face of determining the bulk volume of specimens which were prepared from several graded mixes and compacted to produce mixes at different air voids. Then the bulk densities of these mixes were determined using four methods.

The European Standard (EN12697) describes the following four procedures for measuring bulk density:

1. Bulk density — dry (for specimens with a very closed surface).

2. Bulk density — saturated surface dry (SSD) (for specimens with a closed surface).
3. Bulk density — sealed specimen (for specimens with an open or coarse surface).
4. Bulk density by dimensions (for specimens with regular surface and with geometric shapes; squares, rectangles, cylinders…etc).

In this study, the above four methods for measuring the bulk density were studied. Also, a comparison between these methods was made by testing many samples that are different in the void ratio target. The linear and nonlinear regression analysis were used to represent the data of the voids that were calculated from the bulk density results.

The methodology of the study are summarized in the following steps:

- Reviewing previous studies about the relationship between bulk density and void ratio, and the methods for measuring bulk density and void ratio, and the reflection on HMA quality.
- Studying the asphalt material components and the types of three HMA mixtures: Dense, Mastic, and Porous asphalt.
- Preparing three types of asphalt mixtures at laboratory by taking twelve samples from each type of mixture, and then carrying out the tests of samples using four different methods to measure the bulk density and void ratio.
- Analyzing the results, then implementing regression analysis and drawing a box plot.
- Conclusion, recommendations, and future research plan.

Table 1.1: Number of specimens prepared in laboratory work

Asphalt mixture	Specimens for Marshal tests	Specimens for bulk density test
Dense Asphalt	12	12
Mastic Asphalt	12	12
Porous asphalt	9	12

1.5 Study Contribution

This study contributes in improving the current practices with a wide applicability for determining bulk density of various HMA mixtures which contain large air void ratio from void-less in porous asphalt to more than 20% in mastic asphalt. Additionally, the study will specify the best method for calculating the upper and lower limits of void ratio in regards to the selected method used in evaluating the bulk density.

1.6 Study Outline

This thesis consists of five chapters. Chapter one contains an introduction to the study, problem statement, study objective in addition to the research methodology. The second chapter handles the theoretical framework of HMA, focusing on the materials components, layers, and asphalt types according to the gradation of aggregates, then it focuses on the volumetric properties especially the bulk density and void ratio. Chapter three presents the study methodology and some important concepts needed in asphalt mixture design. Chapter four concludes the study findings, and discusses the results in the light of regression analysis. Finally, chapter five summarizes the study conclusion, recommendations, and further studies.

Chapter 2

Theoretical Framework

2. Theoretical Framework

2.1 Introduction

Hot Mix Asphalt pavement is known by many different names: asphalt concrete, plant mix, bituminous mix, bituminous concrete, and many others.

Hot Mix Asphalt is a combination of two primary ingredients - aggregates and an asphalt binder. The aggregates total ninety to ninety-five percent of the total mixture by weight. They are mixed with approximately four to eight percent asphalt binder to form HMA (Colorado Asphalt Pavement Association , 2006).

Bituminous mixes are complex multiphase materials consisting of a gradation of aggregate, air voids, and bitumen. The purpose of a pavement is to carry traffic safely, conveniently, and economically throughout its design life. (Cebon, 2000)

Hot-mix asphalt pavements function properly when they are designed, produced and placed in such a manner as to give them certain desirable performance characteristics. These characteristics contribute to the quality of hot-mix pavements. These include permanent deformation (rutting) resistance, durability, flexibility, fatigue resistance, skid resistance, impermeability, workability, and economics. Ensuring that a paving mixture has each of these properties is a major goal of the mix-design procedure. Therefore, the technician should be aware of what each of the properties is, how it is evaluated, and what it means in terms of pavement performance. (Bu, Jiang, & Jiao, 2000)

There are two types of asphalt binder, which can be used in HMA, worldwide asphalt cement, which is the most used binder, and modified asphalt cement, with certain properties. The function of bitumen binder is to glue aggregate particles into a cohesive mass. Mineral aggregate, which constitutes more than ninety percent of the asphalt mixture, acts as a stone framework to impart strength and toughness to the system. (McGennis et al.,1955)

2.2 Asphalt Layers

The pavements can be classified based on the structural performance into two, flexible pavements and rigid pavements. HMA pavements are classified as “flexible” pavements because the total pavement structure deflects, or flexes, under loading. A flexible pavement is a structure consisting of superimposed layers of processed materials above the natural soil sub-grade, whose primary function is to distribute the applied vehicle loads to the sub-grade by grain-to-grain transfer as shown in Figure 2.1.

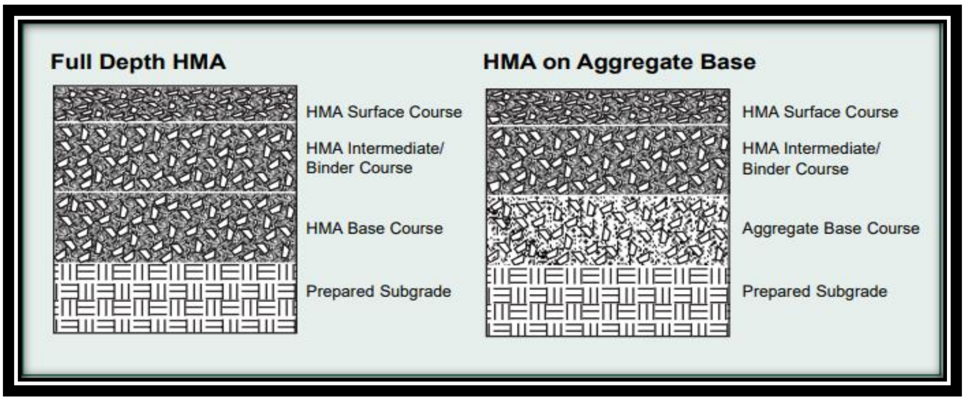


Figure 2.1: Pavement Layers. (Pavement Interactive, 2012)

Flexible pavement structure consists of two asphalt layers are as following:

- **Surface course:** wearing layer which is directly in contact with traffic loads and generally contains superior quality materials. It’s function is to provide the following characteristics:
  - Friction, smoothness, drainage, etc.
  - It must be tough to resist the distortion under traffic and provide a smooth and skid- resistant riding surface.
  - It must be water proof to protect the entire base and sub-grade from the weakening effect of water.

- **Binder course:** The intermediate layer, this is the layer directly below the wearing course. Its purpose is to distribute traffic loads to the base course and provides the bulk of the asphalt concrete structure. The binder course generally consists of aggregates having less asphalt and doesn't require quality as high as the surface course.

The other layers which form the flexible pavement, such as: Base course and Sub – base course, are providing additional load distribution, structural support and improve drainage. These Layers composed of crushed stone, crushed slag, and other untreated or stabilized materials. (Jendia, 2000; NAPA, 2001).

2.3 Asphalt Mixture

An asphalt mixture pavement is composed of a binder and aggregate blended together. The properties of asphalt mixture depend on: the quality of its components (asphalt binder and aggregates), the mix proportions and construction process. (Mathew, 2009)

The disruption to traffic flows and costs of replacing degraded road surfaces are significant, leading to a demand for more durable materials. So the individual material properties of each component may affect the overall performance of the pavement. If pavements are to perform long-term and withstand specific traffic and loading, the materials making up the pavements are required to be of high quality. ((NCHRP), 2012)

There are many methods available for mix design which vary in the size of the test specimen, compaction, and other test specifications, in an effort to create a mixture that is capable of providing acceptable performance (Pennsylvania Department of Transportation, 2003). Marshall Method of mix design is the most popular one which will be used to design the mixtures preparing in this study.

The majority of the asphalt mixture is aggregate –As table 2.1 shown. (Hassan, 2009).

Table 2.1: Asphalt mixture component.

Component	Hot Mix Asphalt Composition
Asphalt Binder	(4 – 8) %
Aggregate (Fine and Coarse)	(92-96) %

2.3.1 Asphalt Binder

The black cementing agent known as bituminous materials or asphalts are extensively used for roadway construction, primarily because of their excellent binding characteristics and water proofing properties and relatively low cost. Bituminous material consists chiefly high molecular weight hydrocarbons derived from distillation of petroleum. (Txdot Designation, 2007)

The desirable properties of bitumen depend on the mix type and construction. In general, Bitumen should possess following desirable properties.

- The bitumen should not be highly temperature susceptible: during the hottest weather the mix should not become too soft or unstable, and during cold weather the mix should not become too brittle causing cracks.
- The viscosity of the bitumen at the time of mixing and compaction should be adequate. This can be achieved by use of cutbacks or emulsions of suitable grades or by heating the bitumen and aggregates prior to mixing.
- There should be adequate affinity and adhesion between the bitumen and aggregates used in the mix. (Mathew, 2009)

2.3.2 Aggregates

According to aggregate resources, there are two types of aggregates: natural aggregates such as sand, gravel, crushed stone and rock dust, and artificial aggregate such as recycling aggregates and slag.

Aggregates are the principal load-supporting components of HMA, provide stable, safe, and durable properties to the mixtures (Jendia, 2000).

Aggregates constitute the greatest part among other components used in roads pavement. Table 2:2 shows the percentage of aggregates in whole weight mixture

Table 2.2: Aggregates percentage in many types of pavement. (Jendia , 2000)

Type of Pavement	Aggregate weight %
Aggregate road base	100%
Cement bound layer	95%
Asphalt layer	96%
Cement concrete layer	88%

Factors that should be included in aggregate particles are size, shape, gradation, durability, porosity, and cleanliness. Therefore, aggregate particles with rough faces, angularity and harshness are desired when preparing HMA mixtures. (Colorado Asphalt Pavement Association , 2006).

2.4 Asphalt Mixture Types

Asphalt pavements classified in terms of technology, usage**,** and many of standards and determinants related to the materials used and their properties. This study will discuss HMA pavements that sorted mainly as dense-graded mixes, closed- graded mixes “Mastic”, and open-graded hot mix asphalt in accordance with aggregate mineral gradation.

The grade of asphalt selected depends on:

- The type of construction
- Climatic conditions
- Amount and nature of traffic

There are also other types of asphalt but are limited to maintenance and rehabilitation works. (Rodriguez, 2017). As figure 2.2 shows, Asphalt mixtures can be categorized into four different types.

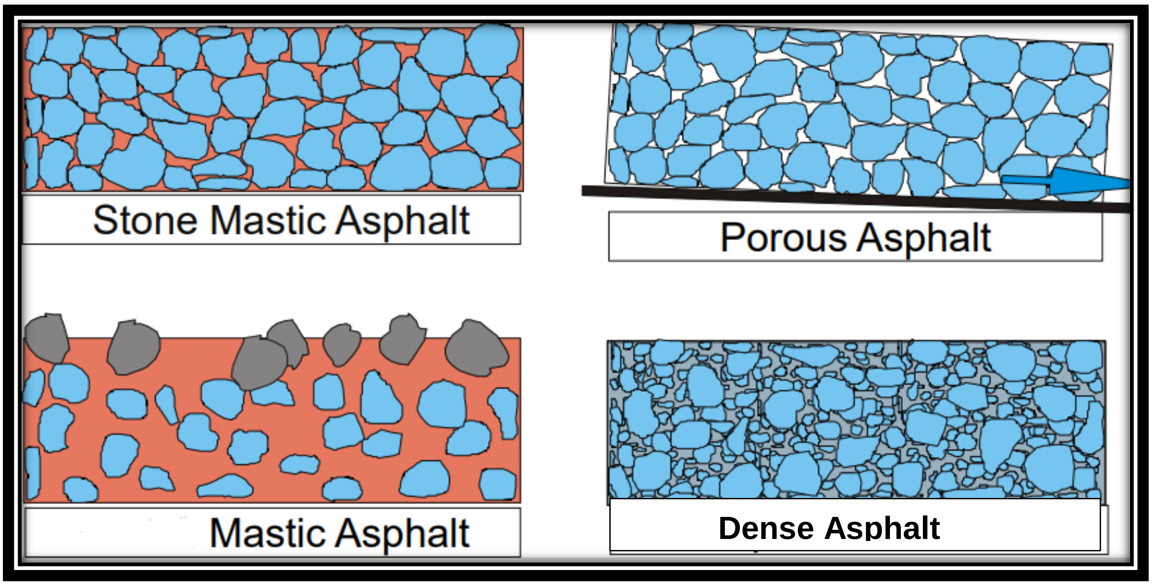


Figure 2.2: Aggregate packing arrangements of asphalt mixture types. (Cooley, 2008)

Each type of these mixtures can be used in wearing course. Their general properties and suitable specifications are described below.

2.4.1 Dense-Graded Mixes

The most used mixture is the dense graded mixture which is proportioned to have continuously graded mix, its strength relies on the interlock between aggregate particles, bitumen and filler. The mix is designed to have low air voids and low permeability to provide good durability and good fatigue behavior. (Pellinen, et.al, 2015).

Dense-graded HMA mixes are generally referred to by their nominal maximum aggregate size, the most popular wearing pavements used in Germany are 0/5,0/8,0/11,0/11.5 S, 0/16 S. These types of asphalt, which are classified as DGA mixtures, are ideal for all traffic conditions and have great performance under structural conditions, friction, and for surfacing and repairing needs (Jendia,2000). Dense graded asphalt mixes shall comply with the property requirements stated in Table 2.3.

Table 2.3: Marshall Properties for DGA. (Australian Standards, 2017)

Parameter	**Min**	**Max**
Marshall Stability	8.0 KN	-
Marshall Flow	2.00 mm	4.00 mm
Air Voids :		
• **Nominal 16 mm**	4	7
• **Nominal 11 mm**	3	6
• **Nominal 8 mm**	1	3
Asphalt Binder	5%	8%

2.4.2 Stone Matrix Asphalt

SMA is characterized by a gap-graded aggregate gradation. It consists of up to 80% by weight of coarse aggregate and up to 13% by weight of filler. SMA is a tough, stable, rut resistant mixture that relies on stone-to-stone contract for its strength and a rich mortar binder for its durability. This type of pavements have performed very well in Europe and parts of the United States. The pavement was originally developed in Sweden. (Myers, 2007)

The gradation of SMA contains only a small percentage of aggregate particles in the mid-size range which leaves more room for the mortar of fine aggregate and asphalt binder, which ranges between 6.5 to 7.5 percent by weight of mixture. (Kevin , 2005)

SMA mixes shall be designed using 50 blow compaction Marshall with a 3 percent air void target. Early mix designs were performed with the Marshall Compactor but most designs now use the Gyratory Compactor. Table 2.4 below shows a summary of many specifications for designing SMA. (Mahoney, 2000)

Table 2.4: AASHTO MP8-01: Specification for designing SMA. **(Myers, 2007)**

Property	Requirements
Asphalt Content, %	6 minimum
Air Voids, %	2-4 %
VMA, %	17

2.4.3 Mastic Asphalt

It's also called "None compacted asphalt", "void-less asphalt", Mastic asphalt is a mixture of a bitumen binder, stone filler, and mineral powder heated and mixed in the hot state. Mastic road asphalt mix pavements have been used for over 50 years in Europe and for over 7 years in Russia in several types of uses such as the construction of building in the isolated system for internal and external isolation. Besides that for the top and bottom layer of pavement in road construction with a thickness between (20mm-50mm) and(12mm-15mm) as job requirements. (Russian Roads New Look, 2017).

Table 2.5: Composition of mastic mixtures. (Khuri, 1987)

L.S Sieve		**Percentage by Weight**	
Passing	Retained	Minimum	Maximum
2.36 mm	600 micron	0	22
600 micron	212 micron	4	30
212 micron	75 micron	8	18
75 micron	-	25	45
Bitumen Content		12	17

The properties of the mastic road asphalt are optimal for use in cases requiring a reliable waterproofing covering, fully impermeable with high abrasion resistance and increased operational life, it reached to 20-30 years. Mastic asphalt has wet consistency as it contains a larger quantity of the binder, fine and filler materials as Table 2.2 shown, compared to the common other types of asphalt.

Mastic asphalt is a blend of fine aggregate, filler and bitumen. The aggregate and filler are usually limestone. Filler (passing the 0.075mm sieve) makes up about 50% of the mixture and the bitumen content is at least 11%. (BS EN 13108-6, 2008)

The requirements of Mastic asphalt mixture design, according to European Standard, shall be as table 2.6 shown.

Table 2.6: En 13108-1:2006: Specification for designing MA. **(BS EN 13108-6, 2008)**

Property	**Requirements**	
	Minimum	**Maximum**
Marshall Stability (KN)	2.5	7.5
Marshall Flow (mm)	6	14
Air Voids (%)	0.5	2
VFB (%)	78	*
VMA (%)	25	*

2.4.4 Porous Asphalt

Porous Asphalt is composed of an asphalt open-graded friction course (OGFC) manufactured with larger-diameter aggregates to achieve an effective porosity of approximately 19%. These pavements, used mostly for paving light traffic load roads, allow water to drain through the pavement surface into a stone recharge bed and infiltrate into the soils below the pavement. Porous pavements were widely used in USA and Europe countries in 1970s. (NAPA , 2018)

PA formed a system consisted of an open-graded surface course placed over a filter course and an open-graded base course (or reservoir) all constructed on a permeable subgrade. Porous pavements are generally designed for parking areas or roads with lighter traffic. Because Porous asphalt mixtures have significantly higher percentages of air voids ranging from 16% to 22%, that’s why Failures of porous asphalt pavements have been associated with lack of stiffness. (Schaus, 2007)

(Australian Standards, 2017) Specifications of Porous asphalt wearing Course shall satisfy the limiting values of many Marshall Properties, listed in Table 2.7.

Table 2.7: Limiting values of Marshall Properties for Purse asphalt. (NAPA , 2018)

Parameter	**Min**	**Max**
Marshal Stability	4kN	-
Marshal Flow	2.0 mm	4.0 mm
Air Voids	12.0%	25.0%

Porous asphalt mixes consist of coarse aggregate with a percent passing on the 4.75 mm sieve that ranges between 10% and 35%, with a small proportion of filler in the mix. (Vavrik, 2000)

2.5 Bulk Specific Gravity

Bulk specific gravity is the ratio of the mass in air of a volume of material to the mass in air of an equal volume of water at the same reference temperature. It includes both voids within individual particles as well as voids between particles (General Issues in Asphalt Technology Committee, 2007). Figure 2.3 shows air voids as a part of bulk volume. Accurate measurement of volume of air voids has become a major concern due to use of coarse-graded mixes which was increased significantly since the introduction of Super-pave mix design method, therefore bulk specific gravity, is important to the evaluation of asphalt aggregate mix specimens taken in the field or compacted in the laboratory (Nick M., 2003).

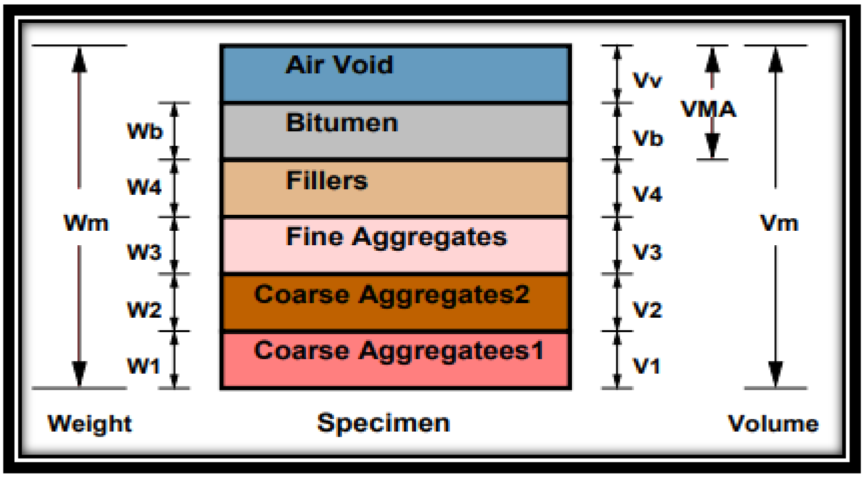


Figure 2.3: Phase diagram of a bituminous mix. (Mathew, 2009)

2.5.1 Bulk Specific Gravity in Codes

There are a number of methods available to obtain asphalt density and each one uses a slightly different way to determine specimen volume, which may result in different density values. In water displacement methods, which are based on Archimedes principle, specimen volume is calculated by weighing the specimen in and out of a water bath. The difference in weights is then converted to the volume of the specimen. The three methods that are used in EN 12697 for obtaining the density of the compacted asphalt sample are a dry method (no water in sample); a saturated surface dry method (SSD) where water fills the asphalt air voids; a method based on sample dimensions (DIM); and a method where sample is sealed, for instance, wrapped with parafilm.

Among the different available methods of determination of bulk specific gravity, the saturated surface dry method, as indicated in AASHTO T166-88 (1990) is the most widely used. Although a good test, the method does not produce accurate results if the air voids are very high or if very coarse-graded mixes are used. Currently used (AASHTO)

Table 2.8 shown the most practical methods for tested Gmb according to ASTM, AASHTO.

Table 2.8: Existing Methods with References (Crouch, 2002).

Method	Author/Reference
Water Displacement (SSD Method)	AASHTO T-166 , ASTM 2726 or EN 12697-6
Water Displacement (Dry Method)	EN 12697-6
Dimensional Analysis	AASHTO T-269 or EN 12697-6
Paraffin Sealing Method	AASHTO T-275, ASTM D 1188, EN 12697-6

The definitions given below are consistent with those advanced by ASTM, AASHTO and The Asphalt Institute.

2.5.2 Theoretical Maximum Specific Gravity

It is called also "Voids free bulk density" (VFBD), the theoretical maximum specific gravity (Gmm) of a HMA mixture is the specific gravity without air voids, the theoretical maximum specific gravity was determined using the AASHTO T 209-99 procedure. When mixture components are in the loose state, that means weight and specific gravity of each type of component were used to calculate Gmm. As equation 2.1 shows.

AASHTO T 209-99: Gmm is calculated using the following formula:

$$\text{Theoretical Maximum Specific Gravity} = \frac{\text{Total Weight of Mix } (W1 + W2 + W3 + Wb)}{\frac{W1}{G1} + \frac{W2}{G2} + \frac{W3}{G3} + \frac{Wb}{Gb}} \quad (2.1)$$

Where:

$W1$ = the weight of coarse aggregate in the total weight.
$W2$ = the weight of fine aggregate in the total weight.
$W3$ = the weight of filler in the total mix.
Wb = the weight of bitumen in the total mix.
$G1$ = the specific gravity of coarse aggregate.
$G2$ = the specific gravity of coarse aggregate.
G3 = the specific gravity of coarse aggregate.
Gb = the specific gravity of bitumen.

The other method evaluates Gmm according to AASHTO T 166, a sample of un-compacted asphalt mixture was treated by Pycnometer device to ensure all air has been displaced from the mixture as figure 2.4 shows, and equation 2.2 was applied to calculate Gmm.

Figure 2.4: specimen in Gmm testing device

$$\text{Theoretical Maximum Density} = \frac{\text{A}}{(\text{A} + \text{D} - \text{E})} \quad (2.2)$$

Where:

A = sample mass in air (g)

D = mass of flask filled with water (g)

E = mass of flask and sample filled with water (g)

Typical values for theoretical maximum specific gravity range from approximately 2.400 to 2.700 depending on the aggregate specific gravity and asphalt binder content. Unusually light or heavy aggregates may result in a value outside this typical range. (Pavement Interactive, 2012)

Theoretical maximum specific gravity is a critical HMA characteristic because it is used to calculate percent air voids in compacted HMA as part of asphalt mix design procedure with bulk density value, Gmm is used along with bulk specific gravity values from field cores and laboratory compacted specimens to calculate air voids and the in-place air voids of a HMA pavement for quality control in construction stage.

2.6 Air Voids

Air void content is the single most important property that is used for design and construction quality control of hot mix asphalt. Air void, as noticed in Figure 2.5 representative the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture.

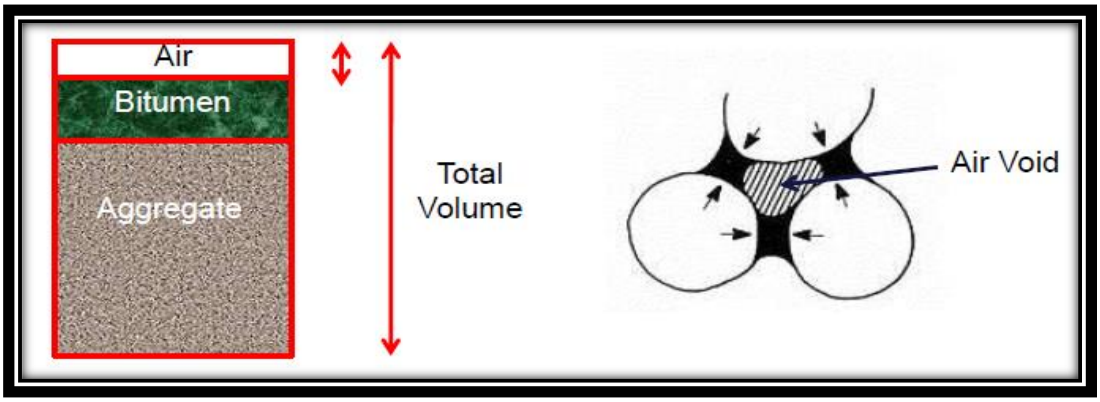
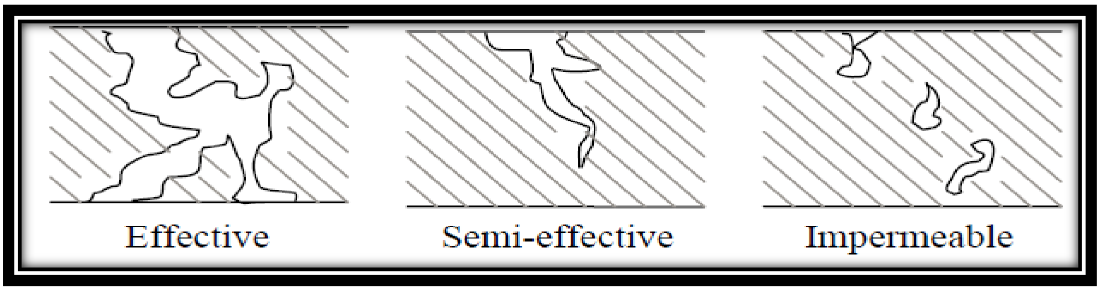


Figure 2.5: Small pockets of air between aggregate particles. (Cooley,et al., 2003)

The aim of dense asphalt mix design is to achieve an asphalt mix with the lowest practicable air voids without compromising long-term performance. But in the other types of asphalt such as OGFC and SMA there was other consideration in the target air voids content in the pavements to achieve satisfied properties for different uses. Figure 2.6 illustrated the forms of void in three types of mixtures, effective voids which are in connected in Pours asphalt, the semi effective form existed in dense asphalt when voids connected partially, the last form of voids, impermeable without any connected between air pockets that form existed in mastic asphalt pavement. (Mallick, 2002).

Figure 2.6: Air Void Forms in pavement. (Kassem, 2011.)



Too many air voids and the asphalt becomes permeable to water and air, which causes reduced service life. Too few air voids and the asphalt becomes rutted and deformed under trafficking. (Pavertrend™, 2016)

To obtain the air void content of asphalt Va, which is defined as the ratio of volume of voids to total volume of the compacted mix, one has to first measure pavement density, Va was determined using the bulk specific gravity, and theoretical maximum density. The air void content is calculated as the ratio of the asphalt pavement density to the maximum density.

