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Master Thesis in
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Study of the Effect of Crushed Waste Glass as Coarse Sand and Filler in the Asphalt Binder Course

دراسة تأثير مخلفات الزجاج المطحونة كرمل خشن ومادة مالئة في الطبقة الأسفلتية الرابطة

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Dedication

With all humility, I would like to dedicate this thesis to my beloved mother, father, sisters, and brothers for their endless support.

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I thank almighty Allah for giving me patience and determination to accomplish this work. I would also like to express my special deep gratitude to Prof. Eng. Shafik Jendia, the supervisor of my thesis, for all his help and advice. His great guidance and counsel have greatly helped me achieve this work, especially during the practical part and the writing of the reports.

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Abstract

Recycling is considered to be one of the most important bases of sustainability. Almost all the products we utilize, whether they are metal, concrete, plastic, wood, or even glass, will eventually turn into wastes that must be disposed. The best way to deal with these wastes is to recycle and reuse them as raw materials or modifiers. This will reduce the drain on the natural resources of the raw materials, and it will reduce the spaces used as landfills. Among these wastes is glass, which is widely used in our daily life. However, the disposal of waste glass is not an easy matter. That is because glass is neither incinerated nor decomposed material. Waste glass has been used in the road construction as an alternative to the aggregates in the hot asphalt mixes in many countries so as to guarantee the sustainable management of the waste glass. This research studies the effects of crushed waste glass as coarse sand and filler in the asphalt binder course on the properties of Marshall Hot Mix Asphalt. It also compares the glasphalt mix properties with the local and international specifications. Cleaned and crushed, waste glass resulted from glass bottles has been added to the asphalt mixture using a gradation of (0/4.75) mm. This gradation was the same as the gradation of Trabia (0/4.75) mm aggregate that was alternated to glass. Marshall Method was used to determine the Optimum Binder Content (OBC) and to evaluate the properties of the glasphalt mix. In total, 33 samples were prepared, 15 of which have been used to determine the OBC, and the rest have been used to find out the effects of adding different percentages of crushed waste glass to the asphalt mixture. Examining Marshall samples showed that the OBC of bitumen ought to be 5.1 % of the total weight of the asphalt mix. Also, examining Marshall samples containing different percentages of glass showed that the optimum percentage of glass that can be used in the binder course is 7.5% of the weight of the aggregates. This percentage is alternated only to Trabia (0/4.75) mm in the asphalt mix. The results of the experiments (Marshall stability, flow, specific gravity & air voids) are consistent to the local and international specifications. This research recommends doing more studies on the use of glass in the asphalt mixes using different percentages and different sources of glass. It also recommends combining glass with other materials such as plastic and iron filings and then finding out their effects on the asphalt mixes properties.