- Va% is calculated using the following formula:

$$Air\ Voids = \left[1 - \left[\frac{G_{mb}}{G_{mm}}\right]\right] * 100\% \qquad (2.3)$$

Most mix design criteria are designed to limit the in-service voids from 3 to 5 percent, but it may range from 0 to 22% or 25% with existence of other mixture types. (Terhi Pellinena, 2015)

Air voids ratio bonded basically in the traffic load after construction. So, pavements have heavy traffic load should have high design air voids due to compaction in the operational life. On the contrary, pavements with light traffic load should have low voids where there is very little further compaction of the asphalt mix after placing to prevent rutting, fatigue and provide a high level of durability and long service life. (Kassem E., 2011.)

Field compaction should attempt to place the asphalt as close as possible to the design air voids so that the asphalt performs as expected. Reduced compaction leads to:

- Higher air voids and therefore increased the risk of moisture entry
- Early oxidation which results in premature raveling.
- A reduction in the structural performance of stiffness and fatigue resistance of the asphalt mix.
- 1% excess voids result in approximately about 10% reduction in life. (Palmer, 1989).

2.6.1 Voids in the Mineral Aggregate (VMA)

VMA is the percentage of the volume of voids space between the aggregate particles before adding bitumen, so it equals the sum of the volumetric percentage of bitumen (Vb) and the air void (VA) of mixture after compaction. (Jendia S. (., 2000)

$$VMA\,[\%] = Va + Vb \qquad (2.4)$$

The volume of inter-granular void space between the aggregate particles of a compacted paving mixture that includes the air voids and volume of the asphalt not absorbed into the aggregate. Figures 2.7 shown Diagrammatic Representation of Air Void and Voids in Mineral (VMA). (Crouch, 2002)

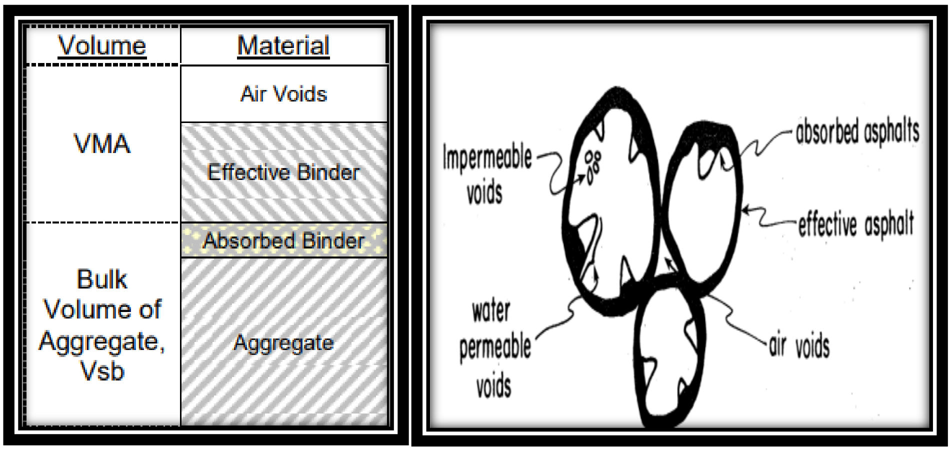


Figure 2.7: Diagrammatic representation of air void and voids in mineral. (Crouch,2002)

VMA is calculated using the following formula:

$$VMA = 100 - \frac{Gmb \times Ps}{Gsb} \tag{2.5}$$

Where:

Gmb = bulk specific gravity of the completed mixture;

Ps = aggregate content, percent by mass (= 100 – asphalt content);

Gsb = bulk specific gravity of the combined aggregate.

2.6.2 Voids Filled with Bitumen (VFB)

The percent of the volume of the VMA that is filled with asphalt cement. VFB is inversely related to air voids: as air voids decrease, the VFA increases. (Roberts, 2015).

VFB is calculated using the following formula:

$$VFB = \frac{VMA - Va}{VMA} \tag{2.6}$$

2.7 Financial Aspect of the Volumetric Properties

The volumetric properties play an important role in estimating the payments due to any contracting company doing paving work in developed countries, as illustrated in equation (2):

$$\begin{aligned}\mathrm{SCPF} = {} & 0.20(\mathrm{PF}_{BINDER}) + 0.35(\mathrm{PF}_{VOIDS}) \\ & + 0.10(\mathrm{PF}_{VMA}) + 0.35(\mathrm{PF}_{DENSITY})\end{aligned} \tag{2.7}$$

Where:

SCPF = Sublot Composite Pay Factor for Mixture and Density.

PF_{BINDER} = Sublot Pay Factor for Binder Content

PF_{VOIDS} = Sublot Pay Factor for Air Voids at N_{des}

PF_{VMA} = Sublot Pay Factor for VMA at N_{des}

$\mathrm{PF}_{DENSITY}$ =Sublot Pay Factory for Density.

2.8 Literature Review

Some studies have attempted to examine the relationship between asphalt volumetric properties and performance of pavement in operational life and trying to answer the question about the importance of determining more exactly bulk density, voids ratio, and VFB. Some researches of bulk density and void ratio are mentioned below:

- Zhang, et al., (2016), discussed The volumetric properties of drainage layer mixtures, Four methods to measure bulk specific gravity and as consequently void ratio were have been compared on asphalt-treated permeable base (ATPB) mixture. Report was found significant difference exists among these methods as the air void content increases. Then, suggested that for specimens of 24% or larger air void contents the vacuum sealing method should be chosen for better results.
- Kassem, et al., (2011), discussed the effect of air void on mechanical properties of HMA, the methodology depends on distribution of voids in asphalt specimens, the results showed that specimens with more uniform air void distribution had less variability in terms of resistance to fatigue cracking compared with specimens with less uniform air void distribution.
- Silvia, et al., (2011), studied the effect of air voids on the mechanical performance of asphalt mixtures that are subjected to the combined action of moisture diffusion and mechanical loading. This study relay on the x- ray to computed air void size and distribution pattern. Article contributed to developed model can be used to analyze the interrelated effects of internal structure distribution, moisture diffusion and mechanical properties of the mixture constituents on performance.
- ▪ Allex, et al., (2009), studied Connected Air Voids Content in Permeable Friction Course Mixtures, The study evaluated two laboratory methodologies (vacuum and dimensional analysis) for determining air voids and two types of analysis to compute interconnected AV content based on X-ray Computed Tomography (X-ray CT) and image analysis techniques. The result concluded that dimensional analysis is recommended over the vacuum method to determine the water-accessible AV content of compacted PFC mixtures.

- Cooley, et al., (2003), concluded that measuring bulk density rely basically on the gradation of mixture. Saturated surface dry method can be used for mixtures contain fine – graded aggregates, it has finer aggregate particle more than 10% but vacuum- sealing method can be used for all other gradation.

- Sudip and Rajib, (2002), investigated the use of an alternative method for determination of bulk specific gravity and estimation of water permeable voids of dense graded HMA mixes, this research made comparison between saturated surface dry method and the vacuum seal method. The result concluded that the vacuum seal method provided a better estimation of air voids in a compacted HMA mix.
- Harvey, et al.,(1994), presented a comparison of the standard methods of air-void content measurement, measurement of bulk specific gravity using unsealed specimens and using specimen sealed with paraffin wax, the results indicates that each methods have different value of void content and paraffin wax method has good estimation for sample with roughly coarse shape.

2.9 Summary

This chapter presented a theoretical framework of essential topics in asphalt such as asphalt layer, asphalt mixture, and asphalt types, then moved into the volumetric properties of asphalt especially the bulk specific gravity and void ratio. Finally the chapter mentioned previous studies related to bulk specific gravity and void ratio and their effect on pavement performance.

The following points are summarized in this chapter:

- Asphalt are the most of interesting topic for the researches, especially when it is the most prominent branch of the infrastructure.
- Pavement’s quality, performance, durability, and function are affected by pavement’s components and their properties, which are mentioned in chapter three.
- The existence of many deformities and defects in traditional mixtures led to appearance of other mixtures such as stone matrix asphalt, porous asphalt, and mastic asphalt.
- Asphalt types have been summarized: The most used mixtures are the dense graded mixtures (DAC), which are proportioned to have tight aggregate packing. The Stone Mastic Asphalt (SMA) is a heavy duty mixture with strong

aggregate skeleton filled with bitumen-rich mastics. Porous Asphalt (PA) has a similar aggregate skeleton, but without mastics, as this mixture is intended to be water permeable, and Mastic asphalt mixture which depends on the bond between binder asphalt and filler which compromise 50% of total volume mixture.

- It is not possible to achieve the complete quality in asphalt mixtures because every property acts separately. For example high voids achieve permeability while stiffness of pavement was decreasing. So the design criteria aim to achieve optimal asphalt design.
- The variety in asphalt mixture types led to wide range of the properties' values. For example void ratio value ranges from 0.0% in mastic asphalt to 25% in porous asphalt. This requires more accurate tools for measuring these properties.

Chapter 3

Material and Testing Program

3. Material and Testing Program

3.1 Introduction

Density is an important component of hot-mix asphalt (HMA) for pavement quality and long-term performance. The insufficient density of an in-place HMA pavement is the most frequently cited construction-related performance problem. (Kvasnak, et al., 2007)

This study is based on laboratory testing as the main procedure to achieve study goals. Chapter Three deals with two topics. First, is to evaluate material properties such as aggregates, bitumen binder. Second, is to describe how mixture types are prepared and volumetric properties are determined.

3.2 Laboratory Test Procedure

All tests are conducted using equipment and devices available in the laboratories of the Association of Engineers-Gaza Material Testing Laboratory. The following discusses the Laboratory test stages:

Stage (1):

- Evaluation of the properties of used materials such 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.

Stage (2):

- Prepare Job mix Asphalt with different bitumen contents and Marshal test is conducted to obtain optimum bitumen content. The value of the optimum bitumen is used to prepare three asphalt mixes with various gradation: Dense asphalt (Dense graded), Porous asphalt (open graded) and Mastic asphalt.

Stage (3):

- Prepare 36 specimens, 12 samples from each type of mixture.
  Determining the bulk density and void ratio carried out by using four different methods (Saturated surface dry – Dry – Dimension – Paraffin sealing).

Finally, laboratory test results are obtained and analyzed. Figure 3.1 displays the laboratory work stages.

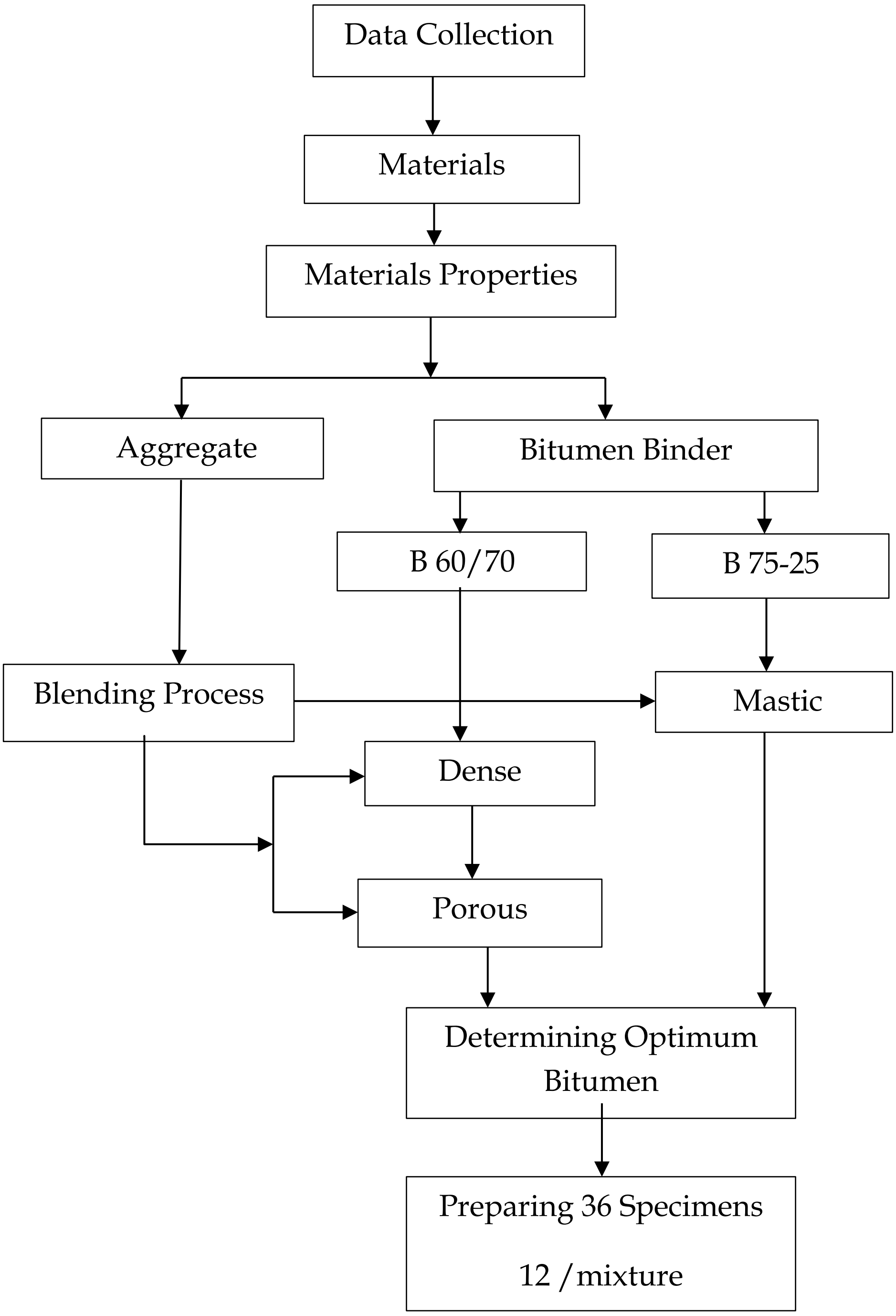


Figure 3.1: Laboratory testing procedure.

3.2.1 Materials Selection

Materials needed for this study are the constituents of hot mix asphalt, Table 3.1 presents main and local sources of these materials.

Table 3.1: Main and local sources of used materials

Material	**Source**	
	Main	**Local**
Aggregates	Crushed rocks (Palestine)	AL Qaoud Factory
Bitumen 60/70	(Palestine)	AL Qaoud Factory
Bitumen 75-25	(Palestine)	Mansour Factory

3.2.2 Materials Properties

3.2.3 Bitumen Properties

Asphalt binders 60/70& 75-25 were used in this research, 60/70 for dense and porous asphalt and 75-25 for mastic asphalt replaced the other type of binder, bitumen 85-25 which technical advantages, Durability, Flexibility, Water Resistant and Chemical Stability (IBPC, 2017) was not available in Gaza. The following is a brief definition of bitumen types:

- B 60/70: Bitumen penetration grade 60/70 means the penetration value is in the range 60 to 70 mm at standard test conditions.
- B75-25: The bitumen grade 75-25 means the softening point is 75°c and penetration is 25 mm .
- B85-25: The bitumen grade 85-25 means the softening point is 85°c and penetration is 25 mm . (Raha company, 2016)

The use of B75-25 instead of B85-25 because of the match between two types in penetration value and approximation in their softening point temperature.

The use of B85-25 or B75-25 in mastic asphalt mixture is due to mastic asphalt dependence on the bond between bitumen and filler (morter), morter constitutes about 50% of the total mixture volume, this percentage makes void ratio equals approximately zero. As B85-25 or 75-25 under load can not reach softening point unless under temperature more than70° C, this makes pavement failure under temperature and load excluded with penetration range (20-30) mm. While in the other asphalt mixture types, B60/70, which has softinng point temperature about a half that of B85-25 , is used because when the pavement reach its softining point, the load is resisted by aggregate skelton.

In order to evaluate bitumen properties number of laboratory tests have been performed such as specific gravity, ductility, flash point, softening point and penetration.

- **Bitumen Penetration Test**

Penetration: A measure of hardness and consistency.

Penetration is the vertical distance, which a standard needle (5cm length and 0.1cm diameter) can penetrate through an asphalt under a standard situation of: 1- Load of 100 gm. 2- Temperature of 25 ^{0} C. 3- For 5 seconds.

The depth of penetrations measured.

- Test specification: ASTM D5/D5M -13.
- Container dimension: 75 mm x 55mm
- 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

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Penetration**	1/10 mm	62.15	60-70	ASTM D5/D5M -13
B 75-25			21.2	20-30	

Figure 3.2: Penetration test for a bitumen sample bitumen properties

- **Ductility Test**

Ductility: The ductility of binder is an indication of its elasticity and ability to deform under load and return to original condition upon removal of load. (Kadiyali, 2005) The distance of 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 shows ductility test of a bitumen sample.

Table 3.3: Bitumen ductility test results

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Ductility**	cm	150	Min 100	ASTM D113-86
B 75-25			37	Min 4	

Figure 3.3: Ductility test of a bitumen sample

- **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.

Table 3.4: Bitumen Softening Point Results

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Softening point**	° C	48.5	48-56	ASTMD36-2002
B 75-25			74.3	70-80	

- **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).

- Test specification: ASTM D92-12b
- Test results are listed in Table 3.5
- 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

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Flash Point**	° C	300	Min 230 C°	ASTM D92-12b
B 75-25			304	Min 250 C°	

➢ Density Test

- Test specification: ASTM D 3289-08.
- Test results are listed in Table 3.6.

Table 3.6: Bitumen density test results

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Density**	g/ml	1.03	0.97-1.06	ASTM D 3289-08
B 75-25			1.05	1.03-1.06	

➢ Solubility Test

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

- Test specification: ASTM D 2042-09
- Test results are listed in Table 3.7.

Table 3.7: Bitumen solubility test results

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Solubility**	%	99.2	Min 99.0%	ASTM D 2042-09
B 75-25			99.3	Min 99.0%	

➢ 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.

- Test specification: ASTM D3381/D3381M-13
- Test results are listed in Table 3.8.

Table 3.8: Bitumen Viscosity Test Results

Binder Type	Test	Unit	Result	Requirements	Specifications
B 60/70	**Viscosity**	135 ° C	390	Min. 300	ASTM D3381/D3381M-13.
B 75-25			340	Min. 300	

- **Summary of Bitumen Properties**

The main characteristic of the binder are listed in Table (3.9, 3.10) display various bitumen properties and compared with ASTM specifications limits for two bitumen binder types: B 60/70, B75-25respectively.

Bitumen 85-25 was not used in the laboratory work because it is not available in the local market, very close bitumen type properties to B85-25 is B75-25 that used as a binder in mastic asphalt, the last one used in isolation work.

Table 3.9: Summary of B 60/70 properties.

Test	**Unit**	**Result**	**Requirements**	**Specifications**
Penetration	**1/10 mm**	62	60-70	ASTM D5/D5M -13.
Ductility	**cm**	150	Min 100	ASTM D113-86
Softening point	**° C**	48.5	48-56	ASTMD36-2002
Flash point	**° C**	300	Min 230 C°	ASTM D92-12b
Density	**g/ml**	1.03	0.97-1.06	ASTM D 3289.
Solubility	**%**	99.2	Min 99.0	ASTM D 2042-09
Viscosity	**135 ° C**	390	Min. 300	ASTM D3381/D3381M-13

Table 3.10: Summary of B 75-25 properties.

Test	**Unit**	**Result**	**Requirements**	**Specifications**
Penetration	1/10 mm	21.2	20-30	ASTM D5/D5M -13
Ductility	cm	37	Min 4	ASTM D113-86
Softening point	° C	70.3	70-80	ASTMD36-2002
Flash point	° C	304	Min 250 C°	ASTM D92-12b
Density	g/ml	1.07	1.03-1.09	ASTM D 3289
Solubility	%	99.3	Min 99	ASTM D 2042-09
Viscosity	135 ° C	340	Min. 300	ASTM D3381/D3381M-13

In general, there is a matching in specification requirement Between B 75-25 and B 85-25 especially in penetration test. It is important to mention that these types of binders are used in the same sector such as road construction; pavement, crack seal and repairmen, civil works, roofing, construction industries; sealing and insulating buildings. For more details about B82-25 specification in Appendix B.

3.2.4 Aggregates Properties

One local source of aggregates used to construct hot-mix asphalt pavements was used in the study. The natural aggregates (coarse and fine) were 100 percent crushed limestone. Several laboratory tests were made on the aggregate to determine its properties results and details in appendixes.

Three NMAS, 19 mm, 12.5 mm, and 9.5 mm, were selected to represent the asphalt mixes prepared. As listed in Table 3.11 and shown in Figures 3.4. Aggregates used in asphalt mixes can be divided as shown in Table 3.11

Table 3.11: 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
	Filler	0/0.075

Figure 3.4: Different sizes of used aggregate.

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)
- Los Angles abrasion (ASTM C 131)
- Sand Equivalent (AASHTO T 176)

Table 3.12: Specific gravity test of aggregates

	Unit	Folia	Adasia	Simsimia
S.S.D Weight	g	2880.0	2930.0	3130.0
Weight in Water	g	1746.8	1810	1936
Volume of Solids	cm^3	1133.2	1120.0	1194.0
Specific Gravity		2.541	2.616	2.621
Dry Specific Gravity		2.483	2.568	2.570

Table 3.13: Water absorption test of aggregates

	Unit	Folia	Adasia	Simsimia
S.S.D Weight	g	2880.0	2930.0	3130.0
Oven Dry Weight	g	2815.5	2877	3070
Water Absorption	%	2.291	1.842	1.954

Table 3.14: Specific gravity test of Sand & Filler

	Unit	Trabia	Filler
Dry Weight	g	351.0	127.0
Pycnometer + water	g	1816.5	1816.5
Pycnometer + water+Sample	g	2033.5	1895.0
Specific Gravity		2.672	2.671

Table 3.15: Aggregates quality test results

Test property	**Folia**	**Adasia**	**Simsimia**	**Trabia**
Abrasion Loss (500 Cycles) %	20.4	22.5	25.9	*
Sand Equivalent %	*	*	*	74

- **Sieve Analysis**
    - According to specification (ASTM C136)
    - Table 3.16 and Figure 3.10 show aggregates sieve analysis results.

Table 3.16: Aggregates sieve analysis results

Sieve No.	**Sieve size (mm)**	**Cumulative % Passing**				
		Folia	**Adasia**	**Simsimia**	**Trabia**	**Filler**
		0 / 19	**0/ 12.5**	**0/ 9.50**	**0/4.75**	**< 0.075**
1"	**25.00**	100.0	100.0	100.0	100.0	100.0
3/4"	**19.00**	10.84	100.0	100.0	100.0	100.0
1/2"	**12.50**	0.37	50.1	100.0	100.0	100.0
3/8"	**9.50**	0.16	7.6	91.6	100.0	100.0
#4	**4.75**	0.16	1.1	51.0	96.7	100.0
#8	**2.36**	0. 12	1.1	5.7	92.9	100.0
#16	**1.180**	0.08	1.1	3.4	79.0	100.0
#30	**0.600**	0. 08	1.1	2.7	59.3	100.0
#50	**0.300**	0.08	1.1	2.4	32.8	99.2
#80	**0.150**	0.06	0.2	0.8	13.9	96.0
#200	**0.075**	0.02	0.2	0.6	6.9	89.1

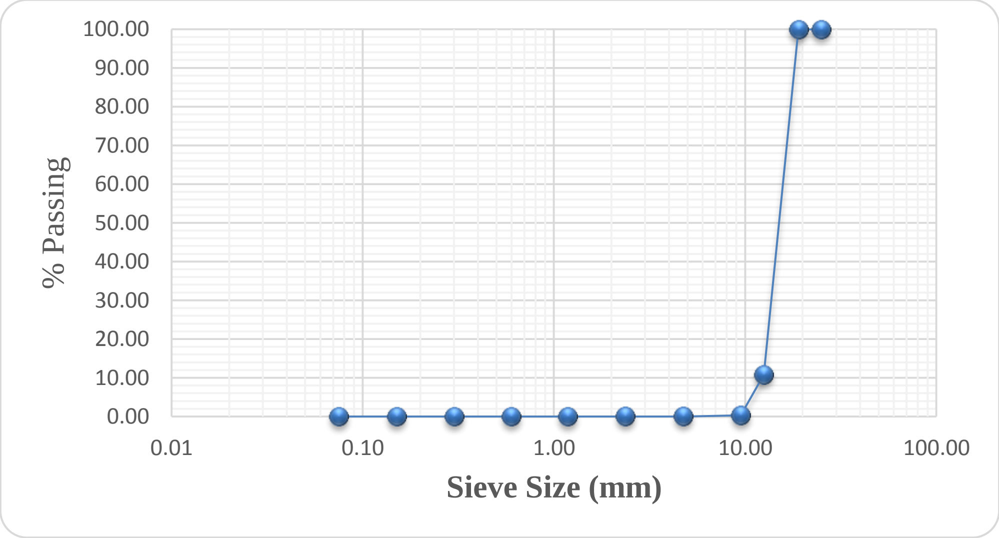


Figure 3.5: Gradation curve (Folia 0/ 19.0)

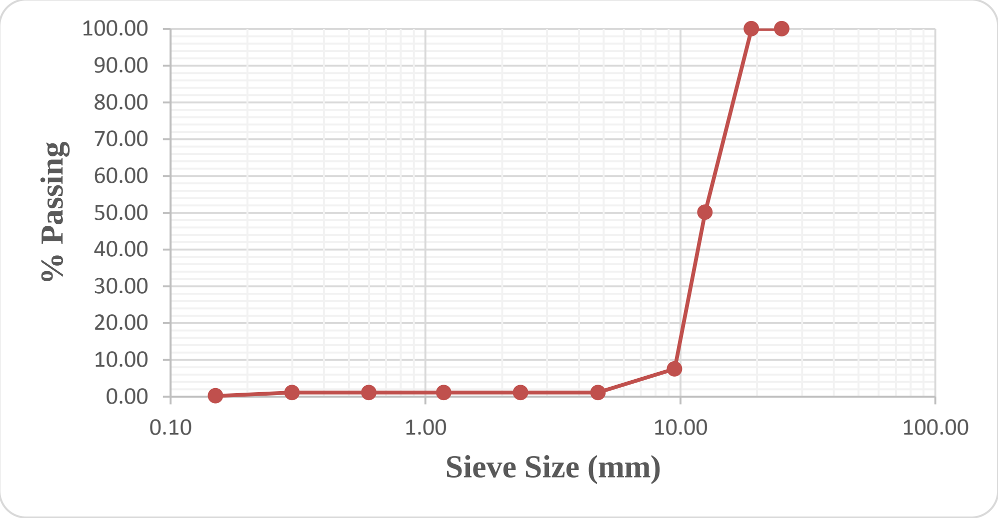


Figure 3.6: Gradation curve (Adasia 0/ 12.5)

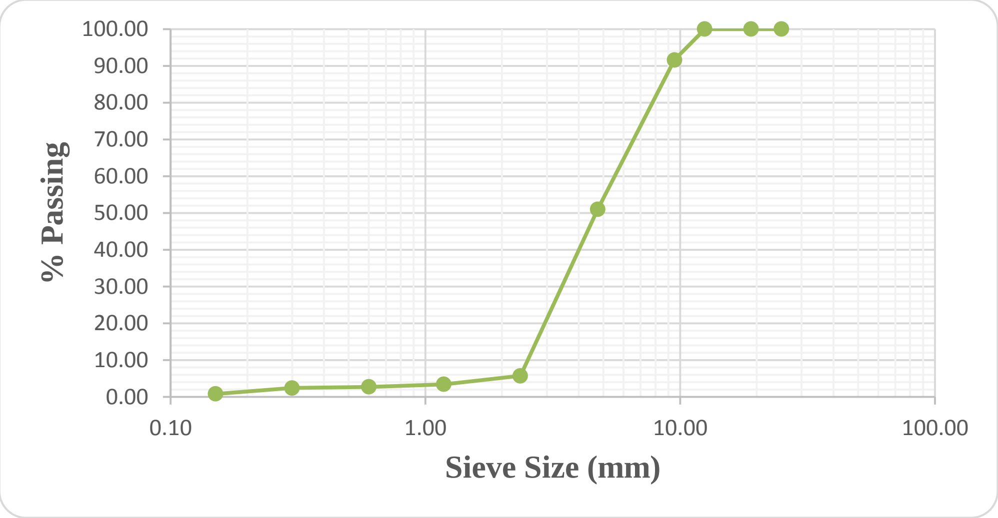


Figure 3.7: Gradation curve (Simsimia 0/ 9.50)

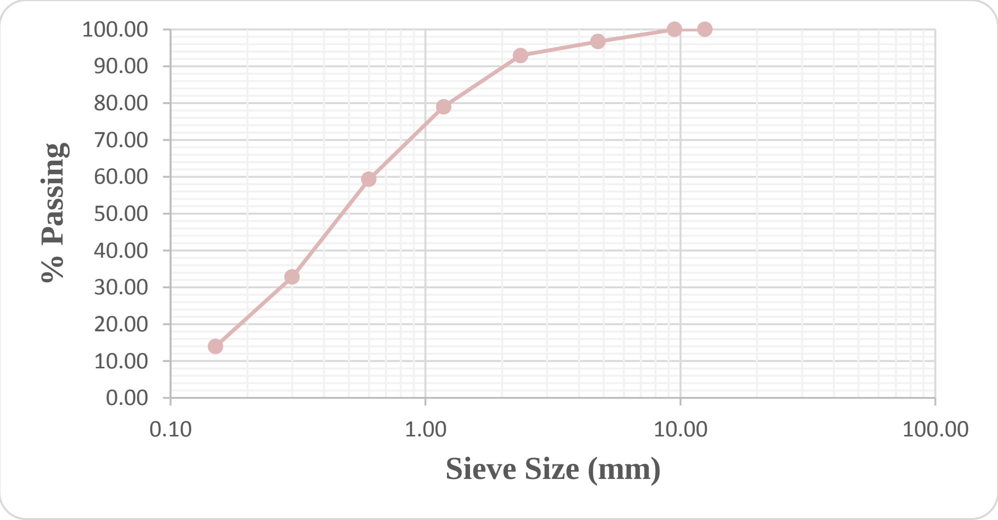


Figure 3.8: Gradation curve (Trabia 0/ 4.75)

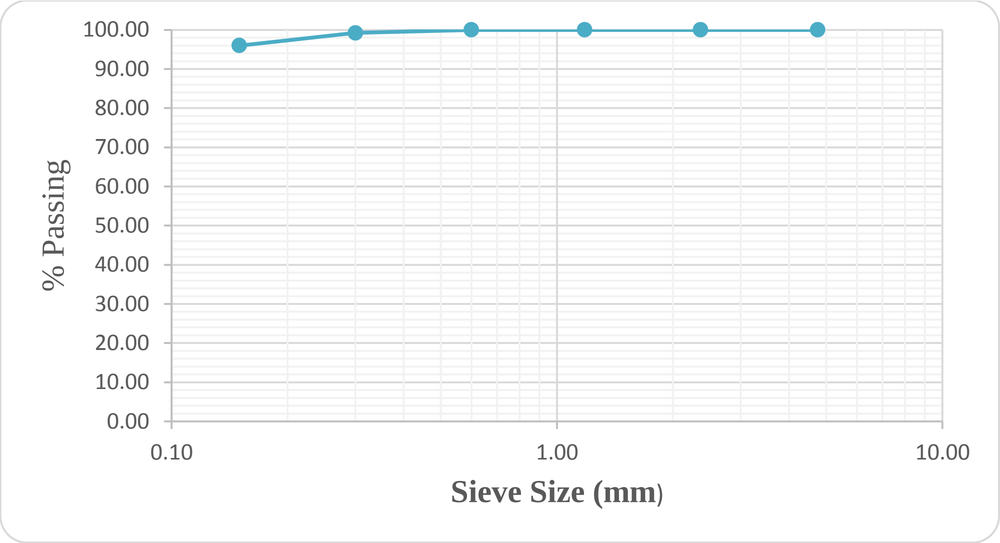


Figure 3.9: Gradation curve (Filler)

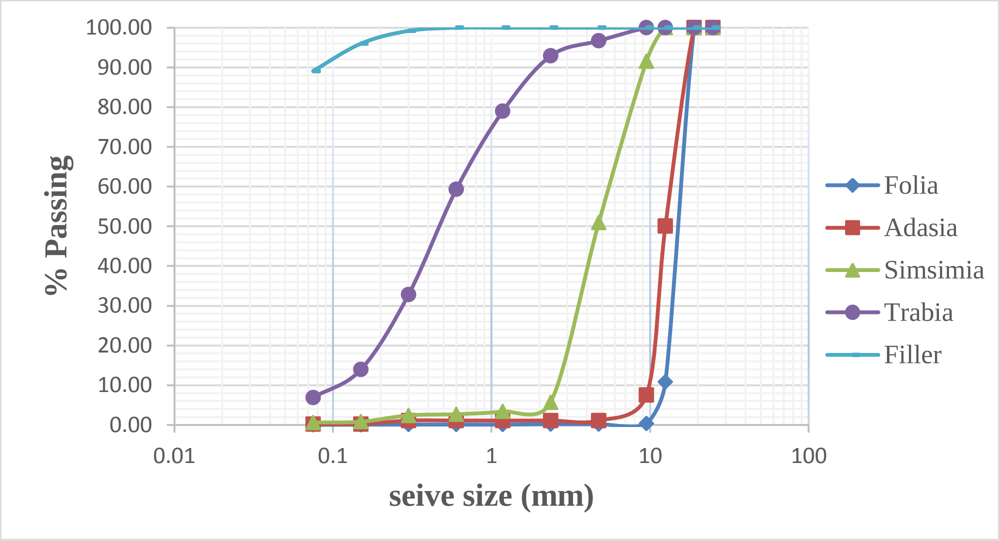


Figure 3.10: Aggregates gradations curves

3.2.5 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 the mathematical trial method. This manner depends on suggesting different trial proportions for aggregate materials from the 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).

3.2.6 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 in a mix where the desired properties of strength and durability are met.

Three types of mixtures were prepared as the following

- **For Dense Asphalt**, the amount of 12 samples, each one approximately 1200g of aggregates types and filler put together is heated to a temperature of 160-170˚C. Bitumen is heated to a temperature of 160˚C with four trials percentage of bitumen (from 4.5 - 6% with 0.5 % incremental), by weight of the mineral aggregates. Then the heated aggregates and bitumen are thoroughly mixed at a temperature of 160 - 170˚C. The mix is placed in a preheated cylindrical mould and compacted by a hammer having a weight of 4.5 kg and a free fall of 45.7 cm giving 75 blows on both sides at a temperature of 160˚C to prepare the laboratory specimens to obtain the optimum bitumen content (OBC) of dense asphalt.
- **For Mastic Asphalt,** the amount of 12 samples, each one approximately 1200g of aggregates types and filler put together is heated to a temperature of 180-195˚C, were prepared, using three different bitumen contents (11.5%, 12%,12.5%,13%),the specimens of mastic asphalt prepared at 180 C mix temperature, (BS EN 13108-6, 2008) is using around 10 Superpave gyratory compactor to prepare mastic asphalt sample, but in the laboratory work, 15 blows by marshal hammer provide satisfactory compaction.

- **For Porous Asphalt,** the amount of 9 samples, each one approximately 1200g of coarse aggregates types put together to made incorporating the recommended combined Grading with bitumen content (3.5%, 4 %, 4.5%). the specimens of porous asphalt prepared at 160 C mix temperature, then 75 blows by marshal hammer provide satisfactory compaction.

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 of each mixtures. The following graphs are then plotted:

Steps for Marshal Method (AASHTO, 2013):

- Preparation of test specimens.
- Bulk specific gravity determination. Bitumen Content;
- Stability and flow test determination. Bitumen Content;
- Density and voids determination (Va) vs. Bitumen Content;
- Voids Filled with Bitumen (VFB) vs. Bitumen Content These graphs are utilized to obtain optimum bitumen content.

3.2.7 Determination of Optimum Bitumen Content (OBC)

The optimum bitumen content (OBC) for the 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 void (Va = 3-5%) (% mb)Va

Marshal graphs are utilized to obtain these three values.

$$\boldsymbol{Optimum\ bitumen\ content\ (OBC)\%} = \frac{(\%mb)_{stability} + (\%mb)_{bulk\ density} + (\%mb)_{V_a}}{3} \qquad (3.1)$$

3.2.8 Bulk Density Test Methods

Specific gravity is a measure of a material’s density (mass per unit volume) as compared to the density of water at 73.4°F (23°C). Therefore, by definition, water at 73.4°F (23°C) has a specific gravity of 1. (VicRoads Standard Sections, 2017). According to EN 12697-6, Four methods used for measuring bulk density, the procedures to carry out each one are listed below, more details in Appendix D.

- **Procedure A: Bulk Density – Dry**

Carry out the procedure as follows:

1. Determine the mass of the dry specimen (m_1).
2. Immerse the specimen in the water-bath kept at the known test temperature.

3. Determine the mass of the specimen immediately the water has settled after immersion (m_2).

- **Procedure B: Bulk Density – Saturated Surface Dry (SSD)**

Carry out the procedure as follows:

1. Determine the mass of the dry specimen (m_1).
2. Immerse the specimen in the water-bath at the known test temperature. Allow the water to saturate the specimen sufficiently long enough for the mass of the specimen not to change at least 30 min .
3. Determine the mass of the saturated specimen when immersed (m_2), taking care no air bubbles adhere to the surface of the specimen or leave the specimen when weighing.
4. Remove the specimen from the water, dry the surface from adhered drops by wiping with a damp Chamois.
5. Determine the mass of the saturated, surface wiped specimen in air immediately after drying (m_3).

- **Procedure C: Bulk Density – Sealed Specimen**

Carry out the procedure as follows:

1. Determine the mass of the dry specimen (m_1).
2. Seal the specimen in such a way, that the internal voids in the specimen being part of the volumetric material composition are not penetrated and that no extra voids are included between seal and specimen or in seal folds. After sealing the specimen shall be inaccessible to water when submerged.
3. When using " paraffin wax ", obtain sealing using the following procedure:
    - Bring the "paraffin wax" to its melting temperature of + 10 °C and maintain this temperature at ± 5 °C.
    - Immerse the specimen partially in the "paraffin wax" for less than 5 s, agitating the specimen to make the air balls free. After cooling and solidification of the paraffin wax on this part of the specimen, repeat the same procedure on the other part. Repeat these procedures until a continuous film of "paraffin wax" is obtained, which totally cover the specimen.
4. Determine the mass of the dry sealed specimen (m_2).
5. Immerse the specimen in the water-bath kept at the known test temperature.

6. Determine the mass of the sealed specimen under water (m_3), taking care no air bubbles adhere to the sealing when weighing.

➢ Procedure D: Bulk Density by Dimensions

Carry out the procedure as follows.

1. Determine the dimensions of the specimen according to EN 12697-29.
2. Determine the mass of the dry specimen (m_1).

- h is the height of the specimen.
- d is the diameter of the specimen.

Table 3.17: Bulk density equations (g/ cm^3)

Method	Equation
Dimensional	$Gmb_{,\mathrm{dim}} = (\frac{m_1}{\frac{\pi}{4} \times h \times d^2} \times 10^3)$
Dry method	$Gmb_{,dry} = \frac{m_1}{m_1 - m_2} * \rho_w$
Saturated surface dry	$Gmb_{,ssd} = \frac{m_1}{m_3 - m_2} * \rho_w$
Paraffin sealing	$Gmb_{,\mathrm{sea}} = (\frac{m_1}{(m_2 - m_3)/\rho_w - (m_2 - m_1)/\rho_{\mathrm{sm}}})$

Chapter 4

Results and Data Analysis

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 bulk density and void ratio in HMA mixtures using different methods according to EN12697.

In chapter three, the properties of materials were tested, and the marshal method was mentioned in order to design asphalt mixtures. Also, methods for determining bulk density with their equations were demonstrated.

Laboratory testing program contains preparing three wearing coarse asphalt mixtures which are: Dense Asphalt (DA), Mastic Asphalt (MA), and Porous asphalt (PA). Then twelve specimens were prepared from each mixture type and the bulk densities were determined by four methods which are: Dimensional Method (DIM), Dry Method (DM) , SSD method, and Paraffin Sealing Method (PSM), and the void ratios were calculated at every bulk density value. As Figure 4.1 explain the proposed methodology.

The Results are presented in this chapter in four sections: Dense asphalt, Mastic asphalt, and Porous asphalt. Where each section contains: Marshal tests for mixture, determining optimum bitumen content, bulk density results, and the calculated air void ratio.

In the last section a series of statistical analyses, including linear and nonlinear regressions were performed on the results in order to compare air void ratio results for each one of the three methods with the air void ratio results for the SSD method.

In each mixture type, a box plot was used to display air void results of the four methods.

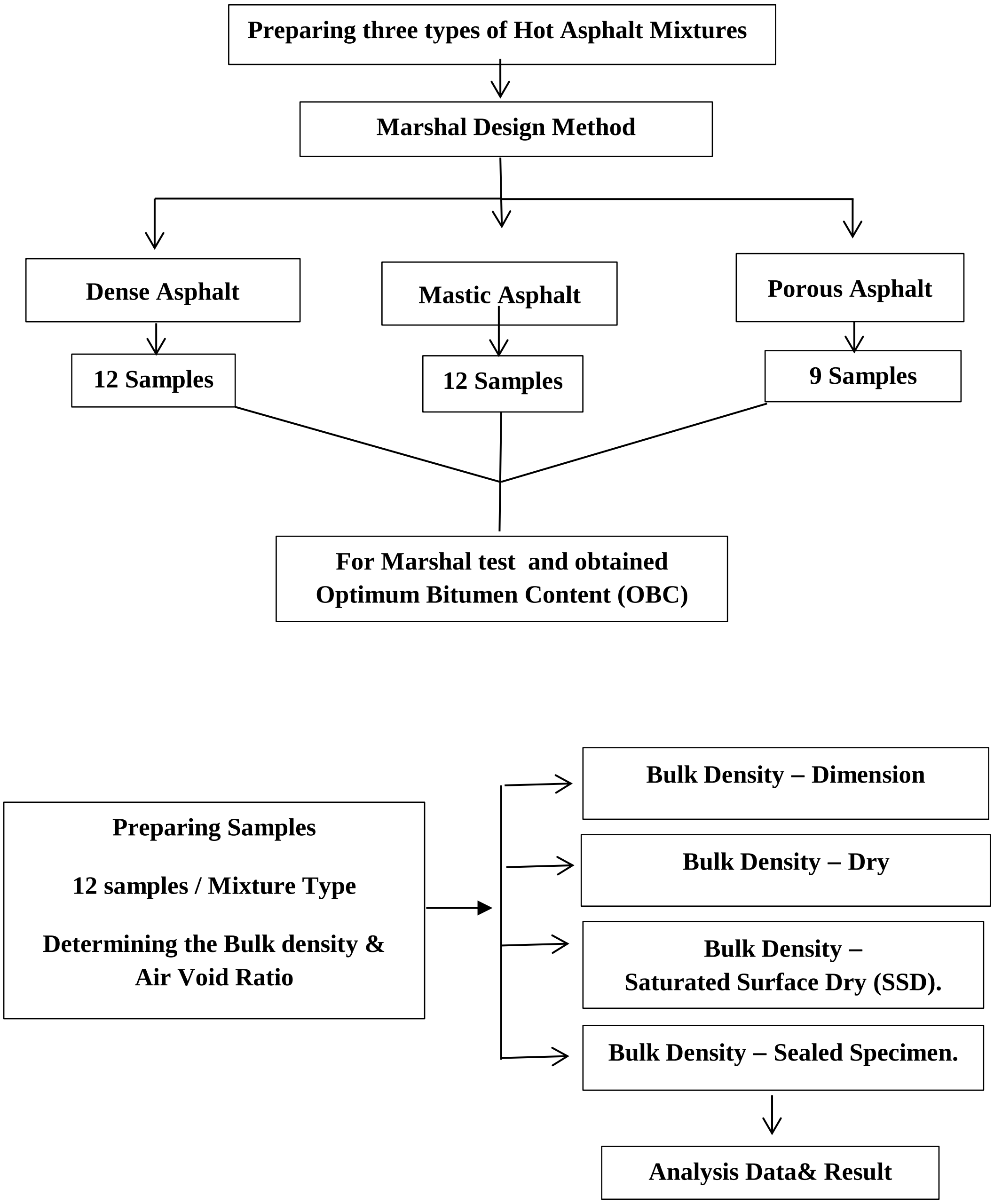


Figure 4.1: Proposed Methodology

4.2 Dense Asphalt Mixture

4.2.1 Blending of Aggregates

The mineral type used for dense asphalt mixes is crushed limestone. The determination of aggregate proportions depends on the number of aggregate types to be blended, and the limits of the desired gradation, Table A.1 in appendix (A) shows that DA contains three types of aggregates: coarse, fine, and filler, Table 4.2 shows aggregate gradation. The final ratio of each aggregate material in DA course is shown in Table (4.1). The proposed aggregates gradation curve is found to be satisfying FHWA specification for dense asphalt course gradation. The gradation of the final aggregate mix with FHWA gradation limits is presented in Table 4.3 and Figure 4.2:

Table 4.1: Dense Asphalt proportion of each aggregate material from proposed mix

Aggregate Type	% by Total Weight of Aggregates
Adasia Aggregate	18.5 %
Simsimia Aggregate	26.6 %
Trabia Aggregate	51.9 %
Filler	3.0 %
Total	100.0 %

Table 4.2: Aggregate gradations of dense asphalt mixture

Sieve No.	Sieve size (mm)	Cumulative % Passing			
		Adasia	**Simsimia**	**Trabia**	**Filler**
		0/ 12.5	**0/ 9.50**	**0/4.75**	**< 0.075**
1"	**25.00**	100.0	100.0	100.0	100.0
3/4"	**19.00**	100.0	100.0	100.0	100.0
1/2"	**12.50**	50.1	100.0	100.0	100.0
3/8"	**9.50**	7.6	91.6	100.0	100.0
#4	**4.75**	1.1	51.0	96.7	100.0
#8	**2.36**	1.1	5.7	92.9	100.0
#16	**1.180**	1.1	3.4	79.0	100.0
#30	**0.600**	1.1	2.7	59.3	100.0
#50	**0.300**	1.1	2.4	32.8	99.2
#80	**0.150**	0.2	0.8	13.9	96.0
#200	**0.075**	0.2	0.6	6.9	89.1

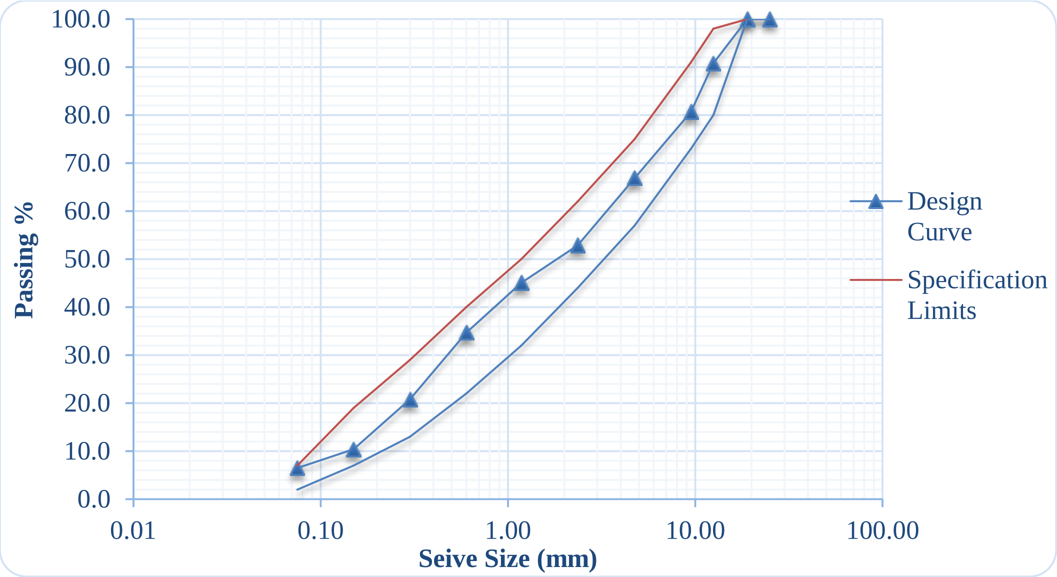


Figure 4.2: Gradation curve of dense asphalt mix with FHWA Specification.

Table 4.3: Gradation of proposed mix with FHWA Specification limits.

Sieve No.	Sieve Size (mm)	% Passing	FHWA Standard specification limits (%)	
			Min	Max
1"	**25.00**	100.0	100	100
3/4"	**19.00**	100.0	100	100
1/2"	**12.50**	90.8	80	98
3/8"	**9.50**	80.7	73	91
#4	**4.75**	66.9	57	75
#8	**2.36**	52.9	44	62
#16	**1.180**	45.1	32	50
#30	**0.600**	34.7	22	40
#50	**0.300**	20.8	13	29
#80	**0.150**	10.4	7	19
#200	**0.075**	6.5	2	7

4.2.2 Marshall Mix Design

As mentioned in Chapter (3). Marshall Method of mix design is the most popular method used mainly to determine the optimum bitumen content. For Dense Asphalt, the amount of 12 samples, each one approximately 1200g of aggregates types and filler put together is heated to a temperature of 160-170˚C. Bitumen is heated to a temperature of 160˚C with four trials percentage of bitumen (from 4.5 -

6% with 0.5 % incremental), by weight of the mineral aggregates. Then the heated aggregates and bitumen are thoroughly mixed at a temperature of 160 - 170˚C. The mix is placed in a preheated cylindrical mould and compacted by a hammer having a weight of 4.5 kg and a free fall of 45.7 cm giving 75 blows on both sides at a temperature of 160˚C to prepare the laboratory specimens to obtain the optimum bitumen content (OBC) for DA.

- Table 4.4 illustrate Details of Marshal Test results.
- Table 4.5 summarizes the average result of properties at each binder content percentage.

Table 4.4: Details of Marshal Test results in Dense Asphalt Mixture.

Bitumen % (by total weight)	**Sample No.**	**Stability (Kg)**	**Flow (mm)**	**ρA (g/cm3)**	**Va (%)**	**(VMA) (%)**	**(VFB) (%)**	**Stiffness (Kg/mm)**
4.5	1	1392.0	2.20	2.33	5.70	15.88	64.2%	632.71
	2	1438.0	2.30	2.33	5.60	15.81	64.5%	625.20
	3	1412.4	2.20	2.33	5.80	15.96	63.8%	642.00
	Avg.	**1414.11**	**2.23**	**2.33**	**5.70**	**15.88**	**64.2%**	**633.30**
5	1	1672.6	2.70	2.34	4.81	16.15	70.3%	619.50
	2	1677.7	2.70	2.33	4.92	16.26	69.7%	621.38
	3	1680.3	2.80	2.34	4.83	16.18	70.1%	600.10
	Avg.	**1676.89**	**2.73**	**2.34**	**4.85**	**16.20**	**70.0%**	**613.66**
5.5	1	1672.6	3.40	2.33	4.20	16.68	74.8%	491.95
	2	1652.3	3.30	2.34	4.16	16.64	75.0%	500.69
	3	1659.9	3.40	2.34	4.02	16.51	75.7%	488.21
	Avg.	**1661.61**	**3.37**	**2.34**	**4.13**	**16.61**	**75.1%**	**493.62**
6	1	1494.1	3.80	2.33	3.61	17.20	79.0%	393.19
	2	1506.9	3.90	2.33	3.55	17.15	79.3%	386.39
	3	1473.7	3.90	2.33	3.51	17.12	79.5%	377.87
	Avg.	**1491.58**	**3.87**	**2.33**	**3.56**	**17.16**	**79.3%**	**385.82**

Table 4.5: Summary of Marshal Test Results in Dense Asphalt Mixture.

Binder Content % of Total Mix	**Stability Kg**	**Flow mm**	**ρA (g/cm3)**	**Stiffness Kg/mm**	**VMA %**	**VFB %**	**Va %**
4.50%	1414.1	2.2	2.3323	633.3	15.9	64.2	5.7
5.00%	1676.9	2.7	2.3357	613.7	16.2	70.0	4.9
5.50%	1661.6	3.4	2.3365	493.6	16.6	75.1	4.1
6.00%	1491.6	3.9	2.3335	385.8	17.2	79.3	3.6

4.2.3 Optimum Bitumen Content

- **Stability – Bitumen Content Relationship**

Stability is the maximum load required to produce failure of the specimen when the load is applied at constant rate 50 mm / min (Jendia, 2000).

Figure (4.3) display the stability results for different bitumen contents are represented. The stability value increases with increasing binder content up to a maximum (5.3%) at this point the stability value (1700 kg), after which the stability decreases.

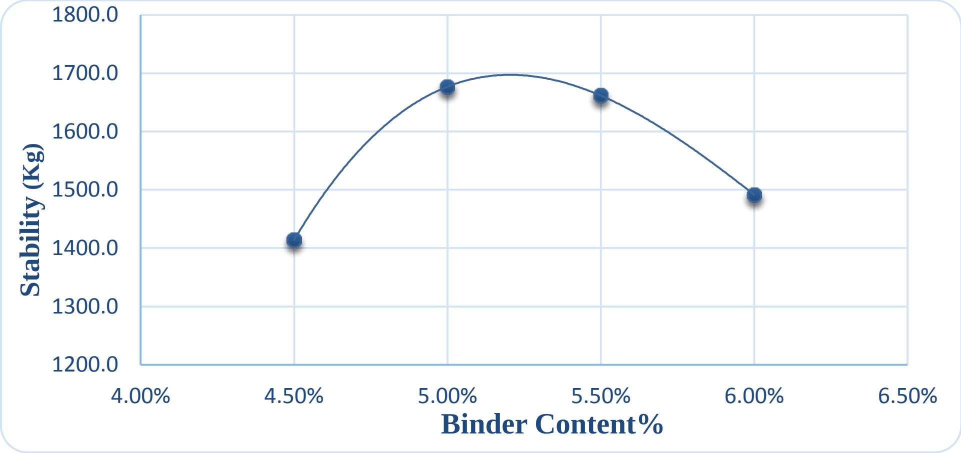


Figure 4.3: Stability vs. bitumen content

- **Flow – Bitumen Content Relationship**

Flow is the total amount of deformation which occurs at maximum load(Jendia,2000). Figure (4.4) display the Flow results for different bitumen contents are represented. Flow of asphalt mix increases as the bitumen content increase. The best value of flow @ 3mm achieve with bitumen content equal 5.3%.

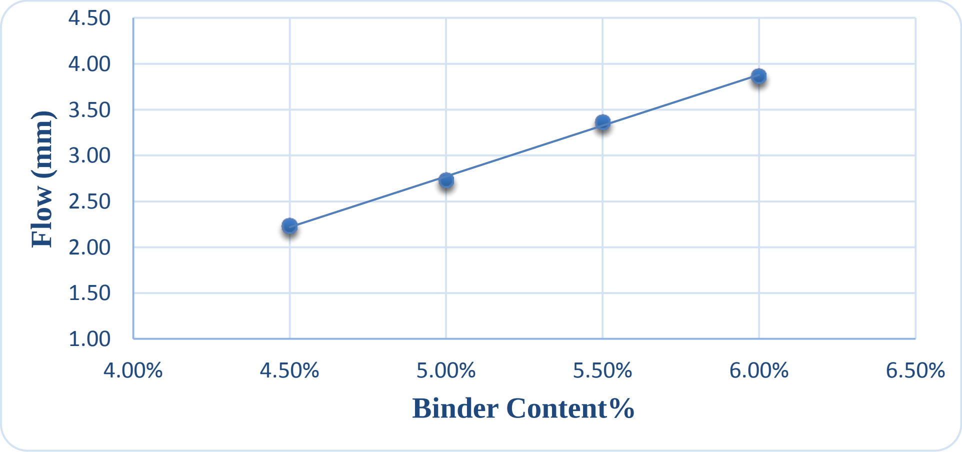


Figure 4.4: Flow vs. bitumen content

- **Bulk density – Bitumen Content Relationship**

Gmb is the real density of the compacted mix. Figure (4.5) display the Bulk density results for different bitumen contents are represented. Bulk Specific gravity of asphalt mix increases as the bitumen content increase till it reaches the peak (2.3365g/cm^3) at bitumen content 5.3 % then it started to decline gradually at higher bitumen content.