ملخص البحث

يعتبر إعادة تدوير النفايات إحدى الركائز الأساسية لعملية الإستدامة، فالصناعات التي تخدم الإنسان سواء كانت معدنية ،خرسانية، بلاستيكية ، خشبية أو حتى زجاجية .... إلخ فهي في نهاية الأمر سوف تتحول إلى نفايات يجب التخلص منها، و الحل الأمثل للتعامل مع هذه النفايات هي إعادة تدويرها واستخدامها مرة أخرى كمواد أولية أو كمحسنات بحيث يتم الحد من استنزاف الموارد الطبيعية للمواد الخام وتقليل المساحات المستهلكة كمكبات للنفايات. ومن بين هذه النفايات الزجاج الذي يستخدم على نطاق واسع في مجالات مختلفة ويعتبر التخلص منه مشكلة بيئية لأنه مادة غير قابلة للتحلل وغير قابلة للاحتراق. في العديد من الدول تم استخدام زجاج النفايات في أعمال إنشاء الطرق كتعويض عن الركام في الخلطات الأسفلتية الساخنة بالشكل الذي يضمن عملية إدارة مستدامة للنفايات الزجاجية. يهدف هذا البحث إلى دراسة تأثير استخدام مخلفات الزجاج المطحونة كرمل خشن ومادة مالئة في الطبقة الأسفلتية الرابطة على خواص مارشال للخلطات الأسفلتية الساخنة ومقارنة النتائج مع متطلبات المواصفات المحلية والعالمية للخلطات الأسفلتية. حيث تم إضافة الزجاج المطحون يدوياً الناتج عن الحاويات الزجاجية للمشروبات الغازية إلى الخليط الأسفلتي بتدرج (0/4.75) وهو نفس تدرج أحد الحصويات المكونه للخليط الحصوي وهي الترابية (0/4.75) التي تم استبدال الزجاج بجزءٍ منها. تم استخدام طريقة مارشال لتصميم الخلطات الأسفلتية لتحديد محتوى البيتومين الأمثل (OBC) وكذلك لاختبار خصائص الخليط الأسفلتي المضاف إليه الزجاج المطحون، حيث تم إعداد 33 عينة مارشال، وقد استخدمت 15 عينة منها لتحديد محتوى البيتومين الأمثل و العدد المتبقي من العينات تم استخدامه لدراسة آثار إضافة النسب المختلفة من الزجاج المطحون الى الخليط الأسفلتي. وقد بينت نتائج فحص عينات مارشال أن محتوى البيتومين الأمثل هو 5.1% من وزن الخليط الأسفلتي. وكذلك بعد فحص عينات مارشال التي تحتوي على نسب مختلفة من الزجاج تبين أن نسبة الزجاج المثلى التي يمكن استخدامها في الطبقة الأسفلتية الرابطة هي 7.5 % من وزن الحصويات بحيث يتم استبدال هذه النسبة من الترابية (0/4.75) فقط ، وقد كانت قيم نتائج الاختبارات (تحديد درجة الثبات، الانسياب، الكثافة الظاهرية ونسبة فراغات الهواء في الخليط الأسلفتي) ضمن الحدود المسموح بها عالميا ومحليا. أوصت الدراسة بإجراء مزيد من الدراسات على استخدام الزجاج في الخلطات الأسفلتية بنسب وتدرجات مختلفة واستخدام الزجاج أيضا من مصادر مختلفة وكذلك محاولة دمج الزجاج مع مواد أخرى مثل برادة الحديد أو البلاستيك ودراسة أثر ذلك على خصائص الخلطات الأسفلتية.

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Abbreviations

HMA	Hot Mix Asphalt
OBC	Optimum Bitumen Content
ASTM	American Society of Testing and Materials
MSW	Municipal Solid Waste
d_{25}	Density of bitumen at 25°C
ρ_{bit}	Theoretical maximum density of asphalt mix
ρ_A	Density of Asphalt mix
$\rho_{\min}$	Density of aggregate in the blend
SSD	Saturated surface dry condition
VFB	Voids Filled Bitumen
VMA	Voids Mineral Aggregates
Vb	Bitumen Volume
Va	Air Voids

Chapter 1. Introduction

1.1 Background

With the rapid economy growth and continuously increased consumption, a large amount of waste materials is generated (Wu, S. *et al*., 2003).

The vast quantities of waste (such as scrap tires, glass, blast furnace slag, steel slag, plastics, construction and demolition wastes) accumulating in stockpiles and landfills throughout the world are causing disposal problems that are both financially and environmentally expensive.

Dealing with the growing problem of disposal of these materials is an issue that requires coordination and commitment by all parties involved. One solution to a portion of the waste disposal problem is to recycle and use these materials in the construction of highways (Arnold G. *et al*., 2008).

The use of waste materials (recycling) in the construction of pavements has benefits in not only reducing the amount of waste materials requiring disposal but can provide construction materials with significant savings over new materials. The use of these materials can actually provide value to what was once a costly disposal problem (Jony H. *et al*., 2011).

Crushed glass is a readily available, environmentally clean, relatively low cost material whose engineering performance properties generally equal or exceed those of most natural aggregates (Wartman J. *et al*., 2004).

Waste glass is considered one of the most important parts of the collected waste materials, it is nonmetallic and inorganic, it can neither be incinerated nor decomposed, so it may be difficult to reclaim. Waste glass has been used in highway construction as an aggregate substitute in hot mix asphalt paving. Many countries have recently incorporated glass into their roadway specifications, which had encouraged greater use of the material. While the use of waste glass as filler in hot mix asphalt is still not widely experimented (Jony H. *et al*., 2011).

When crushed waste glass is incorporated in HMA mix the resulting mixture is sometimes referred to as “glasphalt” (Kandhal, P., 1992).

Studies and surveys indicate that glass constitutes around 6.5% of municipal solid waste of the Gaza Strip (Abdalqader, 2011).

The reuse of glass in the Gaza strip will partially contribute in reducing the amount of waste, the area of lands used as landfills and the use of basic raw materials and natural resources.

1.2 Problem statement

Although the glass is a nonmetallic inorganic material that cannot be decomposed or burned and many countries have recently incorporated glass into their roadway specifications, till now there is no use of recycled glass in the Gaza strip.