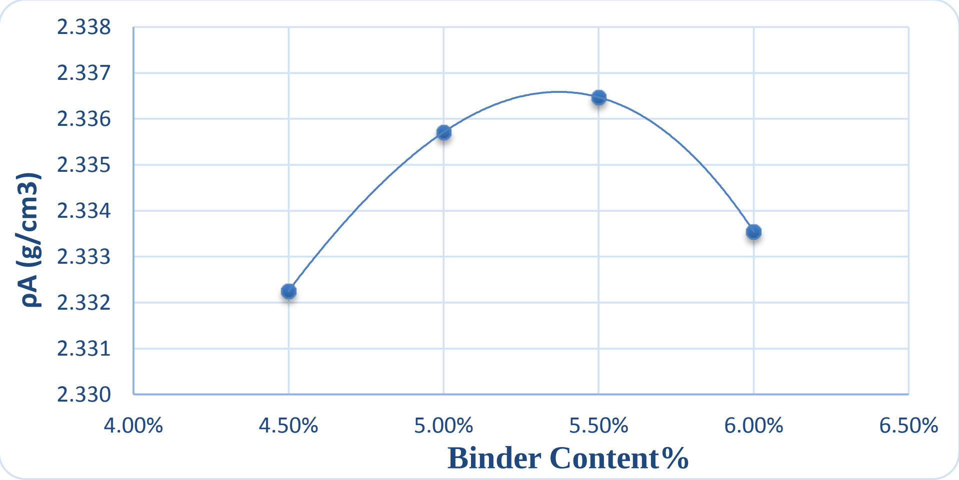


Figure 4.5: Bulk density vs. bitumen content

- **Air Voids Content (Va %) – Bitumen Content Relationship**

The air voids content (Va %) is the percentage of air voids by volume in the specimen or compacted asphalt mix (Jendia, 2000).

Figure (4.6) display the (Va%) results for different bitumen contents are represented. The percent of air voids decreases with increasing asphalt content due to the increase of voids percentage filled with bitumen in the asphalt mix.

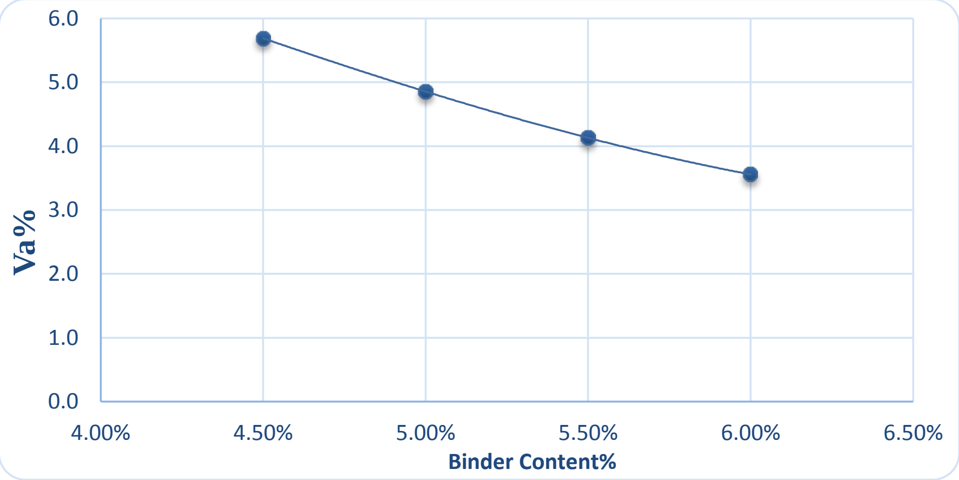


Figure 4.6: Mix air voids proportion vs. bitumen content

➢ 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 (4.7) 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.

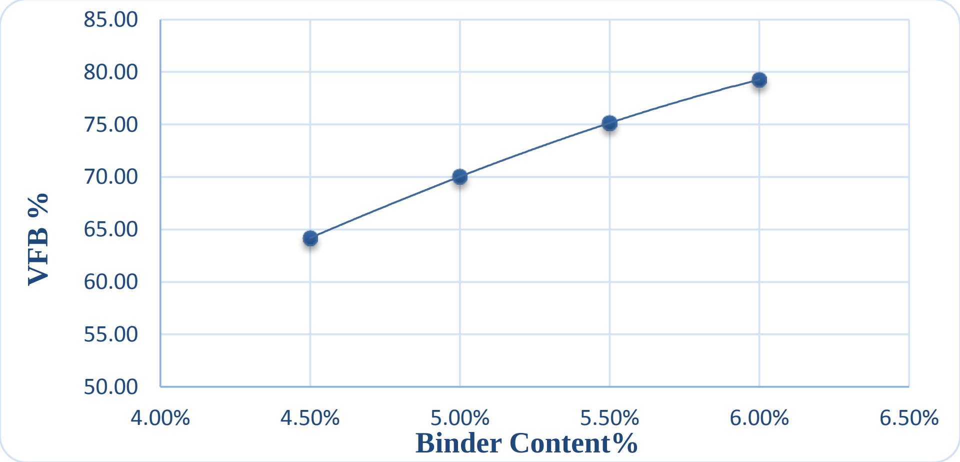


Figure 4.7: Voids filled bitumen proportion vs. bitumen content

➢ 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 4.8 display the VMA results for different bitumen contents are represented. VMA decrease steadily as bitumen content increase and fill a higher percentage of voids in the asphalt mix.

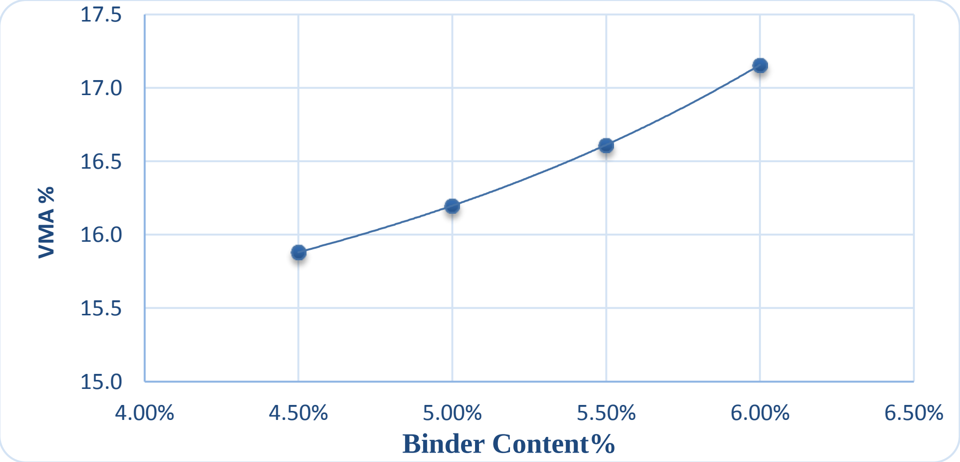


Figure 4.8: Voids in mineral aggregates proportion vs. bitumen content.

- **Determination of Optimum Bitumen Content (OBC)**

Figures (4.3, 4.5and 4.6) are used to find three values respectively.

- Bitumen content at the maximum stability (% mb) Stability = 5.3 %
- Bitumen content at the maximum value of bulk density (% mb) bulk density =5.40%
- Bitumen content at the median of allowed percentages of air voids @Va=4% = 5.6%
- Optimum bitumen content (OBC) = (5.3+5.40+5.6)/3≌ 5.40%

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

Table 4.6: Recommended to select the optimum asphalt bitumen content (MPWH,1998)

Mix Properties	Unit	Job Mix Results	Specification limits	
			Minimum	Maximum
Stability	Kg	1672.6	900	*
Flow	mm	3.4	2	4
Gmb	g/cm^3	2.34	2.300	
Stiffness	Kg/mm	492.2	400	*
Va	%	4.2	3	5
VMA	%	16.4	13.0	*
VFB	%	74.7%	60	75

4.2.4 Determination of the Bulk Density

The main topic in this study is determining the bulk density in asphalt mixture types by using four methods. In chapter three, procedures of the four methods, that followed to determine bulk density, were mentioned according to (EN 12697-6). Table 4.7 summarizes equations to calculate bulk density by each method.

Table 4.7: Equations of bulk density determining methods

Method	Equation
Dimensional Method	$$Gmb_{,\mathrm{dim}} = \left(\frac{m_1}{\frac{\pi}{4}\times h\times d^2}\times 10^3\right)$$ Where: m_1 is the mass of the dry specimen, in (g); h is the height of the specimen, in (cm); d is the diameter of the specimen, in (cm).
Dry Method	$$Gmb_{,dry} = \frac{m_1}{m_1 - m_2}\times\rho_w$$ Where: m_1 : is the mass of the dry specimen, in grams; m_2 : is the mass of the specimen in water, in grams; p_w is the density of the water, in (g/cm^3);
Saturated surface dry Method	$$Gmb_{,ssd} = \frac{m_1}{m_3 - m_2}\times\rho_w$$ Where: m_1 is the mass of the dry specimen, in grams ; m_2 is the mass of the specimen in water, in grams; m_3 is the mass of the saturated surface-dried specimen, (g); p_w is the density of the water, in (g/cm^3);
Paraffin Sealing Method	$$Gmb_{,\mathrm{sea}} = \left(\frac{m_1}{(m_2 - m_3)/\rho_w - (m_2 - m_1)/\rho_{\mathrm{sm}}}\right)$$ Where : m_1 is the mass of the dry specimen, in grams (g); m_2 is the mass of the sealed specimen dry, in gram (g); m_3 is the mass of the sealed specimen in water,in (g); p_w is the density of the water, in (g/cm^3); p_{sm} is the density of the sealing material (paraffin) at test temperature, in (g/cm^3);

➢ **Number of Samples**

For determining Gmb and Va%, twelve specimens from each mixture were prepared, this number of specimens is due to the following reasons:

- The method for preparing the mixture is manual, so when increasing the specimen's number this requires repeating the process more than once, this makes sample group exposed to different conditions such as temperature.
- By using 12 specimens from each mixtures, 48 values of Gmb can be determined, and this is accurate enough when getting the results.
- Previous studies used approximate number of 12 specimens, for example (Crouch, 2002) used 10 specimens for compering between Gmb determining methods.

In the laboratory, 12 cylindrical specimens were prepared by placing the mixture under a temperature of 160˚C, then they were compacted through a hammer weighting 4.5 kg and with a free fall of 45.7 cm giving 75 blows on both sides. After 24 hours. The bulk density was determined by using the four methods. Table 4.9 shows the results of bulk density.

Table 4.8: Codes used to present the results of DA.

Mixture type	Dense Asphalt (DA)
Specimen code	D1,D2,D3,………., D12
Method code	Dimensional ,Method (DIM) Dry method (DM1 SSD method (SSD) Paraffin sealing Method (PSM)

Table 4.9: Results of bulk density (g/cm3) of DA.

Method	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
DIM	2.332	2.313	2.347	2.311	2.312	2.316	2.345	2.342	2.338	2.345	2.350	2.315
DM	2.362	2.361	2.388	2.367	2.362	2.361	2.376	2.374	2.371	2.366	2.369	2.370
SSD	2.36	2.35	2.38	2.36	2.36	2.36	2.37	2.37	2.37	2.359	2.371	2.379
PSM	2.378	2.373	2.410	2.385	2.379	2.344	2.396	2.390	2.391	2.388	2.399	2.386

4.2.5 Determination of Air Void Ratio

Air void content is the single most important property that is used for design and construction quality control of Hot Mix Asphalt (HMA). Generally, air void content is determined from bulk specific gravity (Gmb) and theoretical maximum density (Gmm) of HMA mixes. (Kassem E., 2011.)

The percent air voids for each method were calculated by using the AASHTO T269 equation.

$$Air\ Voids\ (percent) = \left(\frac{G_{mm} - G_{mb}}{G_{mm}}\right) \times 100\ \% \tag{4.1}$$

- The Gmm determined for the dense asphalt mixture by using Pycnometer device, the value of Gmm = 2.473.
- The Gmb determined by divided bulk density of specimens on the density of the water, which equals 1g/cm^3 at 23 °C.

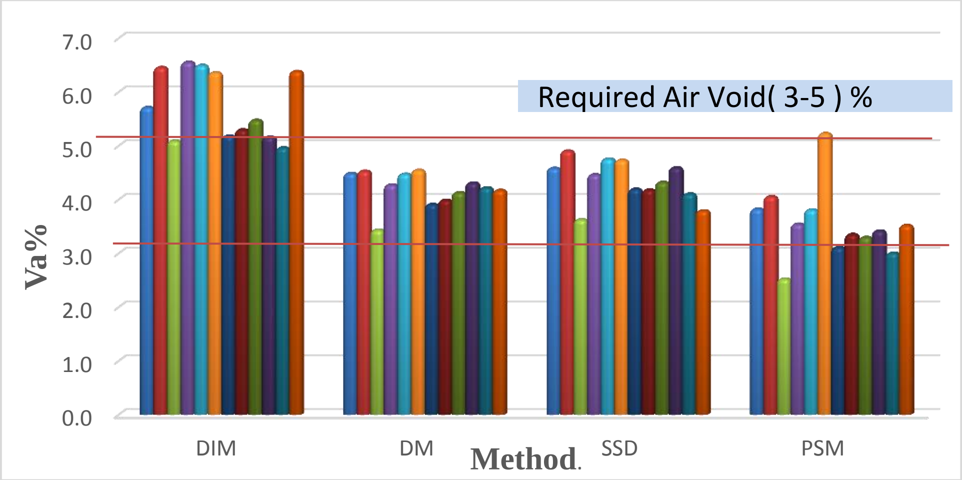


Figure 4.9: Column chart to represent Va% of each test method.

Figure 4.9 shows void ratio value of cylinder-shaped specimen prepared, it will separately measure the bulk density of mixes with dimensional method, dry method, SSD, paraffin sealing method. While calculating the corresponding air voids. According to the data in the Table 4.10 below, the difference of bulk specific gravity of mix got from four different density measurement methods is low, the high rang of value appearance between the maximum value of voids in dimension method 6.56% and the minimum value in paraffin sealing method 2.53%.

Table 4.10: Summary of DA data results of Va%.

Methods	DIM	DM	SSD	PSM
Average	5.76	4.21	4.36	3.56
Max	6.56	4.55	4.91	5.23
Min	4.97	3.44	3.63	2.53

Generally, in Dense asphalt which is the range of voids between 3-5 %. Regarding the voids ratio data which is relay to the density data, the dry measurement method is the highest density which representative the density underweight in water, this leads voids ratio to be low. The dry method has the lowest range of voids, the different between the max value of Va% and the min value is equal approximately 1%. But this method ignored the surface voids that's the reason for the value of the dry test.

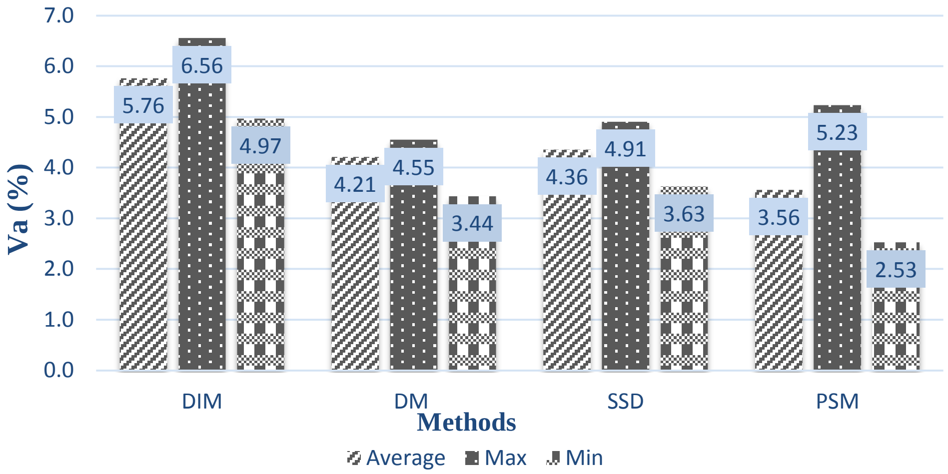


Figure 4.10: Calculated air void ratio graph of each method.

As Figure 4.1 shows, for dense asphalt mixture with voids required between 3-5%. DM, and SSD methods have provided the value of VA% of all specimens of DA within the target limit 3-5 %. In contrast to DIM the upper limit of voids exceeds (5%) in every value of VA%. The PSM provides average value of result with the limit but the minimum value of voids less than lower limit of voids.

According to the results, DM, and SSD are the most logical selected to determine the real bulk density and air voids of dense mixes. And DIM can be used as indicator to check if the air voids of the mix have basically exceeded the design requirement of void ratio or not.

4.3 Mastic asphalt mixture.

4.3.1 Blending of aggregates

MA contains three types of aggregates: coarse, fine, and filler. Numerical method used to determine trial blend of aggregates types proportion in mastic mixture, which is presented in appendix A. The final ratio of each aggregate material in MA mixture is shown in Table 4.11. The proposed aggregates gradation curve is found to satisfy

BS EN 13108-6 specification for mastic asphalt gradation. The gradation of the final aggregate mix with BS EN 13108-6 gradation limits is presented in Table 4.12 and Figure 4.11:

Table 4.11: Mastic Asphalt proportion of each aggregate material from proposed mix.

Sieve No.	**Sieve size (mm)**	**Cumulative % Passing**		
		Simsimia	**Trabia**	**Filler**
		0/ 9.50	**0/4.75**	**< 0.075**
1"	**25.00**	100.0	100.0	100.0
3/4"	**19.00**	100.0	100.0	100.0
1/2"	**12.50**	100.0	100.0	100.0
3/8"	**9.50**	91.6	100.0	100.0
#4	**4.75**	51.0	96.7	100.0
#8	**2.36**	5.7	92.9	100.0
#16	**1.180**	3.4	79.0	100.0
#30	**0.600**	2.7	59.3	100.0
#50	**0.300**	2.4	32.8	99.2
#80	**0.150**	0.8	13.9	96.0
#200	**0.075**	0.6	6.9	89.1

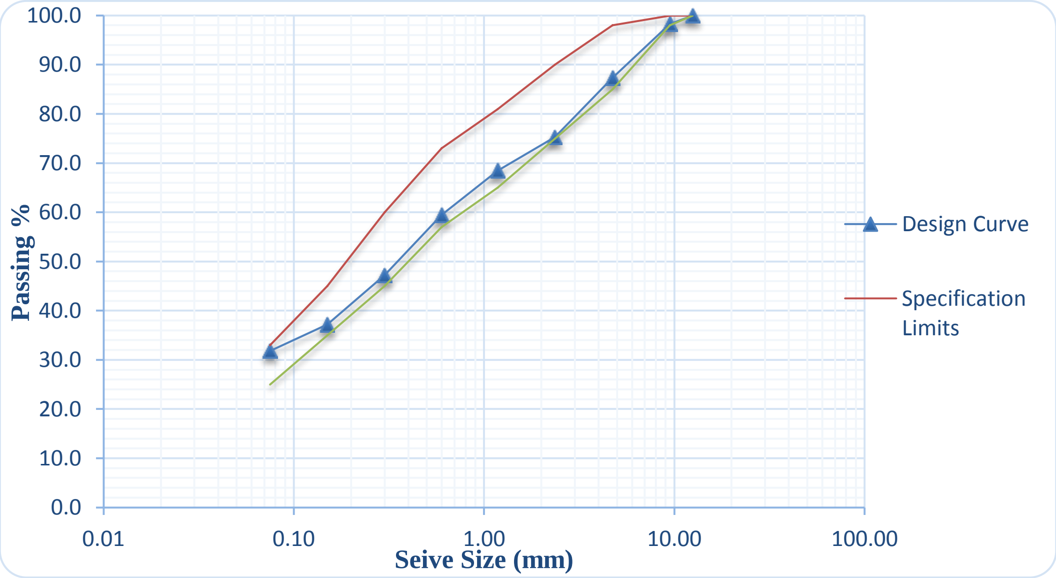


Figure 4.11: Gradation curve of mastic asphalt mix with BS EN 13108-6 Specification.

Table 4.12: Mastic asphalt gradation of proposed mix with BS EN 13108-6 specifications limits

Sieve No.	Sieve Size (mm)	Passing %	(BS EN 13108-6)Standard specification limits (%)	
			Min	Max
3/4"	**19.00**	100	100	100
1/2"	**12.50**	100.0	100	100
3/8"	**9.50**	98.3	98	100
#4	**4.75**	87.3	85	98
#8	**2.36**	75.3	75	90
#10	**1.180**	68.5	65	81
#30	**0.600**	59.5	57	73
#50	**0.300**	47.2	45	60
#80	**0.150**	37.2	35	45
#200	**0.075**	31.8	25	33

Table 4.13: Mastic Asphalt Mix gradations of aggregates

Aggregate Type	% by Total Weight of Aggregates
Simsimia Aggregate	23.0 %
Fine Aggregate	45.0 %
Filler	32.0 %
Total	100.0 %

4.3.2 Marshall Mix Design

For Mastic Asphalt, the amount of 12 samples, each one approximately 1200g of aggregates types and filler put together is heated to a temperature of 180-195˚C, were prepared, using three different bitumen contents (11.5%, 12%,12.5%,13%), detailed marshal test results are shown in table 4.14.

MA has a very fine texture, filler constitutes more than 30% of the total mixture weight , The specimens of MA prepared at 180 C mix temperature, (BS EN 13108-6, 2008) is using around 10 Super-pave gyratory compactor to prepare mastic asphalt sample, but in the laboratory work, 15 blows by marshal hammer provide satisfactory compaction.

Table 4.14: Details of Marshal Test results for Mastic Asphalt Mixture.

Bitumen % (by total weight)	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
11.5	1	1340.8	7	2.28	2.2	27.68	92.1%	191.5
	2	1302.4	6.50	2.29	2	27.50	92.8%	200.4
	3	1267.9	6.50	2.27	2.7	28.00	90.5%	195.1
	Avg.	**1306.7**	**6.7**	**2.28**	**2.3**	**27.80**	**91.8%**	**195.67**
12	1	1519.7	7.9	2.3	0.8	27.6	97.1%	187.5
	2	1570.7	8.4	2.298	0.9	27.7	96.7%	183.3
	3	1557.9	8.5	2.295	1	27.7	96.4%	187.0
	Avg.	**1549.4**	**8.3**	**2.34**	**0.9**	**27.7**	**96.8%**	**192.4**
12.5	1	1672.6	10.6	2.301	0.0	28	99.8%	157.80
	2	1761.8	10.4	2.300	0.1	28	99.8%	161.63
	3	1637.0	10.9	2.299	0.1	28	99.6%	157.40
	Avg.	**1690.5**	**10.6**	**2.30**	**0.1**	**28**	**99.7%**	**158.94**
13	1	1583.4	12.0	2.278	0.3	29.1	98.8%	132
	2	1545.2	13.5	2.281	0.2	29.0	99.3%	114.5
	3	1593.7	13.0	2.281	0.2	29.0	79.3%	122.6
	Avg.	**1574.1**	**12.8**	**2.80**	**0.2**	**29.0**	**99.1%**	**123**

Table 4.15: Summary of Marshal Test Results for Mastic Asphalt Mixture.

Binder Content % of Total Mix	Stability Kg	Flow Mm	ρA (g/cm3	Stiffness Kg/mm	Va %	VMA %	VFB %
11.50%	1306.7	6.7	2.2818	195.7	2.3	27.8	91.8
12.00%	1549.4	8.3	2.2973	192.4	0.9	27.7	96.8
12.50%	1690.5	10.6	2.3002	158.9	0.1	28.0	99.7
13.00%	1574.1	12.8	2.2800	123.0	0.2	29.0	99.1

4.3.3 Optimum Bitumen Content

- **Stability – Bitumen Content Relationship**

Marshall Stability is measured according to ASTM D 6927.

As Figure 4.12 shows, stability value increases with increasing binder content until a peak is reached at mb (12.5%), At that point, the stability value decreases with further increase in binder content.

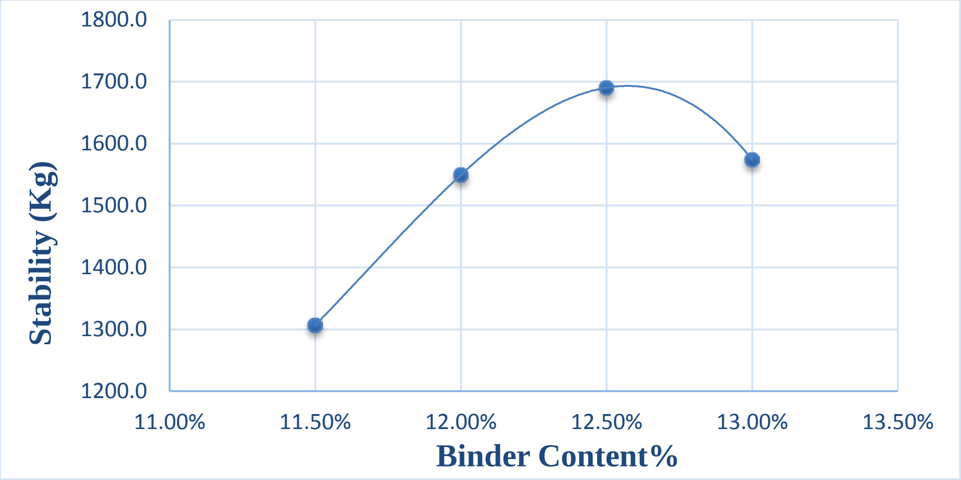


Figure 4.12: Stability vs. bitumen content

- **Flow – Bitumen Content Relationship**

Marshall Flow is measured according to ASTM D 6927.

Flow is determined during the same test used to determine the Marshall Stability value. Marshall Flow value, as figure 4.13 shows, increases with increasing binder content. A range of flow values from 10 to 14 mm are high due to the binder content used in MA is high in compare with other mixtures types.

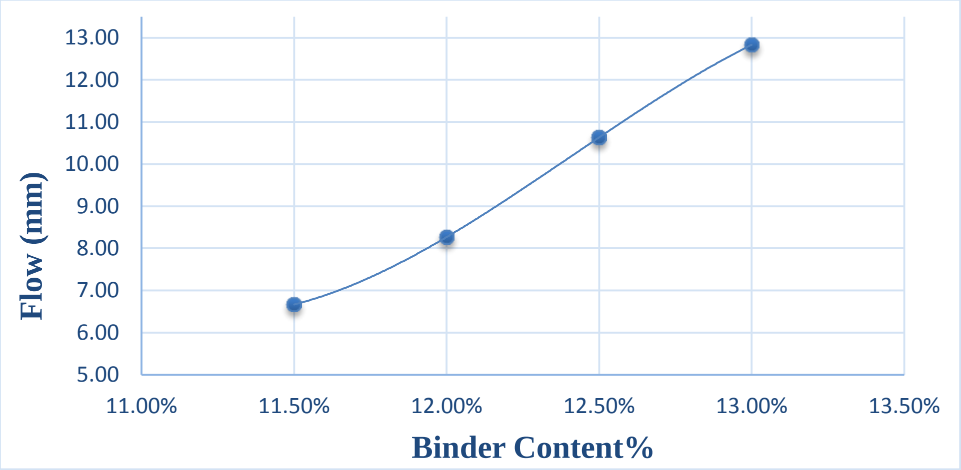


Figure 4.13: Flow vs. bitumen content

- **Bulk density – Bitumen Content Relationship**

Volumetric properties of HMA are determined according to ASTM D 2676. SSD method is used to determine the bulk specific gravity.