The Gaza strip solid waste is estimated about 1,300 ton/day (MoP, 2010). Glass constitutes around 6.5% of municipal solid waste of the Gaza Strip (Abdalqader, 2011).

There are many applications that could make use of the recycled glass such as using glass as aggregate in road base and sub-base, aggregate in asphalt, aggregate in tiles, aggregate in decorative concrete for architectural facades, filtration material, alternative to fill and bedding material, aggregate in concrete and asphalt. The use of glass in these applications will contribute in minimizing the area of landfills and saving the natural resources by reducing the demand of raw materials.

This study was conducted to investigate the effect of using crushed waste glass as coarse sand and filler in the asphalt binder course as an idea to find out the best percentage of crushed glass that could be used to produce the glasphalt under the local conditions in the Gaza Strip.

1.3 Aim and Objectives

a. Aim

The aim of this research is to study the possibility of using crushed waste glass as coarse sand and filler materials in Asphalt Binder Course under the local conditions in the Gaza Strip.

b. Objectives

- Find out the effect of adding different percentages of crushed waste glass on the mechanical properties of asphalt mix.
- Determine the optimum percent of crushed waste glass to be added to the hot mix asphalt.
- Finding useful application for waste glass as a part of the solution for environmental problems resulting from the disposal of waste materials.

1.4 Importance of the study

- Using waste glass as coarse sand and filler in order to improve the properties of asphalt pavement.
- Reducing the amount of waste materials and the area of land used for landfill.
- Preservation of the exits raw materials and natural resources.

1.5 Limitations of the study

Results of this study relied on a set of limitations and criteria that were taken into account during the experimental work. These limitations include:

- Only crushed clean glass from bottles was used in this study and other types of waste glass such as sheet glass, ceramic plates, vacuum tubing, mirrors, medical or laboratory glass, and etc. are not within the concern of this research study.
- The gradation of used crushed waste glass, which was used as a replacement of trabia (0/4.75) aggregate, was very near to the gradation of trabia (0/4.75) aggregate.

1.6 Methodology of the study

To achieve the study aim and objectives, the following methodology has been considered:

a. Literature review and revision of accessible references such as books, studies, scientific papers, reports in the field of recycled materials and researches relative to the topic of this research.
b. Study of asphalt mix design criteria, asphalt production technology and local and international specifications.
c. Implementation of laboratory tests to identify the Optimum Bitumen Content (OBC) using Marshall Mix design procedure for binder course.
d. Collect, clean, and crushed waste bottle glass till reaches the required gradation.
e. Preparation of a series of specimens composed of different percentage of crushed glass content.
f. Testing the specimens which contain different percentages of waste glass and identify the effect of these different percentages of glass on the asphalt mix properties by comparing results with the conventional mix result in terms of the

mechanical properties (bulk density, marshal stability, flow, air voids and etc).

g. Analysis & discussion of testing results.
a. Drawing conclusions and recommendations.

1.7 Thesis structure

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

Chapter 1: Introduction

This chapter contains a general introduction is followed by statement of problem, aims and objectives, limitations, methodology of research and finally the thesis structure.

Chapter 2: Literature review

This chapter covers a general literature review related to hot mix asphalt, waste glass and glasphat and previous researches relevant to the topic of research.

Chapter (3) Materials and experimental program

This chapter highlights two topics, the first one is the experimental evaluation of used materials properties such as aggregates, bitumen and waste crushed glass. The second is the explanation of experimental work which has been done to achieve the aim of the study.

Chapter (4) Data analysis and Results

This chapter contains the accomplished results of the laboratory tests. Briefly tests were conducted to obtain the asphalt binder course gradation curve, bitumen properties, optimum bitumen content (OBC) and the effect of adding different percentages of crushed waste glass on asphalt mix properties. More over determine the best glass content percentage.

Chapter (5) Conclusion and recommendations

The conclusions and recommendations of this study are presented in this chapter.

Chapter 2. Literature Review

2.1 Introduction

Asphalt is basically a mixture of natural raw materials: coarse and fine (sand), aggregates, filler and bitumen. In addition to these standard materials from natural sources, some additives may be incorporated to influence the performance of the product (European Asphalt Pavement Association, 2008).

Large amounts of domestic, industrial and mining waste are generated annually in each country. The use of recycled instead of virgin materials helps easing landfill pressures and reducing demand of virgin materials (Huang, Y. *et al*, 2011).