As Figure 4.14 shows, bulk density value increases as binder content increases till 12.3% when bulk density equals 2.312 (g/cm3), after that the value starts to decrease.

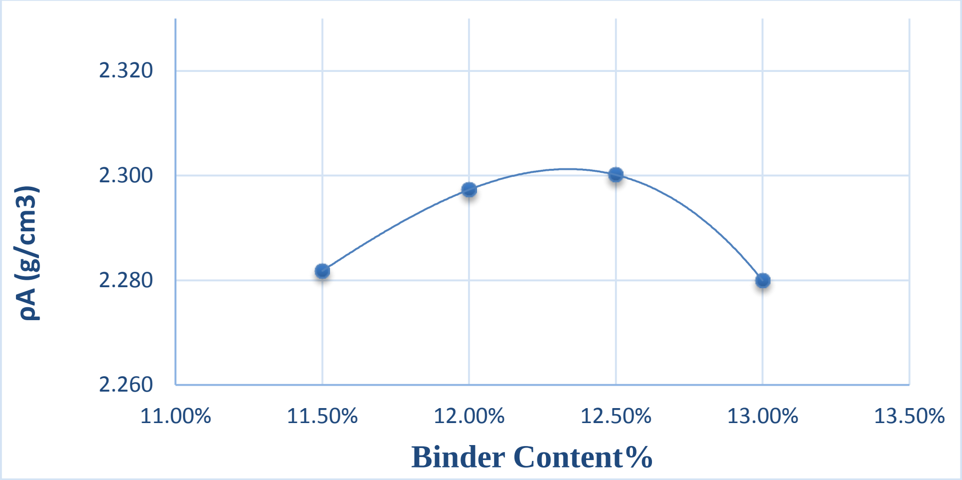


Figure 4.14: Bulk density vs. bitumen content

- **Air Voids Content (Va %) – Bitumen Content Relationship**

A traditional compacted HMA specimen consists of aggregate, binder, and air. But MA is Void less mixture due to the high percentage of mortar exceed 50% of the total mixture weight.

Figure 4.15 displays the Va% results for different bitumen contents. The percent of air voids decreases with increasing asphalt content till binder content is 12.7% when VA% approximates zero.

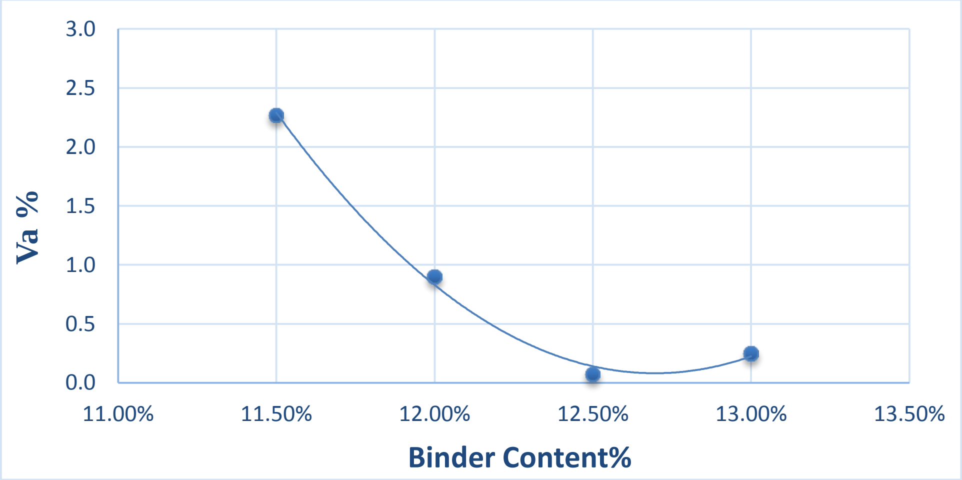


Figure 4.15: Mix air voids proportion vs. bitumen content

- **Voids Filled with Bitumen (VFB %) – Bitumen Content**

The (VFB %) results for different bitumen contents are represented in Figure 4.16. As the percentage of asphalt binder is high the VFB is high. Minimum VFB content value is at the lowest bitumen percentage (11.5%), VFB% increase steadily as bitumen content increase due to the increase of voids percentage filled with bitumen in the asphalt mix.

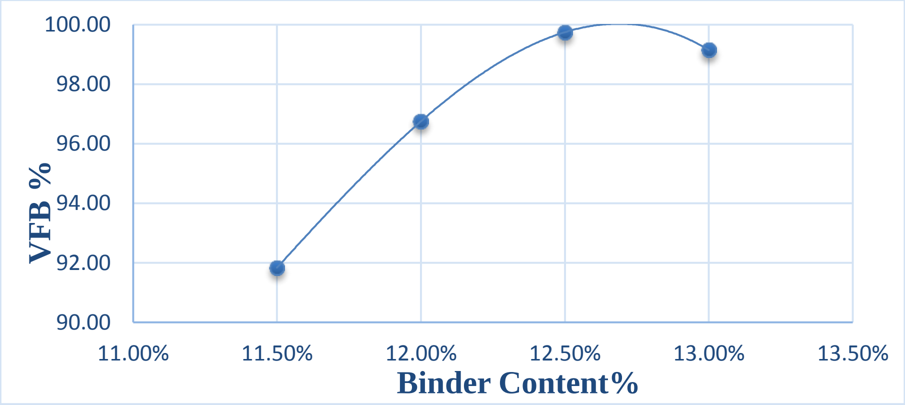


Figure 4.16: Voids Filled Bitumen proportion vs. bitumen content

- **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 4.17 display the VMA results of different bitumen contents. VMA value stay in the same range between 11.5- 12%, then VMA value increases a little as bitumen contents increase .

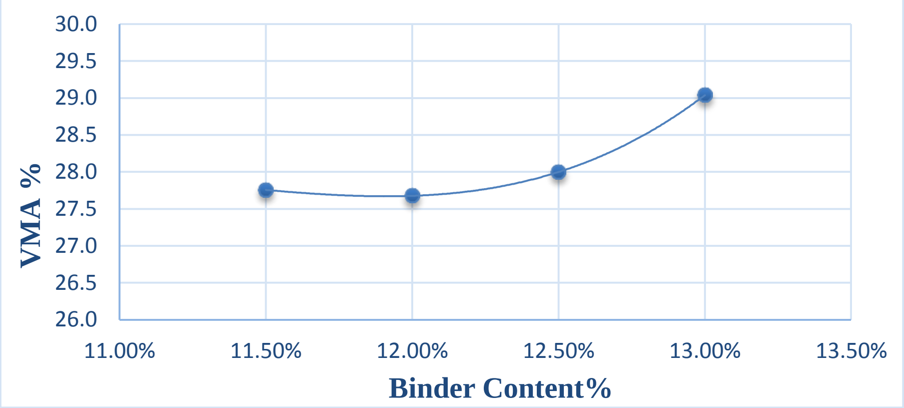


Figure 4.17: Voids in Mineral Aggregates proportion vs. bitumen content.

- **Determination of Optimum Bitumen Content (OBC)**

For mastic asphalt the methodology required corresponding to the India and BS stander different with previous procedure in dense asphalt, the target voids in mastic lead to zero (void less asphalt). So the OBC according to Figures (4.13, 4.15and 4.16) summarize as following:

- Bitumen content at the highest stability (% mb) Stability = 12.5 %
- Bitumen content at the highest value of (ρA %) =12.40%
- Bitumen content at the target percentages of air voids @Va=0% = 12.6%
- Optimum bitumen content (OBC) = (12.5+12.40+12.6)/3= 12.5%.

At the recommended asphalt content the following Characteristics are met:

Table 4.16: Test result of MA compared with specification En 13108-1:2006.

Mix Properties	Unit	Job Mix Results	Specification limits	
			Minimum	Maximum
Stability	Kg	16905	1200	*
Flow	mm	10.6	6	14
Stiffness	Kg/mm	158.9	130	*
Va	%	0.2	*	2
VMA	%	28	25	*
VFB	%	99.7	78	*

4.3.4 Determination of the Bulk Density

In general, MA mixture has low bulk density value and theoretical maximum density value in compare with DA mixtures, and this is due to high mortar level which exceed 50% of the total weight of mixtures, more over MA mineral aggregate free of size particles more than 0/12.5.

In the laboratory, 12 cylindrical specimens (M1- M12) were prepared by placing the mixture under a temperature of 185˚C, then they were compacted through a hammer weighting 4.5 kg and with a free fall of 45.7 cm giving 15 blows – self compacted mixtures with a little compaction effort - on both sides. After 24 hours. The bulk density was determined by using the four methods. Table 4.18 shows the results of bulk density.

- Table 4.17 shows the codes used to present the result of DA.

Table 4.17: Codes used to present the results of MA.

Mixture type	Mastic Asphalt (MA)
Specimen code	M1,M2,M3,………., M12
Method code	Dimensional ,Method (DIM) Dry method (DM) SSD method (SSD) Paraffin sealing Method (PSM)

Table 4.18: Results of bulk density (g/cm3) of MA.

Method	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
DIM	2.267	2.275	2.247	2.253	2.261	2.250	2.250	2.290	2.267	2.297	2.277	2.288
DM	2.300	2.294	2.297	2.297	2.304	2.286	2.289	2.299	2.295	2.300	2.306	2.289
SSD	2.299	2.294	2.296	2.297	2.304	2.285	2.288	2.297	2.293	2.299	2.306	2.286
PSM	2.310	2.308	2.306	2.312	2.317	2.297	2.301	2.311	2.317	2.317	2.339	2.305

As table 4.18 shows the results of bulk density, the specimens code (M5,M9, M10,and M11) have PSM results of Gmb greater than Gmm (2.312 g/cm3), so these specimens were excluded from the results of this method.

Figure 4.18: Bulk density testing of MA specimens.

4.3.5 Determination of the Air Void Ratio

The air void percentages for the mastic mixes were calculated by the four methods Gmb determined using the equation (4.1), TMD/ Gmm which was evaluated by Pycnometer device is (2.312), Va% were presented in Figure 4.19.

It is noticed according to the Figure 4.19 and Table 4.9 that the Gmb and void ratio which measured specimen’s code from M1- M12 is the least different between maximum and minimum value, most of results within 1%. SSD and DM methods are provides very closed results of Va% .

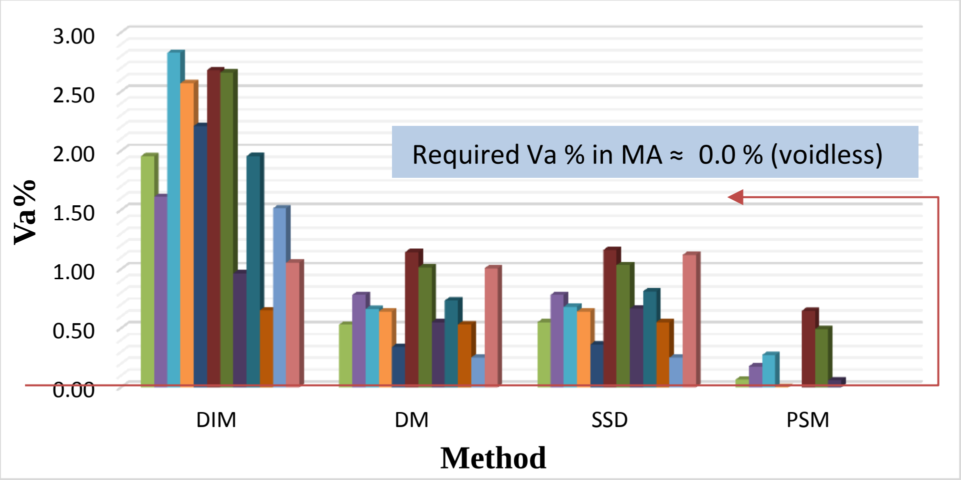


Figure 4.19: Column chart to represent Va% of each bulk density test method.

In addition, the void ratio for 7 specimens by using Paraffin method are presented in Figure 4.19.

Table 4.19: Summary of MA data results of Va%.

Methods	**DIM**	**DM**	**SSD**	**PSM**
Average	1.89	0.68	0.72	0.25
Max	2.83	1.14	1.16	0.65
Min	0.65	0.25	0.25	0.0

As Table 4.19 indicates, DIM method has given Va% with average result 1.89% more than other three methods due to the raveling and deformation have been existed. The surface of two sides not level as the mathematical equation for DIM method proposed. As shown in Figure 4.20.

Figure 4.20: Raveling in MA specimen’s surface.

To sum up, the SSD and DM methods are the best choices for the measure of bulk density in void less/ mastic asphalt mixtures. DIM and PSM give an indication for upper and lower limits of voids respectively as shown in Figure 4.21.

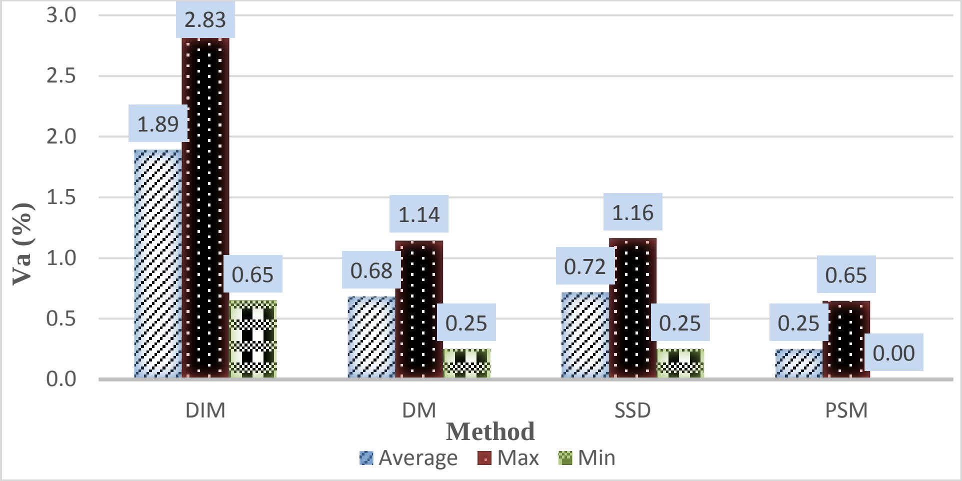


Figure 4.21: Calculated air void ratio graph of each method.

4.4 Porous asphalt mixture.

4.4.1 Blending of aggregates

First, Porous asphalt mixture in this study depends on the limits of the suggested gradation mentioned in (Jendia et al., 2018) article.

PA contains three sizes of coarse aggregates as shown in Table 4.20, aggregates types proportion in porous mixture are presented in appendix A.

Table 4.20: Porous Asphalt proportion of each aggregate material from proposed mix

Aggregate Type	% by Total Weight of Aggregates
Simsimia Aggregate	50.0 %
Adasia Aggregate	45.0 %
Folia Aggregate	5.0 %
Total	100.0 %

The simsimia (0/9.5) mineral type, which is used in PA differs from those used in DA and MA mixtures, the percentage of 0/9.5, which was passed from 0.075mm sieve opening size, was 5.1% as table 4.21 explains

.

Table 4.21: Porous Asphalt Mix gradations of aggregates

Sieve No.	**Sieve size (mm)**	**Cumulative % Passing**		
		Folia	**Adasia**	**Simsimia**
		0/ 19	**0/ 12.5**	**0/ 9.50**
1"	**25.00**	100.0	100.0	100.0
3/4"	**19.00**	95.9	100.0	100.0
1/2"	**12.50**	11.3	50.1	100.0
3/8"	**9.50**	0.6	7.6	92.6
#4	**4.75**	0.4	1.1	53.3
#8	**2.36**	0.3	1.1	9.8
#16	**1.180**	0.2	1.1	6.2
#30	**0.600**	0.2	1.1	5.4
#50	**0.300**	0.2	1.1	5.1
#200	**0.075**	0.2	0.2	5.1

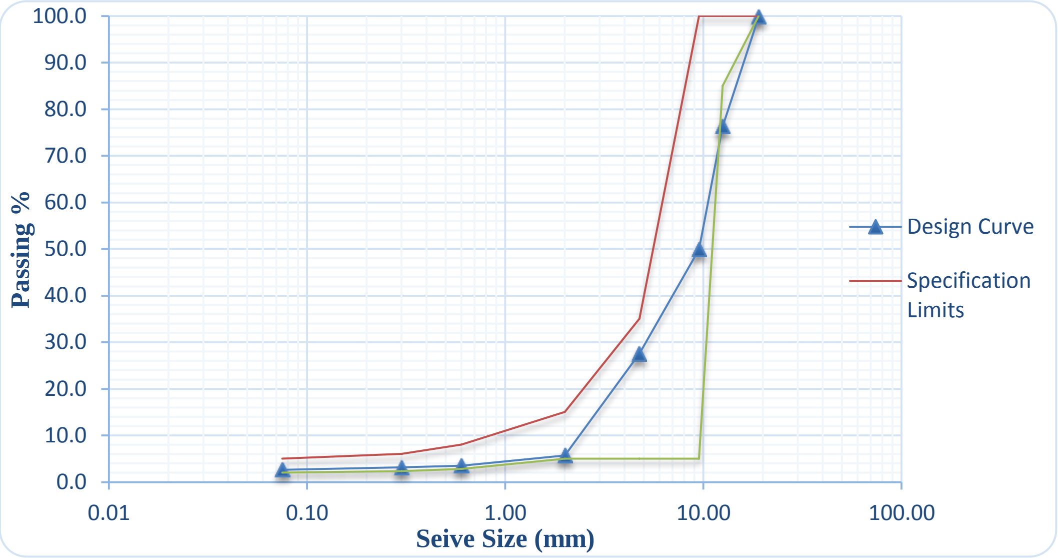


Figure 4.22: Gradation curve of porous asphalt mix according to Jendia et al., (2018)

Table 4.22: Porous asphalt gradation of proposed mix with (Jendia et al., 2018) limits.

Sieve No.	**Sieve Size (mm)**	**% Passing**	**Specifications**	
			Min	**Max**
1"	**25**	100	100	100
3/4"	**19.00**	99.8	100	100
1/2"	**12.50**	76.3	85	100
3/8"	**9.50**	49.9	5	100
#4	**4.75**	27.5	5	35
#8	**2.00**	5.7	5	15
#10	**0.600**	3.5	2.8	8
#30	**0.300**	3.1	2.3	6
#200	**0.075**	2.6	2	5

4.4.2 Marshall Mix Design

For Porous Asphalt, the amount of 9 samples, each one approximately 1200g of coarse aggregates types put together to made incorporating the recommended combined Grading with bitumen content (3.5%, 4 %, 4.5%).Table 4.23 shows the detailed marshal test results, and Summary of the marshal test results is shown in Table 4.24.

Table 4.23: Detailed marshal test results of porous asphalt.

Bitumen % (by total weight)	Sample No.	Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	(VMA) (%)	(VFB) (%)	Stiffness (Kg/mm)
3.5	1	424.0	2.82	1.905	23.2	29.8	22.2	150.36
	2	407.5	2.64	1.850	25.4	31.8	20.1	154.34
	3	337.3	2.70	1.980	20.2	27	25.4	124.91
	Avg.	**389.6**	**2.72**	**1.912**	**22.9**	**29.6**	**22.5**	**143.20**
4.0	1	429.6	3.00	1.94	21.2	28.9	26.6	143.21
	2	412.2	2.79	1.98	19.6	27.4	28.5	147.73
	3	426.6	2.80	1.91	22.4	30.0	25.2	152.37
	Avg.	**422.8**	**2.90**	**1.943**	**21.1**	**25.2**	**26.8**	**147.77**
4.5	1	454.18	2.83	2.02	17.3	26.3	34.2	160.49
	2	490.25	3.25	1.95	20.2	28.9	30.1	150.85
	3	436.07	2.88	1.91	21.8	30.4	28.0	151.41
	Avg.	**460.17**	**3.00**	**1.96**	**19.8**	**28.5**	**30.8**	**154.25**

Table 4.24: Summary of the marshal test results

Binder Content % of Total Mix	Stability Kg	Flow mm	ρA (g/cm3)	Stiffness Kg/mm	Va %	VMA %	VFB %
3.50%	389.6	2.7	1.9117	143.2	22.9	29.6	22.5
4.00%	422.8	2.9	1.9433	147.8	21.1	28.8	26.8
4.50%	460.2	3.0	1.9600	154.2	19.8	28.5	30.8

4.4.3 Optimum Bitumen Content

- **Stability – Bitumen Content Relationship**

Figure 4.23 shows the relationship between binder content and stability value, the stability value take linear shape, starts from 390 kg at mb 3.5%, and increases to 460 kg at mb 4.5%.

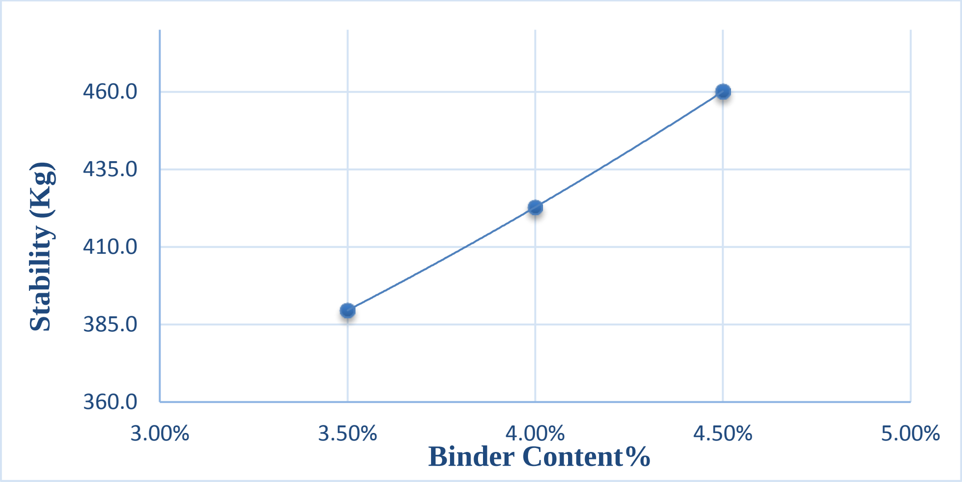


Figure 4.23: Stability vs. Bitumen Content

- **Flow – Bitumen Content Relationship**

The flow is in the limit range and its increasing with closer range from 2.71 mm to 3.00 mm. Figure 4.24 shows the relationship between flow value and binder content.

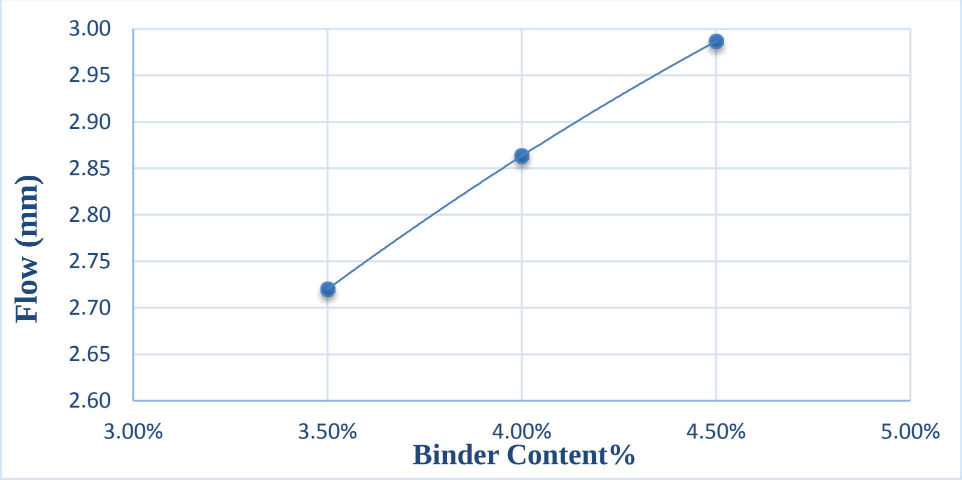


Figure 4.24: Flow vs. Bitumen Content

- **Bulk Density – Bitumen Content Relationship**

The general trend that there is a small effect for changing binder content (3.5, 4, and 4.5) %, the bulk density value increases with narrow range from 1.912 to 1.962 g/cm3 as shown in Figure 4.25.

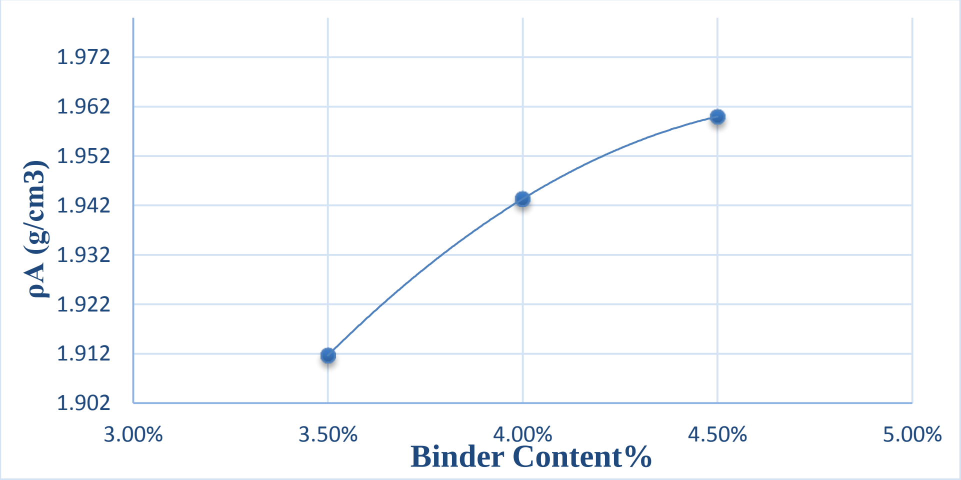


Figure 4.25: Bulk density vs. bitumen content

- **Air voids content (Va %) – Bitumen Content Relationship**

Generally, Va% in PA is too high in compared with dense graded asphalt. Figure (4.26) shows the decreasing in Va% by increasing *mb*%.

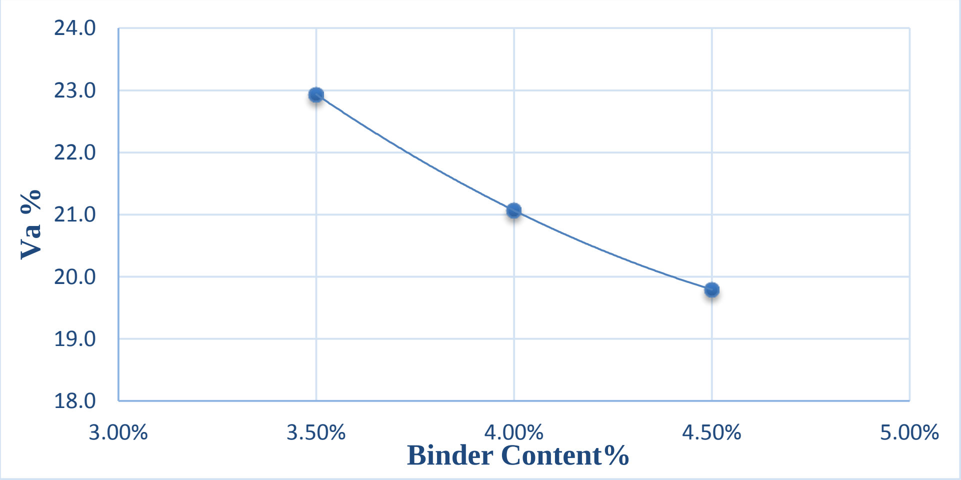


Figure 4.26: Mix air voids proportion vs. bitumen content

- **Voids Filled with Bitumen (VFB %) – Bitumen Content**

The (VFB %) results for different bitumen contents are represented in Figure 4.27. VFB% increases steadily as bitumen content increases due to the increase of voids percentage filled with bitumen in the asphalt mix.

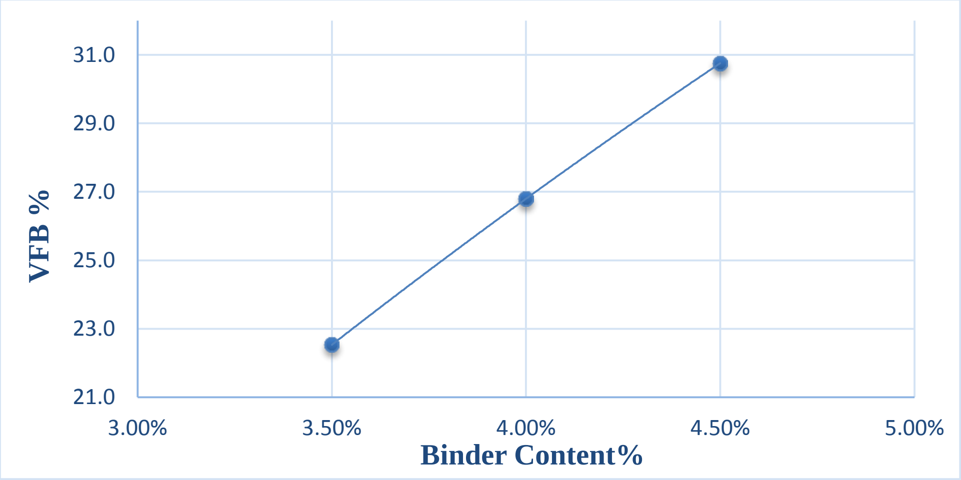


Figure 4.27: Voids Filled Bitumen proportion vs. Bitumen Content

- **Voids in Mineral Aggregates (VMA)–Bitumen Content Relationship**

As Figure 4.28 shows, VMA value is decreased as mb% is increased due to the voids filled with bitumen.

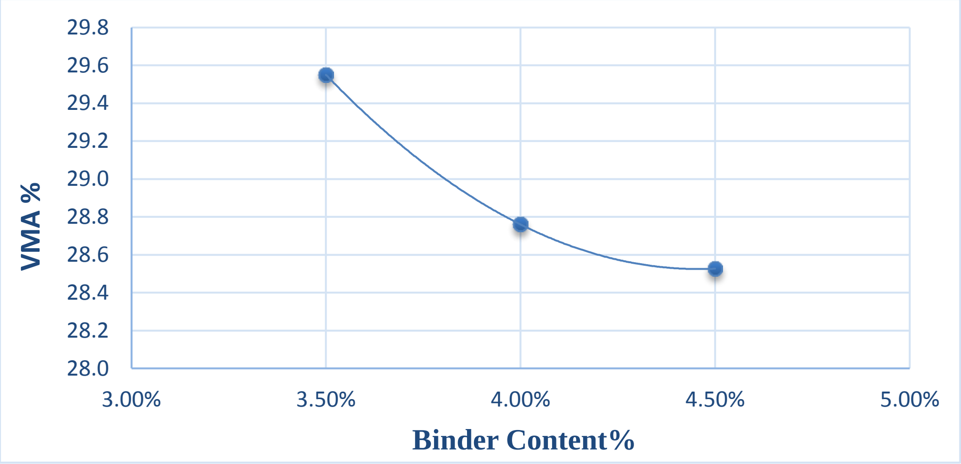


Figure 4.28: Voids Filled Bitumen proportion vs. Bitumen Content

- **Determination of Optimum Bitumen Content (OBC)**

Asphalt (bitumen) content (%) has to be obtained from maximum stability value ,maximum bulk density, , and Air voids required.

- Bitumen content at the highest stability at (% mb) Stability = 4.5 %
- Bitumen content at the highest Gmb value of (mb %) Gmb =4.50%
- Bitumen content at the target percentages of air voids @Va=>20% = 4.0%
- Optimum bitumen content (OBC) = (4.5+4.50+3.5)/3 = 4.2%.

4.4.4 Determination of the Bulk Density

Porous asphalt is the least bulk density among other asphalt mixtures types, this is due to it contains more void ratio reaches up to 20% of the total volume of mixture.

To determined bulk density in PA, 12 cylindrical specimens (P1-P12) were prepared through placing the hot mixture under temperature of 165C, then they are compacted by 50 blows of Marshall hammer per each specimens side. After 24 hours, bulk density is determined by the four methods, which were mentioned in the other topic.

Table 4.25: Codes used to present the results of PA.

Mixture type	Porous Asphalt (PA)
Specimen code	P1,P2,P3,………., P12
Method code	Dimensional method (DIM) Dry method (DM1 SSD method (SSD) Paraffin sealing Method (PSM)

As table 4.26 shows, the value of bulk density, it is clear that there are significant differences between the values of bulk density, the maximum value is 2.633 g/cm3 by PSM, and the minimum value is 1.779 g/cm3 by DIM.

Method	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
DIM	1.932	1.838	1.854	1.901	1.989	1.950	1.852	1.832	1.901	1.779	1.787	1.808
DM	2.359	2.403	2.400	2.374	2.353	2.308	2.386	2.380	2.387	2.366	2.379	2.368
SSD	2.265	2.325	2.309	2.299	2.298	2.287	2.310	2.277	2.283	2.257	2.286	2.270
PSM	2.796	2.107	2.218	2.633	2.298	2.065	2.160	2.199	2.170	2.232	2.153	2.341

Table 4.26: Values of the bulk density (g/cm3) of PA.

As table 4.26 shows the results of bulk density, the specimens code (P1and P4), have PSM results of Gmb greater than Gmm (2.37 g/cm3), so these specimens were excluded from the results of this method.

4.4.5 Determination of the Air Void Ratio

The air void percentages for the PA were difficult to be determined due to the open interconnected voids of the mix structure. The four methods were employed to determine bulk density, then Va% was determined by using the equation (4.1), TMD/ Gmm, which was evaluated by Pycnometer device, is 2.38. Va% is presented in figure 4.29.

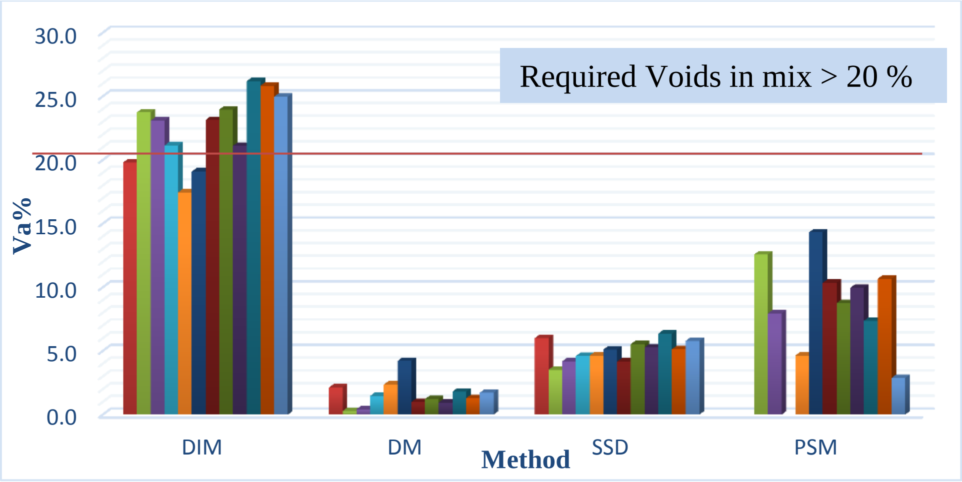


Figure 4.29: Column chart to represent Va% of each bulk density test method.

As table 4.27 shows, the average air voids calculated from the Gmb results obtained by the four methods for the 12 specimens were ranked from P1- P12.

The results obtained by the DIM method produced the highest Va% contents and the results obtained by the PSM produced the second highest Va% contents. The dry method produced the lowest Va% contents.

Table 4.27: Summary of PA data results of Va%.

Methods	DIM	DM	SSD	PSM
Average	22.47	1.58	5.03	9.0
Max	26.20	4.22	6.36	14.32
Min	17.46	0.28	3.53	2.9

The PSM produced Void ratio higher than those obtained by SSD method and lower than those obtained by DIM.

Practically, when PSM was melted and specimen submerged partially, sometimes the pieces of granular specimen material dropped and the mineral sediment in a bowl. So, the temperature of paraffin affects the sample to be brittle! Another reason, theoretically, paraffin coated the surface of specimen, but in real it goes through connected voids in porous mixture and close them, this is the reason of the wide range between the results, max value of voids is (14%), and the un logical excluded values. As shown in figure 4.30.

Figure 4.30: Bulk density by PSM

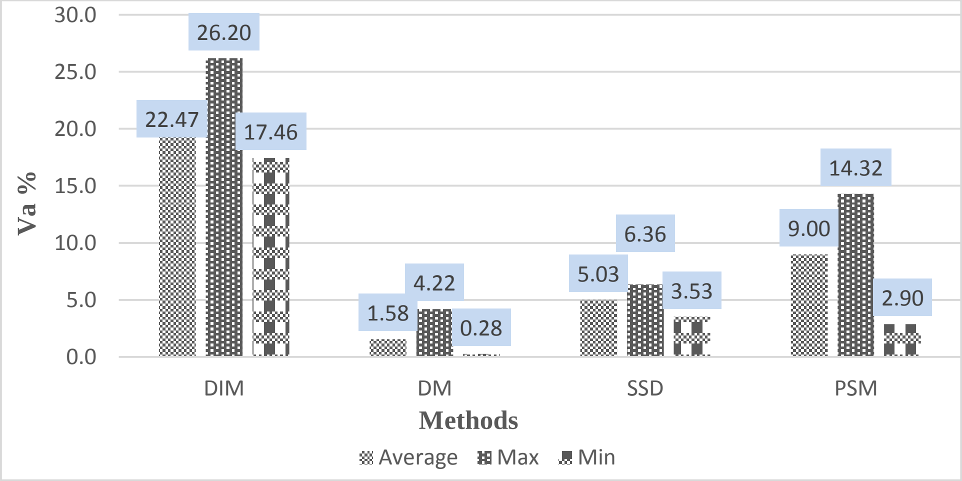


Figure 4.31: Calculated air void ratio graph of each method.

Figure 4.31 explains that DIM was the most accurate method for determination of the Gmb values of the specimens. DIM worked well regards to the cylinder regular shape in determining bulk volume. However, as surface is not circlar in the top and the bottom due to light deformation from the marshal hammer, DIM tends to overestimate sample volume, thus reducing Gmb and increasing apparent air voids.

The overestimation of the volume is due to attempts to approximate a non-planar surface with a planar surface. As evidence of the overestimation, recall that the DIM produced the highest percentage of air voids for every another asphalt mixtures (Dense, Mastic, and Porous). As a result, the dimensional method is the most widely applicable method for determination of Gmb in PA mixture, which has high connected voids more than 15%, although the underestimation of bulk density.

4.5 Data Analysis

4.5.1 Relationship between the Four Methods

Because SSD method is the most widely used in measuring Gmb. So, the comparison procedure between the four methods used in this study based on SSD method. The voids ratio explains the differences in the bulk density results of the four methods.

A linear regression prediction between the Gmb and Va% obtained from SSD method on X- Axis and Dry, Dimensional, Paraffin sealing method on Y- Axis has been conducted.

The relationship of each type of mixtures explained as the following:

- **For Dense Asphalt**

Figure 4.32, shows three relationships: Va% by SSD versus other three methods, according to data analysis, the comment about the results can be mentioned in the following points:

1. The dimensional method provides underestimated results for Gmb so the Va% is always the highest among the other three methods. So the correlation between DIM and SSD method is poor (**R^2 = 0.243).**
2. The differences in Va% values, as a result of the differences in Gmb, were insignificant by the DM in comparison to SSD method. So the correlation between the two methods is high (**R^2 = 0.7264).**
3. PSM could make a good correlation with SSD method despite of providing Va% less than the SSD method’s value. PSM provide the greatest results of Gmb and The lowest results of Va% regards the other three methods .

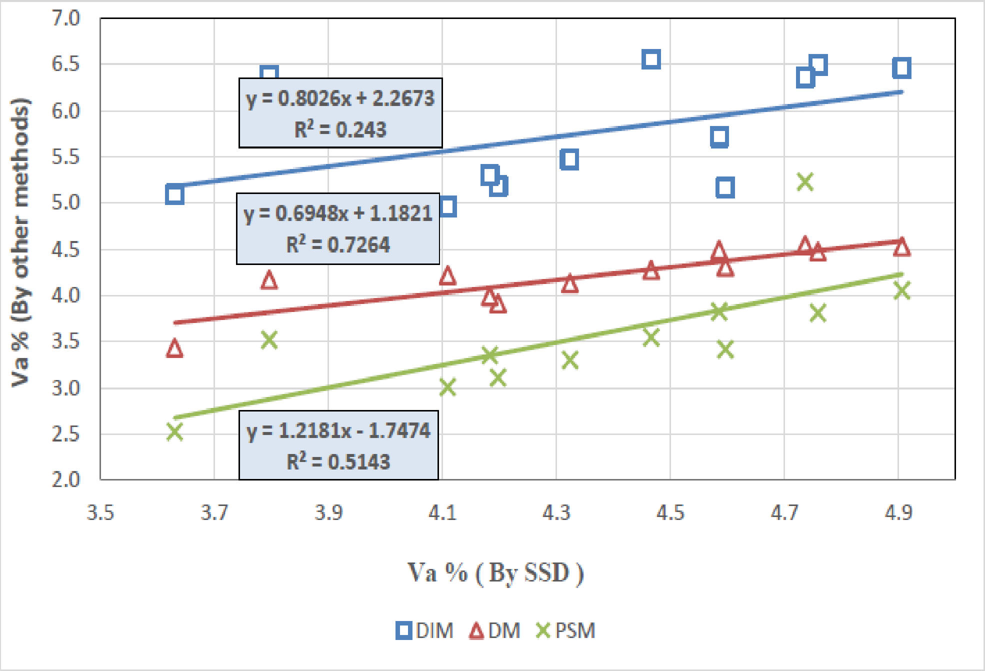


Figure 4.32: Linear relationship between the air void content obtained by SSD method and other three methods in Dense Asphalt.

- To provide more accuracy to predict the upper limit of Voids in DA mixtures, nonlinear regression is accomplished, as shown in Figure 4.33

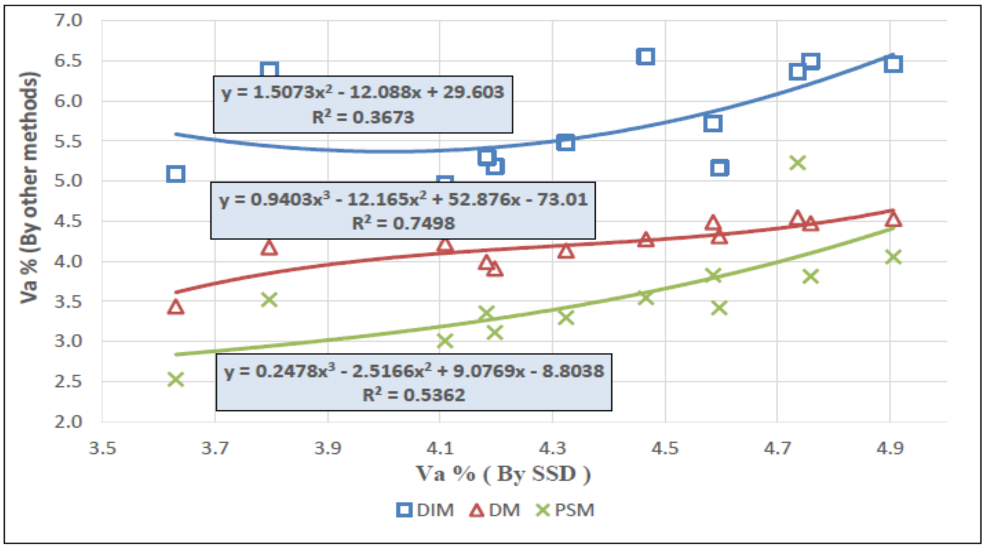


Figure 4.33: Nonlinear relationship between the air void content obtained by SSD method and other three methods in Dense Asphalt.

The equations that represent the relationship between DIM and SSD methods are applied to examine differences of Va%, Table 4.29 explains the results which were calculated by the following equations:

- **$y = 0.8026x + 2.2673$ [Liner regression with $R^2 = 0.243$}**
- **$y = 1.1443x^3 - 13.141x^2 + 50.085x - 57.865$ [Nonlinear regression with $R^2 =0.3747$]**

Table 4.28: Va% of DIM by using the relationship with SSD.

Dense Asphalt	**A**	**B**	**C**	**D**	**$\frac{(B-A)}{B}$*100 %**	**$\frac{(C-A)}{C}$*100 %**	**$\frac{(D-A)}{D}$*100 %**
Va(%) in Sample Code	**SSD**	**Measured DIM**	**Linear R.**	**Nonlinear R.**			
			Predicted DIM	**Predicted DIM**			
D1	4.6	5.7	5.9	5.8	19.3	22.0	20.7
D2	4.9	6.5	6.2	6.7	24.6	21.0	26.9
D3	3.6	5.1	5.2	5.5	29.4	30.8	34.5
D4	4.5	6.6	5.9	5.6	31.8	23.7	19.6
D5	4.8	6.5	6.1	6.2	26.2	21.3	22.6
D6	4.7	6.4	6.1	6.1	26.6	23.0	23.0
D7	4.2	5.2	5.6	5.5	19.2	25.0	23.6
D8	4.2	5.3	5.6	5.5	20.8	25.0	23.6
D9	4.3	5.5	5.7	5.5	21.8	24.6	21.8
D10	4.6	5.2	6.0	5.8	11.5	23.3	20.7
D11	4.1	5.0	5.6	5.4	18.0	26.8	24.1
D12	3.8	6.4	5.3	5.5	40.6	28.3	30.9

As Table 4.28 shows the maximum ratio of comparing DIM and SSD is 40.6% and the minimum ratio is 11.5%, which mean that Va results based on SSD smaller than Va measured and predicted by DIM with approximately(11.5- 40.6) from DIM Va% .

- **For Mastic Asphalt**

As Figures 4.34 shows, except DIM, the relationship between SSD and the other two methods is strong.

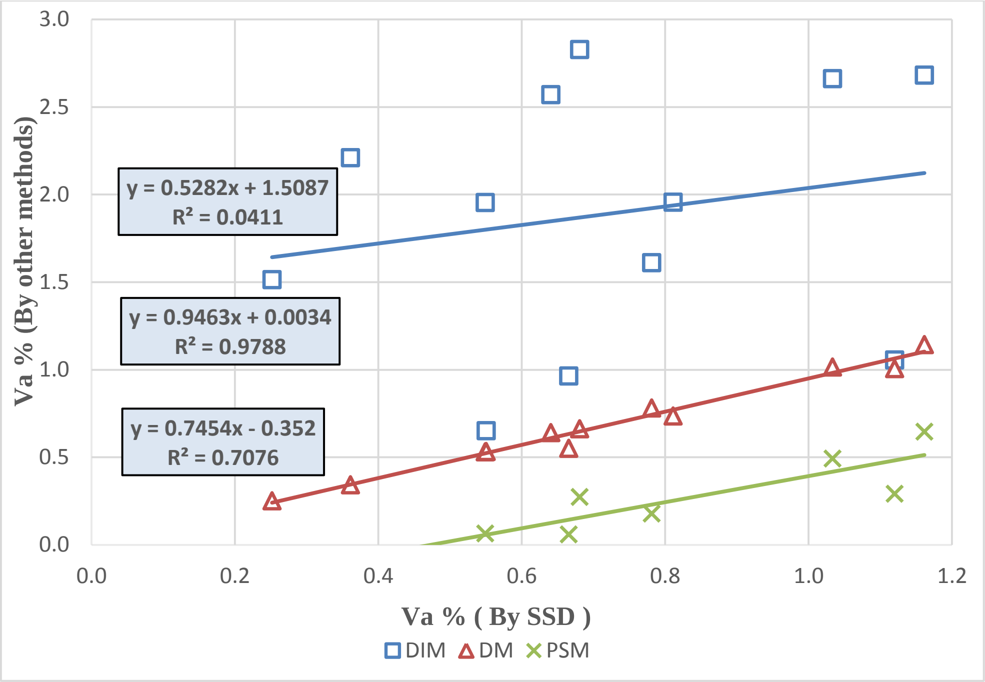


Figure 4.34: Linear relationship between the air void content obtained by SSD method and other three methods in Mastic Asphalt**.**

The relationship between the SSD and both (PSM and DM) methods is used to determine bulk density and to calculate Va% becomes more stronger than the relationship between SSD and both (PSM and DM) which existed in DA mixtures. In contrast the relationship between SSD and DIM becomes weaker.

The results of regression analysis are as follows

1. The results of the SSD and DM methods are almost identical because of the voids of specimens are almost zero, especially the mastic mixture is used as waterproof so the weight after submerging almost equals the weight before submerge the specimens in the water.
2. The Va%, determined by SSD method, increases according to the linear relationship between SSD method and the other three methods, so when it increases in SSD method, it increases in the other three methods.
3. The DIM is the least correlation with SSD method (R^2 = 0.0411), which provides underestimated Gmb results regardless the type of asphalt types.
4. The PSM provides un logical results when measuring Va% because of the closed similarity between the magnitude of Gmm and Gmb, so covering the specimens with melted wax increases it's weight and thus it's density,

according to this; there are negative Va% values, so the Gmb is bigger than Gmm after using the melted wax.

Nonlinear regression accomplish more fitting curve, which is able to represent the value of DIM according to SSD value more than the ability of liner equation.

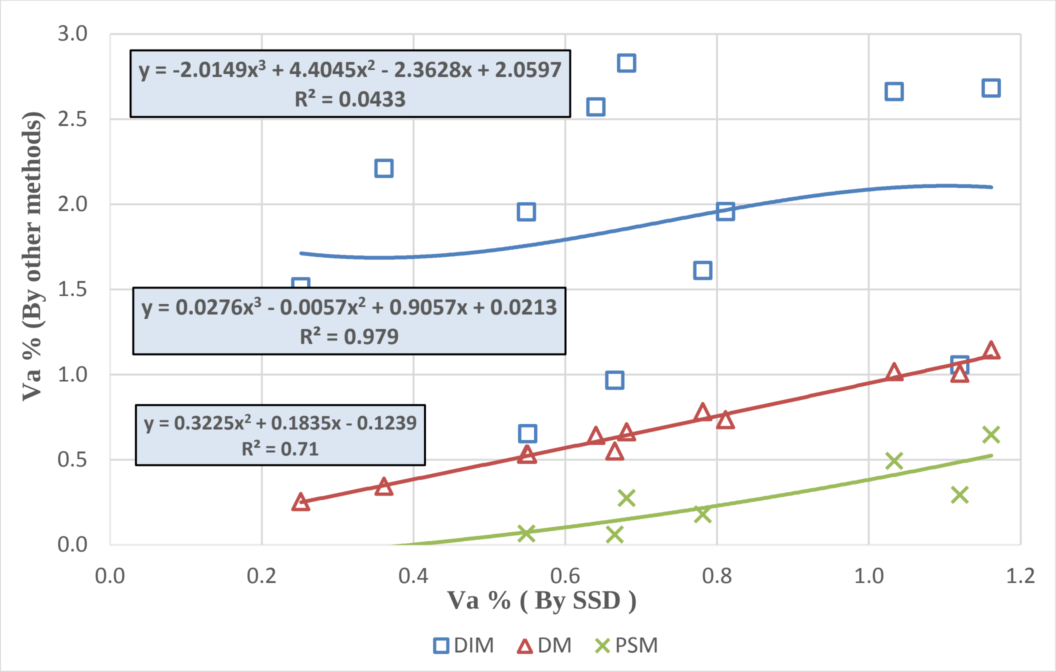


Figure 4.35: Nonlinear relationship between the air void content obtained by SSD method and other three methods in Mastic Asphalt.

As Figure 4.35 shows, there is no correlation between SSD and DIM in mastic asphalt mixture in both regressions results (Linear, and nonlinear).The equations that represent the relationship between DIM and SSD methods are applied to examine differences of Va%, Table 4.29 explains the results which were calculated by the following equations:

- **$y = 0.5282x + 1.5087$ [Liner regression with $R^2 = 0.0411$}**
- **$y = -2.0149x3 + 4.4045x2 - 2.3628x + 2.0597$ [Nonlinear regression with $R^2 =0.0433$]**

Table 4.29: Va% of DIM by using the relationship with SSD for mastic asphalt.

Mastic Asphalt	A	B	C	D			
Va(%) in Sample Code	SSD	Measured DIM	Linear R.	Nonlinear R.	$\frac{(B-A)}{B}$*100 %	$\frac{(C-A)}{C}$*100 %	$\frac{(D-A)}{D}$*100 %
			Predicted DIM Va%	Predicted DIM Va%			
M1	0.5	2.0	1.8	1.8	71.9	68.7	68.7
M2	0.8	1.6	1.9	1.9	51.5	59.8	59.8
M3	0.7	2.8	1.9	1.9	75.9	63.3	63.3
M4	0.6	2.6	1.8	1.8	75.1	64.9	64.9
M5	0.4	2.2	1.7	1.7	83.6	78.6	78.6
M6	1.2	2.7	2.1	2.1	56.7	44.7	44.7
M7	1.0	2.7	2.1	2.1	61.2	50.7	50.7
M8	0.7	1.0	1.9	1.8	31.0	64.2	63.9
M9	0.8	2.0	1.9	2.0	58.5	58.1	58.7
M10	0.6	0.7	1.8	1.8	15.3	68.7	68.7
M11	0.3	1.5	1.6	1.7	83.4	84.7	85.3
M12	1.1	1.1	2.1	2.1	0.0	46.8	46.8

As Table 4.29 shows the maximum ratio of comparing DIM and SSD is 85.3% and the minimum ratio is 0.0%, which mean that Va results based on SSD smaller than Va measured and predicted by DIM with approximately(0.0- 85.3)% from DIM Va%

- **For Porous Asphalt:**

Figure 4:36, shows that there is almost no correlation between the four methods used in this study for measuring void ratio in regard to the bulk density determination in PA mixture, that has voids ratio exceeds 20%.
By regression analysis data the following results can be concluded:

1. The SSD and DM are not capable of determining Gmb and Va% of PA mixtures. The voids measured in DIM exceed those measured in the above two methods by 20%. So by using these two methods, the real volume bulk cannot be evaluated due to water leak inside the connected voids when submerging and weighting the specimen after surface drying.

2. The DIM is the most logical and suitable for determining Gmb. Because of the connected voids in the measured specimens in the other methods, make evaluation of submerged weight and weight after submerging not capable of providing real bulk volume.
3. There is proportional relationship between the SSD method and both DIM and DM in Va% values. While there is reverse relationship between the SSD method and PSM. The last relationship was understood by the decrease in the surface voids, which were included in the PSM and excluded in the SSD.
4. The PSM cannot be supported to measure Gmb due to the un logical results which are shown clearly in the points above and below trend line in figure 4.36.
5. The significant variations in the results of the four methods reflect the need to find more accurate method in determining Gmb in OGFC mixtures.