Waste glass has been used in highway construction as an aggregate substitute in hot mix asphalt paving. Many countries have recently incorporated glass into their roadway specifications, which had encouraged greater use of the material. While the use of waste glass as filler in hot mix asphalt is still not widely experimented (Jony, H. *et al*, 2011).

When crushed waste glass is incorporated in HMA mix the resulting mixture is sometimes referred to as "glasphalt" (Kandhal, P., 1992).

Researches show that glass constitutes around 6.5% of municipal solid waste of the Gaza Strip (Abdalqader, 2011).

The reuse of glass in the Gaza Strip will partially contribute in reducing the amount of waste, the area of land used for landfill and the use of basic raw materials from natural resources.

It's found out that with ensuring proper mix design and using suitable amount of waste glass the properties of the asphalt mixture can be improved.

2.2 Asphalt Concrete Pavements

Roads are built up in several layers, consisting of sub-grade, sub-base, base and surface layer; these layers together constitute the pavement. Because asphalt concrete is much more flexible than portland cement concrete, asphalt concrete pavements are sometimes called flexible pavements. Asphalt concrete is composed primarily of aggregate and asphalt binder. Aggregate typically makes up about 95% of a Hot Mix Asphalt (HMA) mixture by weight, whereas asphalt binder makes up the remaining 5%. By volume, a typical HMA mixture is about 85% aggregate, 10% asphalt binder, and 5% air voids. Asphalt binder glues the aggregate together and that means without asphalt binder HMA would simply be crushed stone or gravel. Small amounts of additives and admixtures are added to many HMA mixtures to enhance their performance or workability (Transportation research board committee, 2011).

2.2.1 Flexible Pavement Layers

Asphalt concete pavements are not a thin covering of asphalt concrete over soil, they are engineered stuctures composed of several different layers. Figure (2.1) illustrates a vertical section of flexible pavement structure.

Figure (2.1): *Flexible Pavement Layers*

Subgrade:

The natural soil surface is the boundary between the base soil (Subgrade) and the upper layers of pavement, and it’s called the formation (Jendia, 2000).

The in-place soils, called the subgrade, serve as the foundation that supports the road. After removal of topsoil and other organic materials, the subgrade may be stabilized by compaction alone, or by compaction after mixing in asphalt emulsion, foamed asphalt, portland cement, lime, or other proprietary stabilizing materials. The properties and characteristics of the subgrade soil determine the pavement thickness needed to carry the expected traffic loads (Blades, C. *et al*, 2004).

Sub-base layer:

The sub-base course is the layer of material beneath the subgrade and the base course. It provides structural support, improve drainage and reduce the intrusion of fines from the subgrade in the pavement structure. Moreover if the base course is open graded the sub-base course with more fines can serve as filler between subgrade and the base course (Blades, C. *et al*, 2004).

Sometimes the subbase course is omitted from a pavement and a relatively thick base course is placed directly on the subgrade soil (Transportation research board committee, 2011).

Base course layer:

The base course is the layer of a specified material of designed thickness placed immediately beneath the surface (wearing) or binder course. It provides additional load distribution. It may be composed of crushed stone, crushed slag, and other untreated or stabilized materials (Mathew, T., & Rao, K., 2007).

Asphalt binder course:

Binder course is a hot mix asphalt (HMA) course between the wearing course and either a granular base course or stabilized base course, an existing pavement, or another HMA binder course (Ontario Provincial Standard Specification, 2002)

Its purpose is to distribute traffic loads so that stresses transmitted to the pavement foundation will not result in permanent deformation of that layer. Additionally, it facilitates the construction of the surface layer (Garcia, J., & Hansen, k., 2001).

- Binder course gradation:

Grading of aggregates complies with American Society for Testing and Materials (ASTM D 3515-01) that indicates international gradation limits for the asphalt binder course. Table (2.1) and Figure (2.2) indicates international gradation limits for the dense graded asphalt binder course (ASTM D 3515-01).