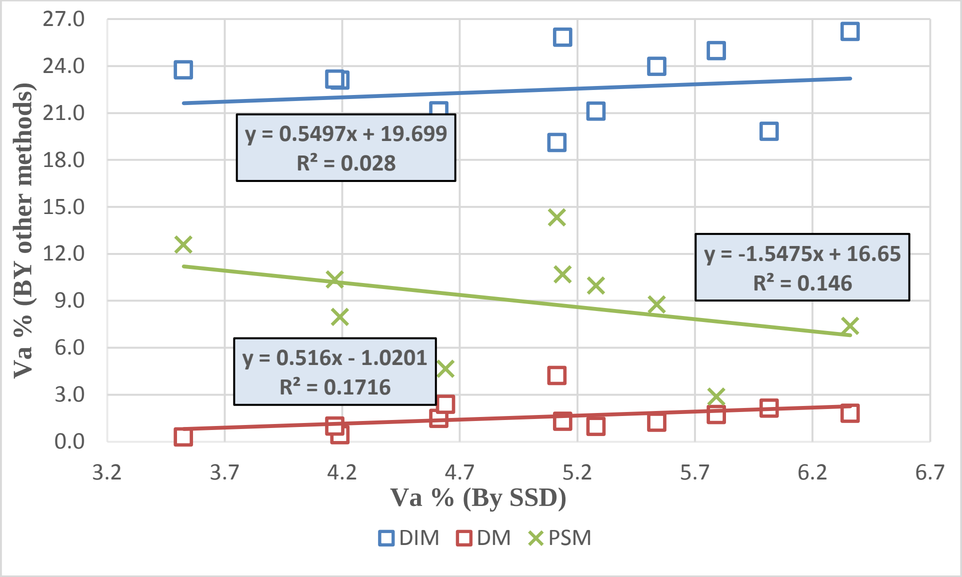


Figure 4.36: Relationship between the bulk specific gravity obtained by SSD method and other three methods in Pours Asphalt.

In order to improve the correlation between SSD and DIM, Nonlinear regression accomplish more fitting curve, but as Figure 4.37 shows , there is no relationship between SSD and DIM methods

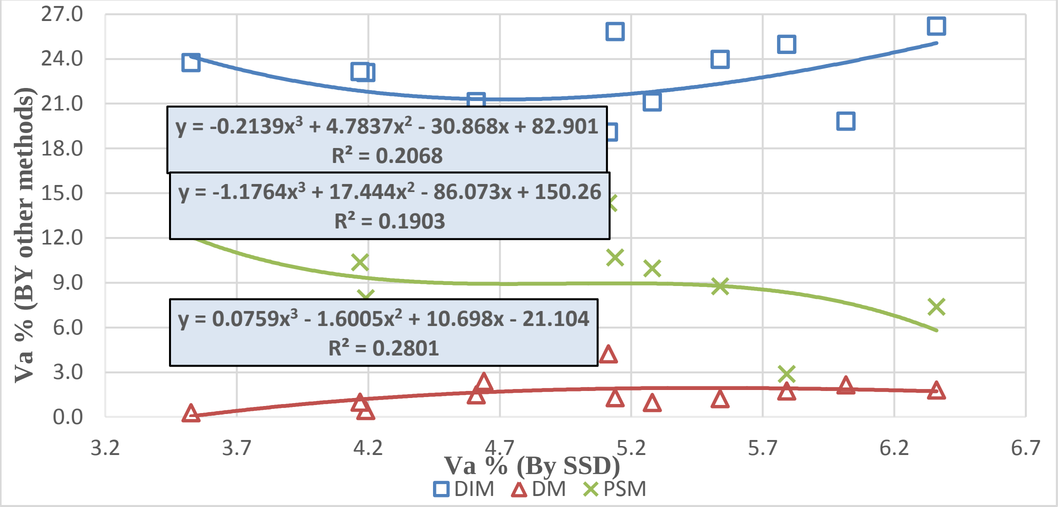


Figure 4.37: Relationship between the air void content obtained by SSD method and other three methods in Pours Asphalt.

To understanding the differences of Va% values by SSD and by DIM measured and predicted using the very week correlation equations.

- **$Y = 0.5497x + 19.699$ { Linear regression with $R^2 = 0.028$}**
- **$Y = -0.2139x^3 + 4.7837x^2 - 30.868x + 82.901${ Nonlinear regression with $R^2 = 0.2068$}**

Table 4.30: Va% of DIM by using the relationship with SSD for porous asphalt.

Porous Asphalt	**A**	**B**	**C**	**D**	$\frac{(B-A)}{B}$***100 %**	$\frac{(C-A)}{C}$***100 %**	$\frac{(D-A)}{D}$***100 %**
Va(%) in Sample Code	**SSD**	**Measured DIM**	**Linear R.** **Predicted DIM Va%**	**Nonlinear R.** **Predicted DIM Va%**			
P1	6.0	19.8	23.0	23.8	69.7	73.9	74.8
P2	3.5	23.7	21.6	24.2	85.2	83.8	85.5
P3	4.2	23.1	22.0	21.8	81.8	80.9	80.7
P4	4.6	21.1	22.2	21.3	78.2	79.3	78.4
P5	4.6	17.5	22.2	21.3	73.7	79.3	78.4
P6	5.1	19.1	22.5	21.5	73.3	77.3	76.3
P7	4.2	23.1	22.0	21.9	81.8	80.9	80.8
P8	5.5	24.0	22.7	22.3	77.1	75.8	75.3
P9	5.3	21.1	22.6	21.8	74.9	76.5	75.7
P10	6.4	26.2	23.2	25.1	75.6	72.4	74.5
P11	5.1	25.8	22.5	21.6	80.2	77.3	76.4
P12	5.8	25.0	22.9	23.0	76.8	74.7	74.8

As Table 4.30 shows, Va results based on SSD do not exceed 15-30 % of Va measured and predicted by DIM.

4.5.2 Deep Understanding to Predict Void Ratio Value in terms of the Selected Method that Used to Determine Bulk Ddensity.

According Table 4.31, and by taking into consideration the results of using the four methods in measuring Gmb, on different asphalt mixtures types, the result of each method can be expected. By the results, bulk volume in DIM was overestimated in comparing with the actual volume because the mathematical calculation for bulk volume depends on Diameter/ height regardless deformation and irregular Surface of specimens, so the voids calculated by this method are always higher than those measured by the other three methods.

Table 4.31: Bulk volume cases for each method.

Method	Bulk volume	Cases	Gmb	Va%
DIM	$\frac{\pi}{4} \times h \times d^2$	Regular shaped Specimen with level surface	(+)	(-)
		Irregular shaped with deformation surface	(-)	(+)
DM	$m_1 - m_2$	(M2)The mass of specimens in water increase	(+)	(-)
		The mass of specimens in water decrease (water inside voids)	(-)	(+)
SSD	$m_3 - m_2$	(m2) The mass of specimens in water increase	(+)	(-)
		(m2) The mass of specimens in water decrease (water inside voids)	(-)	(+)
		(M3) the SSD mass increase (m1+ mass of water inside voids)	(-)	(+)
		(M3) the SSD mass decrease (m1+ little amount of water inside voids)	(+)	(-)
PSM	$=\frac{(m2-m3)}{\rho w} - \frac{(m2-m1)}{\rho\, sm}$	The difference between the paraffin specimen mass before immersion (m2) and mass in water(m3)is greater than the difference between the mass of the sealed specimen(m2)and its mass before sealing (m1)	(-)	(+)
		The difference between the paraffin specimen mass before immersion (m2) and mass in water(m3)is closed to the difference between the mass of the sealed specimen(m2)and its mass before sealing (m1)	(+)	(-)

(+): increase

(-) : decrease

SSD, the most common practical and the best-selected method in measuring Gmb in all mixtures except the porous mixture because the interconnected voids make it difficult to measure SSD weight after the water leak out from the specimen.

DM measures the volume bulk without including the surface voids so Gmb was always overestimated and as sequence void ratio was underestimated. PSM was different in estimating bulk volume. When this method was used in measuring Gmb in dense and mastic mixtures it gave more satisfying result than that of porous mixtures. So it was difficult to expect the bulk volume pattern across all asphalt graded mixtures.

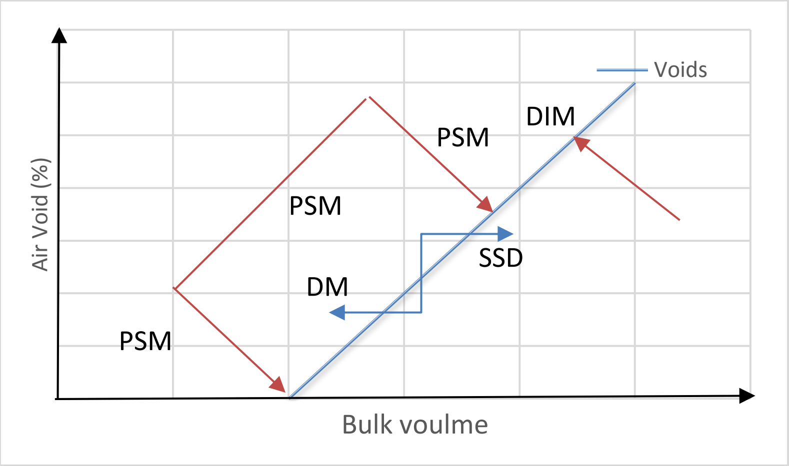


Figure 4.38: An expected vision of the relationship between air voids and bulk volume for specimens by using four methods to measured bulk specific gravity.

As Figure 4.38 explains, when the bulk volume increases the bulk density decreases and the void ratio increases, the bulk volume value by using the four methods DIM, DM, SSD, and PSM. In the PSM, the bulk volume value cannot be expected.

4.5.3 Data analysis using Box plot

The box plot chart was used to display the air void ratio results of each one method. Figure 4.39 illustrates the mechanism for box plot chart.

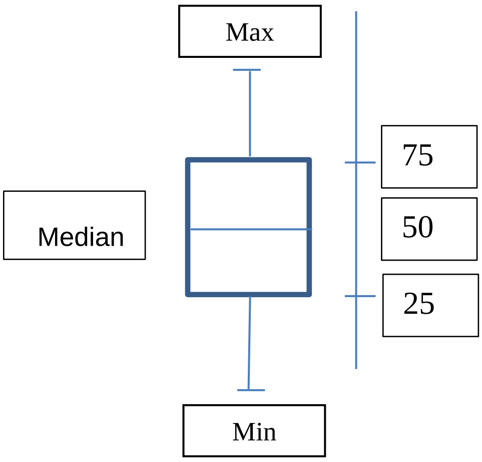


Figure 4.39: Illustrating Box Blot Chart.

It is clear from Figure 4.40 that 75% of the measured specimens by SSD and DM have 4- 5 % VA. While the rest have 3-4% of VA. This means that there is no importance difference between the two methods regarding the dense asphalt. However, the result showed that VA by DIM method exceed 5% concerning 75% of measured specimens.

Also, Figure 4.40 illustrates that PSM method determined 2-5 VA, which reflect the high variance between the results. This indicate that PSM used to measure the lowest VA within the dense asphalt.

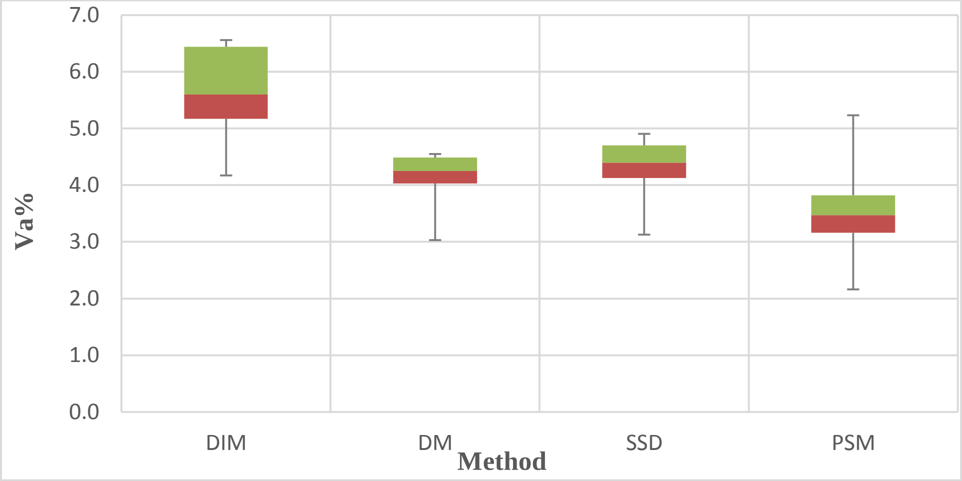


Figure 4.40: Box Blot for Dense Asphalt Void ratio result.

Figure 4.41 shows that the results of the three methods have less that 1% Va%, while 75% of DIM specimen results determined Va between 1 – 2.8%.

Also by the Figure 4.40, in mastic asphalt, the surface voids can be neglected in the light of the similarity of SSD and dry methods results.

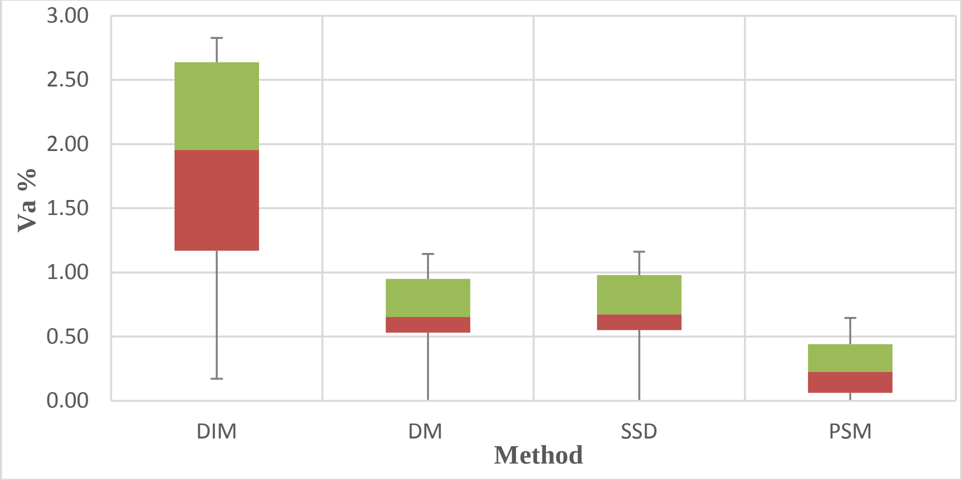


Figure 4.41: Box Blot for Mastic asphalt Void ratio result.

According to Figure 4.42, it is difficult to determine void ratio in porous mixtures by SSD, and dry methods because of interconnected voids. While the paraffin method gives various results between 6-14%. Also it is clear from comparing PSM and DIM methods results that the maximum Va in PSM is lower than the minimum Va in DIM by 4.5%.

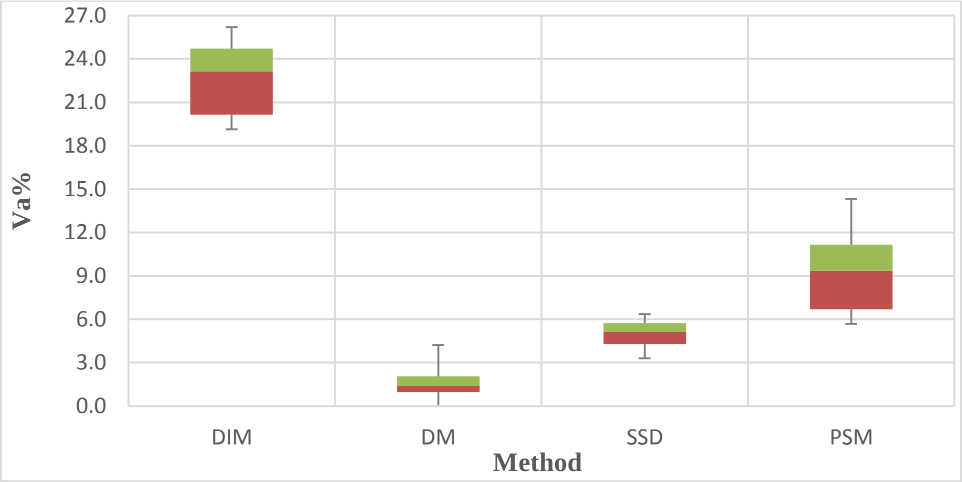


Figure 4.42: Pox Blot for Pours asphalt Void ratio result.

4.5.4 Summary

The following Table 4.32 is used as a reference scale to explain the relationship between the SSD and other three methods by regression analysis.

Table 4.32: The degree of regression relationship according to (Hall, 2005)

Correlation Coefficient, R	**Coefficient of determination R^2**	**Degree of relationship**
$0.9 < R < 1.0$	$0.81 < R^2 < 1.00$	Very highly correlated.
$0.7 < R < 0.9$	$0.49 < R^2 < 0.81$	highly correlated
$0.5 < R < 0.7$	$0.25 < R^2 < 0.49$	moderately correlated
$0.3 < R < 0.5$	$0.09 < R^2 < 0.25$	low correlation

As Table 4.33 shows the relationship between SSD method and the other three methods by using linear and nonlinear regression on the void ratio value which was determined. It is clear that the correlation is strong as void ratio in mixture is low. So, in mastic asphalt, the correlation is the best. But, in porous asphalt there is no correlation between SSD and other three methods.

Table 4.33: Degree of relationship among SSD method and the other three methods.

Asphalt type	**Method**	**SSD method**				**Degree of Relationship**
		Liner Regression		**Non Linear**		
		R	**R^2**	**R**	**R^2**	
Dense Asphalt	**DIM**	49.3 %	0.243	61.2%	0.375	**Week**
	DM	85.2%	0.7264	95.6%	0.92	**Strong**
	PSM	71.7%	0.5143	73.2%	0.536	**Moderate**
Mastic Asphalt	**DIM**	20%	0.0411	33.6%	0.113	**Very week**
	DM	98.9%	0.978	98.9%	0.979	**Very strong**
	PSM	82.9%	0.677	93.4%	0.873	**Strong**
Porous Asphalt	**DIM**	16.7%	0.028	45.4%	0.206	**Very week**
	DM	32.3%	0.1047	34.7%	0.1206	**Week**
	PSM	41.4%	0.1716	58.9%	0.347	**Week**

- Dimensional Method (DIM)
  - In dense and mastic asphalt mixtures the raveling in the specimens surface affects the volumetric measured, so the deformation in the surface is a part of the voids. Therefore, the voids ratio by DIM is greater than the void ratio by other methods.
  - DIM is the only suitable method for determining bulk density and air void ratio in porous asphalt, but it is not the best method due to the underestimated result of bulk density
- Dry Method (DM)
  - DM is Suitable for determining Gmb in Dense asphalt despite of the surface voids are not included in the volume of voids.
  - Dry method and SSD are the best selected method for determining Gmb in mastic asphalt especially when the surface of mastic specimens has zero voids.
  - In porous asphalt the dry method totally failed in determining Gmb and Void ratio due to the weight in water does not represent the bulk volume of specimens.
- SSD Method
  - SSD is considered the best method for determining Gmb and Va in both mixtures DA and MA, this method, as previous results shows, provides logical results in these mixtures because the surface and internal voids are included in the amount of bulk volume.
  - In porous asphalt, SSD totally failed in determining Gmb and Va due to interconnected voids, the water runs throughout specimens in SSD weight, so the mechanism of this method did not work.
- Paraffin Sealing Method (PSM)
  - In dense asphalt, it provides the maximum bulk density and lower void ratio in regards to other three methods, paraffin prevents the specimens from water when they are immersed, so it can be used as indicator to predict the lowest air voids in asphalt specimens.
  - In mastic asphalt, it provides results nearby from those of SSD and DM, but sometimes the un logical results appeared in 5 from12 specimens, when the Gmb results are greater than Gmm . This happens because the paraffin sticks in specimens and becomes a part of their weight and ,when the Gmm is very

close from Gmb in mastic asphalt, this means many of specimens have Gmb greater than Gmm when adding paraffin.

- In Porous asphalt, it succeeds partially in determining Gmb, the results are various between one specimen to another, it can’t be adopted because the melt paraffin has closed the deep or internal voids in addition to the surface, the other reason is the effect of melt paraffin on the cohesion of the specimens, 2 from12 samples became brittle.

Table 4.34 provides guidelines for selecting method to determine bulk density in regards to asphalt mixture types.

Table 4.34: Guidelines for selecting method to determine bulk density.

Asphalt Type	Test method of determining bulk density and void ratio			
	DIM	DM	SSD	PSM
Dense Asphalt	*	√	√√	√
Mastic Asphalt	*	√√	√√	√
Porous Asphalt	√	××	××	×

√√ : The best method √: Suitable method *: As indicator ××: Not applicable

Chapter 5

Conclusion

and

Recommendations

5. Conclusion and Recommendations

4.1 Conclusion

The purpose of this thesis is providing a better understanding of the effect of the selected bulk density measurement method and the asphalt mixture type on the percentage of voids using four method namely; Dimensional Method, Dry Method, Surface-Saturated Dry Method, and Paraffin Sealing Method

The bulk density of asphalt mix is essential for life cycle of pavement, which is: Design stage, placing stage, and operation stage. The calculation of the total air voids (Va), void in mineral aggregate (VMA), and void's filled bitumen (VFB) is independent on the bulk density of mix. As a result, the accuracy of bulk density measurement will be critical for determining OBC of the mixtures and affects the properties of pavement.

This thesis depended on three asphalt mixtures types. The bulk density has been examined through using four methods, three of them has been depending on the principle of Archimedes and the last one determines the bulk volume by using dimension of specimen (diameter/height).

The conclusion of this study could be summarized as follows:

- There are obvious differences in the results of bulk density and as sequence void ratio by using each method in any of three asphalt mixtures. So, the real air voids cannot be determined. But, these differences are varying from one method to another, and from one mixture to another.
- The results showed that there is less variability in the asphalt mixtures which have air voids ratio required in the low range (less than 5%) that agrees with AASHTO regulation and many researches.
- The correlation between three of the four methods (SSD, Dry, and Paraffin sealing) that were used to determine bulk density in dense and mastic asphalt mixtures is strong according to the regression analysis. So, SSD can be used to predict the other two method's values.
- The most widely applicable method SSD, failed obviously in the determination of the void ratio in porous asphalt.

- The dry method is the simplest method since the voids in the surface of specimen does not included in the bulk volume. So, it gives overestimated to the Gmb and less estimated to void ratio.
- In dense and mastic asphalt mixtures, the statistical analysis show that there is a significant difference between the measurement made by SSD and dry methods and the measurement made by the dimensional and paraffin methods. SSD and dry methods are more consistent than those made by the dimensional and Paraffin methods.
- From the four methods, the dimensional analysis method is the only one suitable to measure the Gmb in the porous asphalt. Although the dimensional method gave underestimation for Gmb and overestimation for a void ratio.
- The Paraffin sealing method suitable for determining bulk density and void ratio in dense asphalt, but in mastic asphalt 5/12 of specimens gave un logical bulk density value since the theoretical maximum density (Gmm/TMD) is very closed to bulk density, when sealing the specimen by paraffin the own weight of specimen increasing so the bulk density is increasing. In porous asphalt 2/12 of specimens gave un logical value due to the following reason:
    1. The porous asphalt specimens splitted when submersed in paraffin.
    2. The paraffin is not sealing the surface of specimens only, but also it covers the internal voids of specimens.
    - The value of voids that are determined by SSD form only (60-88) % of the voids that are determining by dimensional method in dense asphalt, (15-70)% in mastic asphalt, and (15-30) % only in porous asphalt

4.2 Recommendations

Recommendations were made to improve air void determination and reduce the test variability.

- Dimension method can be used as an indicator for the upper limit of voids while the paraffin sealing method can be used as an indicator to the lowest limit.
- The study recommends more accurate methods to be used in determining Gmb in porous asphalt rather than a volumetric method (dimensional method), such as vacuum sealing device and other advanced techniques.

- Each type of asphalt mixtures used in this study needs to be studied separately with large scale specimens in order to understand deeply the relationship between the four methods that used to determine the bulk density.

4.3 Future Research Plan

This study rely on the laboratory samples, which were prepared using several aggregates gradations: dense, porous and mastic, the future work is to study the lab sample and field (core sample) to compare between accuracy and variability of result for bulk density and void ratio.

Another future research related to the method was used to prepare job mix, this research tries to make the relationship between the variations of measuring Gmb in the mixtures designed by using Marshal Method compared to mixtures design by the Super-Pave method.

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Appendices

Appendix A

Combined Aggregates

- **Dense Asphalt**

Table A.1: Suggested percentages of Dense Asphalt course aggregate mix

Aggregate mix	**Grain size (mm)**											**Suggested percents for final agg. Mix**
	0.075	0.15	0.3	0.6	1.18	2.36	4.75	9.5	12.5	19	25	
Filler	89.10	6.90	3.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**3**
	2.67	0.21	0.10	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Trabia (0/4.75)	6.90	7.03	18.87	26.50	19.70	13.90	3.80	3.30	0.00	0.00	0.00	**51.9**
	3.58	3.65	9.79	13.75	10.22	7.21	1.97	1.71	0.00	0.00	0.00	
Simsimia (0/9.5)	0.60	0.20	1.60	0.30	0.70	2.30	45.25	40.65	8.40	0.00	0.00	**26.6**
	0.16	0.05	0.43	0.08	0.19	0.61	12.04	10.81	2.23	0.00	0.00	
Adasia (0/12.5)	0.20	0.00	0.90	0.00	0.00	0.00	0.00	6.46	42.54	49.90	0.00	**18.5**
	0.04	0.00	0.17	0.00	0.00	0.00	0.00	1.20	7.87	9.23	0.00	
Sum	6.45	3.91	10.48	13.86	10.41	7.83	14.01	13.72	10.10	9.23	0.00	**100**
∑% passing	6.5	10.4	20.8	34.7	45.1	52.9	66.9	80.7	90.8	100.00	100.00	
Sieve size (mm)	0.075	0.15	0.3	0.85	2.36	4.75	9.5	12.5	19	25	25	
Wearing 0/ 12.5 (min)	2	7	13	22	32	44	57	73	80	100	100	(FHWA, 2003) **Specifications**
(max)	7	19	29	40	50	62	75	91	98	100	100	

Table A.2: Dense Asphalt proportion of each aggregate material from proposed mix

Aggregate Type	**% by Total Weight of Aggregates**
Adasia Aggregate	18.5 %
Simsimia Aggregate	26.6 %
Trabia Aggregate	51.9 %
Filler	3.0 %
Total	100.0 %

Table A.3: Dense Asphalt Mix gradations of aggregates

Sieve No.	**Sieve size (mm)**	**Cumulative % Passing**			
		Adasia	**Simsimia**	**Trabia**	**Filler**
		0/ 12.5	**0/ 9.50**	**0/4.75**	**< 0.075**
1"	**25.00**	100.0	100.0	100.0	100.0
3/4"	**19.00**	100.0	100.0	100.0	100.0
1/2"	**12.50**	50.1	100.0	100.0	100.0
3/8"	**9.50**	7.6	91.6	100.0	100.0
#4	**4.75**	1.1	51.0	96.7	100.0
#8	**2.36**	1.1	5.7	92.9	100.0
#16	**1.180**	1.1	3.4	79.0	100.0
#30	**0.600**	1.1	2.7	59.3	100.0
#50	**0.300**	1.1	2.4	32.8	99.2
#80	**0.150**	0.2	0.8	13.9	96.0
#200	**0.075**	0.2	0.6	6.9	89.1

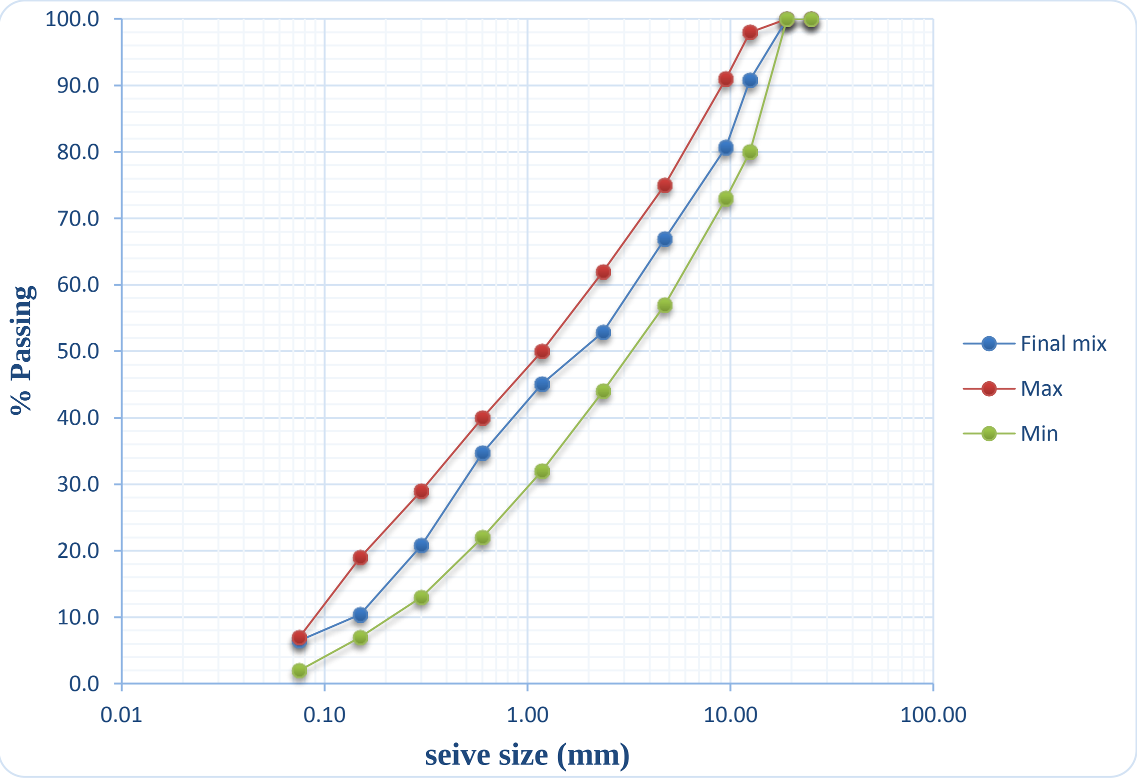

Figure A.1: Gradation curve of dense mix with FHWA specification.

Table A.4: Gradation of proposed mix with (FHWA, 2003) specifications limits

Sieve No.	**Sieve Size (mm)**	**% Passing**	(FHWA, 2003)**specification limits (%)**	
			Min	**Max**
1"	**25.00**	100.0	100	100
3/4"	**19.00**	100.0	100	100
1/2"	**12.50**	90.8	80	98
3/8"	**9.50**	80.7	73	91
#4	**4.75**	66.9	57	75
#8	**2.36**	52.9	44	62
#16	**1.180**	45.1	32	50
#30	**0.600**	34.7	22	40
#50	**0.300**	20.8	13	29
#80	**0.150**	10.4	7	19
#200	**0.075**	6.5	2	7

Table 5A.5: DA Mix component aggregates and binder percentages as follows.

Type (Component)	***% by Total Weight of Mix***
Adasia	17.5 %
Simsimia Agg	25.2 %
Fine Agg.	49.1 %
Filler	2.8 %
Bitumen	5.4
Total	100 %

- **Mastic Asphalt**

Table A.6: Suggested percentages for Mastic Asphalt course aggregate mix

Aggregate mix	Grain size (mm)											Suggested percents for final agg. Mix
	0.075	0.15	0.3	0.6	1.18	2.36	4.75	9.5	12.5	19	25	
Filler	89.10	6.90	3.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**32**
	28.51	2.21	1.02	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Trabia (0/4.75)	6.90	7.03	18.87	26.50	19.70	13.90	3.80	3.30	0.00	0.00	0.00	**45**
	3.11	3.16	8.49	11.93	8.87	6.26	1.71	1.49	0.00	0.00	0.00	
Simsimia (0/9.5)	0.60	0.20	1.60	0.30	0.70	2.30	45.25	40.65	8.40	0.00	0.00	**23**
	0.14	0.05	0.37	0.07	0.16	0.53	10.41	9.35	1.93	0.00	0.00	
Sum	31.76	5.42	9.88	12.25	9.03	6.78	12.12	10.83	1.93	0.00	0.00	**100**
∑% passing	31.8	37.2	47.1	59.3	68.3	75.1	87.2	98.1	100.0	100.00	100.00	
Sieve size (mm)	0.075	0.15	0.3	0.85	2.36	4.75	9.5	12.5	19	25	25	
Wearing 0/ 12.5 (min)	25	35	45	57	65	75	85	98	100	100	100	(BS EN 13108-6, 2008)
(max)	35	45	60	73	81	90	98	100	100	100	100	

Table A.7: Mastic Asphalt proportion of each aggregate material from proposed mix

Aggregate Type	% by Total Weight of Aggregates
Simsimia Aggregate	23.0 %
Fine Aggregate	45.0 %
Filler	32.0 %
Total	100.0 %

Table A.8: Mastic Asphalt Mix gradations of aggregates

Sieve No.	**Sieve size (mm)**	**Cumulative % Passing**		
		Simsimia	**Trabia**	**Filler**
		0/ 9.50	**0/4.75**	**< 0.075**
1"	**25.00**	100.0	100.0	100.0
3/4"	**19.00**	100.0	100.0	100.0
1/2"	**12.50**	100.0	100.0	100.0
3/8"	**9.50**	91.6	100.0	100.0
#4	**4.75**	51.0	96.7	100.0
#8	**2.36**	5.7	92.9	100.0
#16	**1.180**	3.4	79.0	100.0
#30	**0.600**	2.7	59.3	100.0
#50	**0.300**	2.4	32.8	99.2
#80	**0.150**	0.8	13.9	96.0
#200	**0.075**	0.6	6.9	89.1

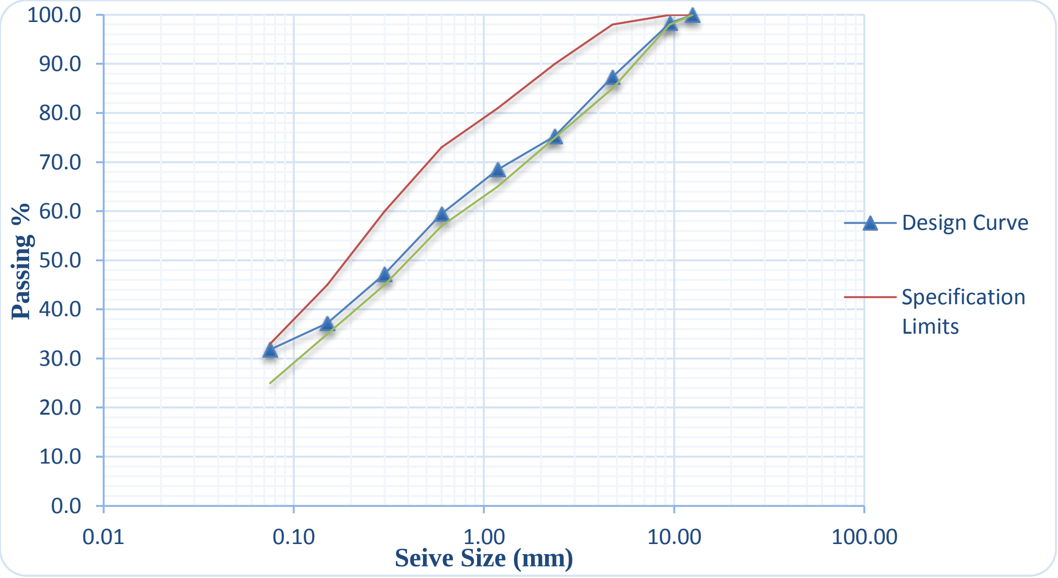

Figure A.2: Gradation curve of mastic asphalt with BS EN 13108-6 (2008) specification

Table A9: Mastic asphalt gradation of proposed mix with (BS EN 13108-6, 2008) specifications limits

Sieve No.	Sieve Size (mm)	Passing %	Project Specifications	
			Min	Max
3/4"	**19.00**	100	100	100
1/2"	**12.50**	100.0	100	100
3/8"	**9.50**	98.3	98	100
#4	**4.75**	87.3	85	98
#8	**2.36**	75.3	75	90
#10	**1.180**	68.5	65	81
#30	**0.600**	59.5	57	73
#50	**0.300**	47.2	45	60
#80	**0.150**	37.2	35	45
#200	**0.075**	31.8	25	33

- **Porous Asphalt**

Table A.10: Suggested percentages for Porous Asphalt course aggregate mix

Aggregate mix	Grain size (mm)									Suggested percents for final agg. Mix
	0.075	0.3	0.6	2	4.75	9.5	12.5	19	25	
Simsimia (0/9.5)	5.10	0.10	0.30	3.47	43.50	39.36	7.39	0.00	0.00	50
	2.55	0.05	0.15	1.74	21.75	19.68	3.70	0.00	0.00	
Adasia (0/12.5)	0.2	0. 9	0.60	0.00	0.12	6.46	42.5	49.90	0.00	45
	0.06	0.00	0.27	0.00	0.05	2.78	21.26	22.57	0.00	
Folia (0/19)	0.14	0.02	0.02	1.00	0.08	0.02	10.71	84.70	4.07	5
	0.01	0.00	0.00	0.05	0.00	0.00	0.54	4.24	0.20	
Sum	2.65	0.46	0.42	1.79	21.81	22.45	26.36	26.52	0.20	100
∑% passing	2.6	3.1	3.5	5.7	27.5	49.9	76.3	99.8	100.00	
Sieve size (mm)	0.075	0.3	0.6	2.36	4.75	9.5	12.5	19	25	
Binder0/ 12.5 (min)	2	2.3	2.8	5	5	5	85	100	100	(FHWA, 2003; Jendia & AbuRahma, 2018)
(max)	5	6	8	15	35	100	100	100	100	

Table A.11: Porous Asphalt proportion of each aggregate material from proposed mix

Aggregate Type	% by Total Weight of Aggregates
Simsimia Aggregate	50.0 %
Adasia Aggregate	45.0 %
Folia Aggregate	5.0 %
Total	100.0 %

Table A.12: Porous Asphalt Mix gradations of aggregates

Sieve No.	Sieve size (mm)	Cumulative % Passing		
		Folia	Adasia	Simsimia
		0/ 19	0/ 12.5	0/ 9.50
1"	25.00	100.0	100.0	100.0
3/4"	19.00	95.9	100.0	100.0
1/2"	12.50	11.3	50.1	100.0
3/8"	9.50	0.6	7.6	92.6
#4	4.75	0.4	1.1	53.3
#8	2.36	0.3	1.1	9.8
#16	1.180	0.2	1.1	6.2
#30	0.600	0.2	1.1	5.4
#50	0.300	0.2	1.1	5.1
#200	0.075	0.2	0.2	5.1

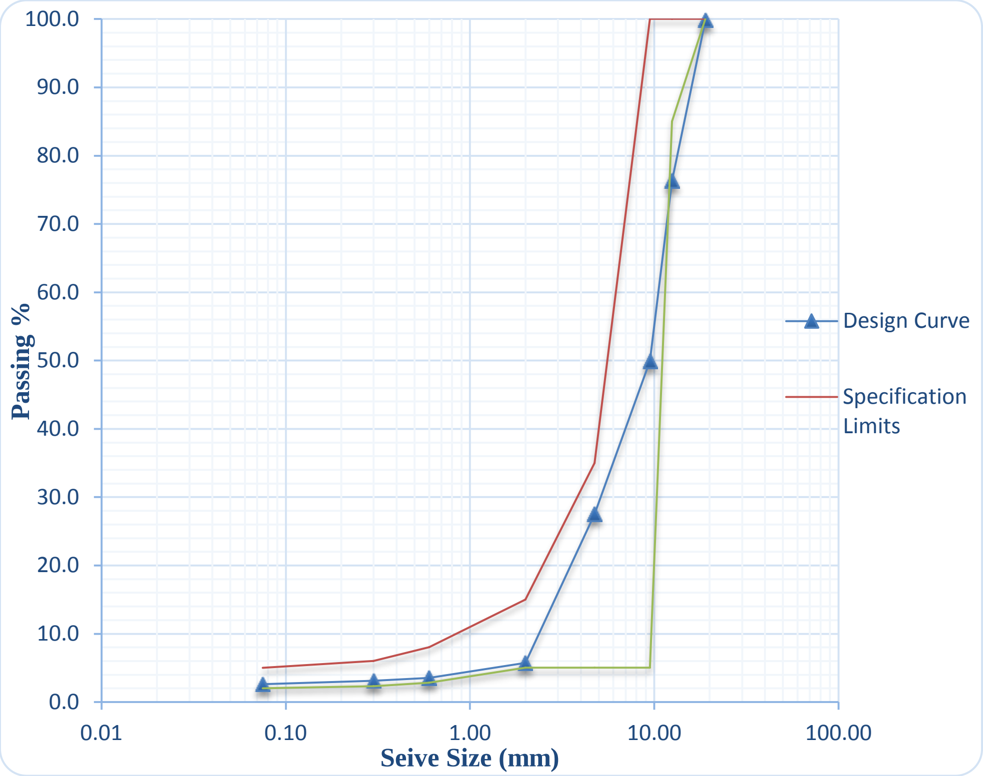

Figure A.3: Job Mix Gradation of Porous Asphalt

Table A.13: Porous asphalt gradation of proposed mix with (FHWA, 2003) specifications limits

Sieve No.	**Sieve Size (mm)**	**% Passing**	**Project Specifications**	
			Min	**Max**
1"	**25**	100	100	100
3/4"	**19.00**	99.8	100	100
1/2"	**12.50**	76.3	85	100
3/8"	**9.50**	49.9	5	100
#4	**4.75**	27.5	5	35
#8	**2.00**	5.7	5	15
#10	**0.600**	3.5	2.8	8
#30	**0.300**	3.1	2.3	6
#200	**0.075**	2.6	2	5

Appendix B

Materials Properties Tests

Table 5B.1: Summary of Bitumen 85-25 Properties IBPC, (2017).

Test	Unit	Requirements	Specifications
Penetration	1/10 mm	20-30	ASTM D5/D5M -13
Ductility	cm	Min 3	ASTM D113-86
Softening point	° C	80-90	ASTMD36-2002
Flash point	° C	250 max	ASTM D92-12b
Density	g/ml	1.0-1.18	ASTM D 3289
Solubility	%	99 min	ASTM D 2042-09
Viscosity	135 ° C	Min. 300	ASTM D3381/D3381M-13

Specific gravity and absorption (ASTM C128-12)

Table B.2: Equations of test properties

Test Property	Equation
Bulk Specific gravity (dry)	$\frac{A}{(B-c)}$
Bulk Specific gravity (SSD)	$\frac{B}{(B-c)}$
Apparent Specific Gravity	$\frac{A}{(A-c)}$
Effective Specific Gravity	$\frac{Dry\ S.G + App.\ S.G}{2}$
Absorption	$\frac{(B-A)}{A}\ x\ 100\%$

Where : A = Weight of oven-dry sample in air, grams

B = Weight of saturated - surface -dry sample in air

C = weight of saturated sample in water

For example:

Coarse aggregate (Folia)

Weight of oven-dry sample in air = 2815.5 g

Weight of saturated - surface -dry sample in air = 2880 g

Weight of saturated sample in water = 1746.8 g

Bulk dry S.G = $\frac{A}{(B-c)} = \frac{2815.5}{(2880-1746.8)} = 2.484$

S.G = $\frac{B}{(B-c)} = \frac{2880}{(2880-1746.8\ )} = 2.541$

Apparent S.G = $\frac{A}{(A-c)} = \frac{2815.5}{(\ 2815.5-\ 1746.8)} = 2.63$

Effective S.G = $\frac{Dry\ S.G+App.\ S.G}{2} = \frac{(\ 2.484\ +\ 2.63)}{2} = 2.557$

Absorption = $\frac{(B-A)}{A}\ x\ 100\% = \frac{(\ 2880-2815.5\ )}{2815.5}\ x\ 100\% = 2.29\ \%$

- **Pycnometer method**

Fine Aggregate

W1 = Weight of Pycnometer filled with water = 1816.5 gr

W2= Weight of the Fine sample dry = 351.0 gr

W3 =Weight of Pycnometer filled with water and the Fine sample= 2033.5 gr

$$\text{Specific Gravity} = \frac{WS*1.02}{(WS\ )-(\ W3-W1)} = 2.67$$

Asphalt mixtures

Table B.3: Theoretical maximum density test.

	Unit	DA	MA	PA
Dry weight	g	820	700.2	400.5
Pycnometer+Water	g	1816.5	1816.5	1816.5
Pycnometer+Water+sample	g	2304.9	2213.9	2048.7
TMA / Gmm		2.473	2.312	2.380

Table B.4: Summary of Gmm results by Pecnometer device

Asphalt Type	Dense Asphalt	Purse Asphalt	Mastic Asphalt
Gmm	2.473	2.38	2.312

Appendix C

Bulk Density Testing and Void Ratio calculating

Bulk Specific Gravity measurement and Void ratio evaluation for specimens group.

1. For Dense Asphalt mixture

1.1 Dimensional Analysis Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	A	b	c	a	b	c	a	b	c	a	b	c
M1 (g)	1197.5	1197	1194	1199	1196.5	1201.5	1200	1199	1192.5	1195	1198.5	1201.7
H	6.32	6.38	6.26	6.41	6.38	6.41	6.31	6.3	6.29	6.27	6.3	6.4
d	10.17	10.16	10.17	10.15	10.16	10.15	10.16	10.17	10.16	10.17	10.15	10.16
A	513.60	517.46	508.72	518.87	517.46	518.87	511.78	511.97	510.16	509.54	509.96	519.08
Density	2.332	2.313	2.347	2.311	2.312	2.316	2.345	2.342	2.338	2.345	2.350	2.315
Void ratio	5.72	6.46	5.09	6.56	6.50	6.36	5.19	5.30	5.48	5.16	4.97	6.39

1.2 SSD Method

Group no.	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**3**	**3**	**4**	**4**	**4**
Sample Item	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**C**	**a**	**b**	**c**
M1 (g) (dry)	1197.5	1197	1194	1199	1196.5	1201.5	1200	1199	1192.5	1195	1198.5	1201.7
M2(water)	690.5	690	694	692.5	690	692.5	695	694	689.5	690	692.5	694.6
M3 SSD weight	1198	1199	1195	1200	1198	1202.5	1201.5	1200	1193.5	1196.5	1197.9	1199.7
M3-M2	507.5	509.0	501.0	507.5	508.0	510.0	506.5	506.0	504.0	506.5	505.4	505.1
Density	2.360	2.352	2.383	2.363	2.355	2.356	2.369	2.370	2.366	2.359	2.371	2.379
Void ratio	4.59	4.91	3.63	4.47	4.76	4.74	4.20	4.18	4.32	4.60	4.11	3.80

1.3 Dry Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	a	b	c	a	b	c	a	b	c	a	b	c
M1 (g) (dry)	1197.50	1197.00	1194.00	1199.00	1196.50	1201.50	1200.00	1199.00	1192.50	1195	1198.5	1201.7
M2(water)	690.50	690.00	694.00	692.50	690.00	692.50	695.00	694.00	689.50	690	692.5	694.6
M1-M2	507.00	507.00	500.00	506.50	506.50	509.00	505.00	505.00	503.00	505.00	506.00	507.10
Density	2.362	2.361	2.388	2.367	2.362	2.361	2.376	2.374	2.371	2.366	2.369	2.370
Void ratio	4.49	4.53	3.44	4.28	4.48	4.55	3.91	3.99	4.13	4.31	4.22	4.18

1.4 Paraffin Sealing Method

Group no.	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**3**	**3**	**4**	**4**	**4**
Sample Item	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**C**	**a**	**b**	**c**
M1 (g) (dry)	1197.5	1197	1194	1199	1196.5	1202	1200	1199	1192.5	1195	1198.5	1201.7
M2 (Pa. sealed dry)	1200.5	1201.5	1200.5	1205	1205.5	1198	1206.5	1203	1198	1203	1204	1205.4
M3(sealed water)	693	691	696.5	694.5	690.5	690	697	696	692	692	697	696.8
M2-M3	507.5	510.5	504	510	515	508	509.5	507	506	511	507	508.6
M2-M1	3	4.5	6.5	5.5	9	-3.5	6.5	4	5.5	8	5.5	3.7
Density	2.378	2.373	2.410	2.385	2.379	2.344	2.396	2.390	2.391	2.388	2.399	2.386
Void ratio	3.83	4.06	2.53	3.55	3.81	5.23	3.11	3.35	3.30	3.42	3.01	3.52

2. For Pours Asphalt

2.1 Dimensional Analysis method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	A	b	c	a	b	c	a	b	C	a	b	c
M1 (g)	1171	1073	885.5	1011.5	1187	1104.5	1115.5	1095	1098	1094.5	1114.5	1070.5
H (cm)	7.57	7.29	6.02	6.64	7.42	7.04	7.3675	7.31	7.1	7.5275	7.65	7.2425
D (cm)	10.10	10.10	10.05	10.10	10.12	10.12	10.200	10.2	10.175	10.2	10.185	10.2
V (cm3)	605.980	583.898	477.742	532.201	596.727	566.498	602.262	597.561	577.553	615.341	623.517	592.043
Density(g/cm3)	1.932	1.838	1.854	1.901	1.989	1.950	1.852	1.832	1.901	1.779	1.787	1.808
Void ratio %	19.82	23.75	23.09	21.14	17.46	19.10	23.15	23.96	21.12	26.20	25.83	24.97

2.2 SSD Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	A	b	c	a	b	c	a	b	C	a	b	c
M1 (g) (dry)	1171	1073	885.5	1011.5	1187	1104.5	1115.5	1095	1098	1094.5	1114.5	1070.5
M2(water)	674.5	626.5	516.5	585.5	682.5	626	648	635	638	632	646	618.5
M3 (SSD)	1191.5	1088	900	1025.5	1199	1109	1131	1116	1119	1117	1133.5	1090
M3-M2	517.0	461.5	383.5	440.0	516.5	483.0	483.0	481.0	481.0	485.0	487.5	471.5
Gmb	2.265	2.325	2.309	2.299	2.298	2.287	2.310	2.277	2.283	2.257	2.286	2.270
Void ratio	6.02	3.53	4.19	4.61	4.64	5.11	4.17	5.54	5.28	6.36	5.14	5.79

2.3 Dry Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	**A**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**
M1 (g) (dry)	1171	1073	885.5	1011.5	1187	1104.5	1115.5	1095	1098	1094.5	1114.5	1070.5
M2(water)	674.5	626.5	516.5	585.5	682.5	626	648	635	638	632	646	618.5
M1-M2	496.5	446.5	369	426	504.5	478.5	467.5	460	460	462.5	468.5	452
Density	2.359	2.403	2.400	2.374	2.353	2.308	2.386	2.380	2.387	2.366	2.379	2.368
Void ratio	2.14	0.28	0.43	1.48	2.37	4.22	0.99	1.23	0.96	1.81	1.29	1.73

2.4 Paraffin Sealing Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**B**	**c**	**a**	**b**	**c**
M1 (g) (dry)	1069.5	1073	885.5	1013	1168.5	1079	1115.5	1095	1098	1095	1115	1071
M2 (sealed dry)	1197	1054	904.5	1113	1207.5	1055	1128	1108	1092	1113	1117	1080
M3(sealed water)	644.5	570	480	594.5	647	564	595	592.7	594	598	596	610
M2-M3	552.5	484	424.5	518.5	560.5	491	533	515.3	498	515	520.9	470
M2-M1	127.5	-19	19	100.5	39	-23.5	12.5	13	-6	18.5	2.4	9.5
Density	2.7961	2.1067	2.2184	2.633	2.2979	2.065	2.1604	2.1989	2.17	2.232	2.153	2.341
Void ratio	-16.02	12.586	7.9514	-9.27	4.65	14.32	10.356	8.7576	9.96	7.379	10.67	2.874

For Mastic Asphalt

3.1 Dimensional Analysis method

Group no.	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**3**	**3**	**4**	**4**	**4**
Sample Item	**A**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**
M1 (g)	1186.9	1187.8	1195.2	1175.7	1174.4	1202.9	1204	1186.2	1184	1197	1183.3	1192.2
H	6.44	6.44	6.54	6.41	6.373	6.54	6.5575	6.40	6.44	6.40	6.42	6.41
d	10.17	10.16	10.18	10.18	10.185	10.2	10.19	10.15	10.16	10.18	10.15	10.17
A	523.59	522.16	532.00	521.94	519.43	534.62	535.00	518.06	522.32	521.12	519.67	521.16
Density	2.267	2.275	2.247	2.253	2.261	2.250	2.250	2.290	2.267	2.297	2.277	2.288
Void ratio	1.95	1.61	2.83	2.57	2.21	2.68	2.66	0.96	1.95	0.65	1.51	1.06

3.2 SSD Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	**A**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**
M1 (g) (dry)	1186.9	1187.8	1195.2	1175.7	1174.4	1202.9	1204	1186.2	1184	1197	1183.3	1192.2
M2(water)	670.8	670	674.8	663.9	664.7	676.6	677.9	670.3	668.1	676.5	670.2	671.3
M1-M2	516.1	517.8	520.4	511.8	509.7	526.3	526.1	515.9	515.9	520.5	513.1	520.9
Density	2.300	2.294	2.297	2.297	2.304	2.286	2.289	2.299	2.295	2.300	2.306	2.289
Void ratio	0.53	0.78	0.66	0.64	0.34	1.14	1.01	0.55	0.73	0.53	0.25	1.01

3.3 Dry Method

Group no.	1	1	1	2	2	2	3	3	3	4	4	4
Sample Item	**A**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**
M1 (g) (dry)	1186.9	1187.8	1195.2	1175.7	1174.4	1202.9	1204	1186.2	1184	1197	1183.3	1192.2
M2(water)	670.8	670	674.8	663.9	664.7	676.6	677.9	670.3	668.1	676.5	670.2	671.3
M3	1187	1187.8	1195.3	1175.7	1174.5	1203	1204.1	1186.8	1184.4	1197.1	1183.3	1192.8
M3-M2	516.20	517.80	520.50	511.80	509.80	526.40	526.20	516.50	516.30	520.60	513.10	521.50
Density	2.299	2.294	2.296	2.297	2.304	2.285	2.288	2.297	2.293	2.299	2.306	2.286
Void ratio	0.55	0.78	0.68	0.64	0.36	1.16	1.03	0.67	0.81	0.55	0.25	1.12

3.4 Paraffin Sealing Method

Group no.	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**3**	**3**	**4**	**4**	**4**
Sample Item	**A**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**
M1 (g) (dry)	1186.9	1187.8	1195.2	1175.7	1174.4	1202.9	1204	1186.2	1184	1197	1183.3	1192.2
M2 (sealed dry)	1193.8	1196	1200.7	1185.2	1182.5	1210.2	1211.7	1193.2	1193.8	1200	1193.6	1197.7
M3(sealed water)	670.9	670.4	675	664	664.9	676.8	678.1	670.5	669.7	679.4	674	673.2
M2-M3	522.9	525.6	525.7	521.2	517.6	533.4	533.6	522.7	524.1	520.6	519.6	524.5
M2-M1	6.9	8.2	5.5	9.5	8.1	7.3	7.7	7	9.8	3	10.3	5.5
Density	2.310	2.308	2.306	2.312	2.317	2.297	2.301	2.311	2.317	2.317	2.339	2.305
Void ratio	0.07	0.18	0.27	0.00	-0.23	0.65	0.49	0.06	-0.21	-0.22	-1.17	0.29

Appendix D

Figure 5D.1: Preparing mixtures and testing Marshall stability & flow

Figure 5D.2: Bulk density tests using the four methods