Table (2.1): *Gradation limits of dense graded Asphalt Binder Course (ASTM D 3515)*

Sieve size (mm)	**Percentage by Weight Passing**	
	Min	***Max***
25.00	100	100
19.00	90	100
12.50	67	85
9.50	56	80
4.75	35	65
2.36	23	49
0.30	5	19
0.15	3	14
0.075	2	8

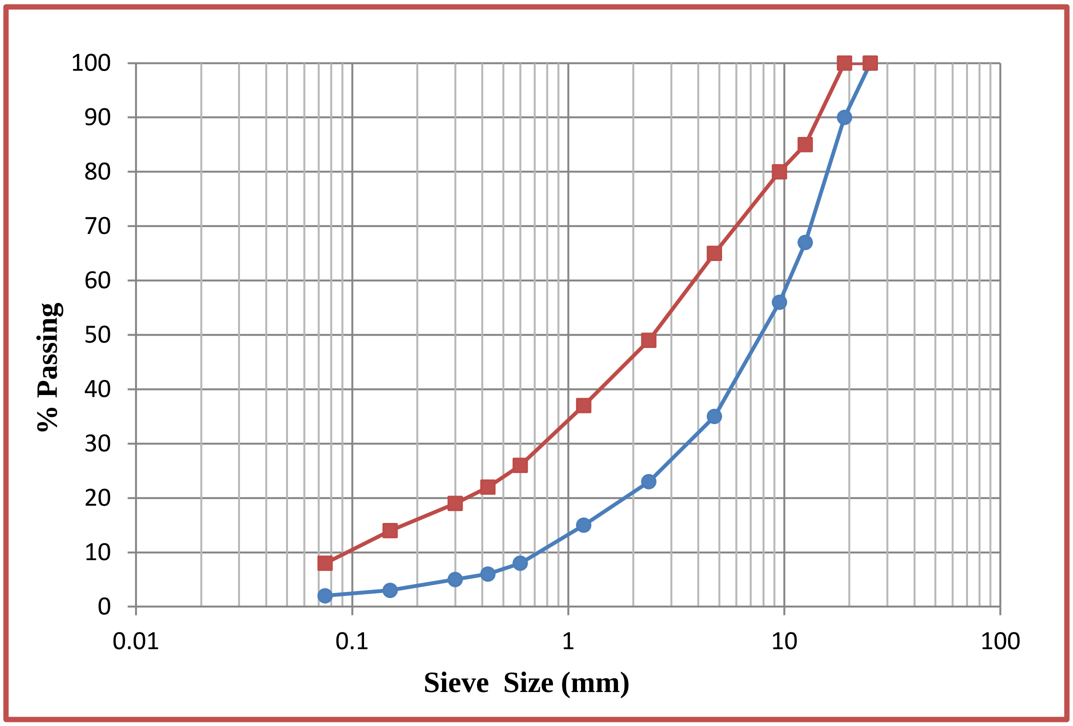

Figure (2.2): *Gradation limits of dense graded Asphalt Binder Course (ASTM D 3515)*

Asphalt wearing course:

It is the top layer of the pavement and it is directly exposed to traffic and environmental forces (Transportation research board committee, 2011).

Wearing course provides characteristics such as friction, smoothness, noise control, rut and shoving resistance, and drainage. In addition, it serves to prevent the entrance of excessive quantities of surface water into the underlying HMA layers, bases, and subgrade (Garcia, J., & Hansen, k., 2001).

2.3 Waste glass in asphalt concrete pavements

2.3.1 Waste Glass

With the rapid economy growth and continuously increased consumption, a large amount of waste materials is generated. Among them, waste glass material is an important part (Wu, S. *et al.,* 2003).

Glass is widely used in our lives through manufactured products such as sheet glass, bottles, glassware, and vacuum tubing. Glass is a transparent material produced by melting a mixture of materials such as silica, soda ash, and CaCO3 at high temperature followed by cooling where solidification occurs without crystallization (Gautam, S. *et al.,* 2012).

Glass is a non-metallic and inorganic material made by sintering selected raw materials, so it can neither be incinerated nor decomposed (Wu, S. *et al.*, 2003).

Glass has most of the properties of high quality natural silica sand and is free of clay and other contaminants. Being almost totally inert, it is extremely durable. It also has extremely low absorption hence provides a greater effective binder content in the mixing of asphalt (Neilson, A., 2009).

The increasing awareness of glass recycling speeds up focus on the use of waste glass with different forms in various fields. (Gautam, S. *et al.*, 2012).

Glass recycling can save energy and decrease environmental waste. Focus on glass recycling technology will also widen the application domain of waste glass and promote further development of glass techniques (Wu, S. *et al.*, 2003).

Glass can be recycled for glass manufacturing; however, it must be sorted by color. The mixed-color glass must be disposed of in landfills and the disposal cost is quite high in some areas (Maupin, G., 1998).

Mixed colored glass is generally unsuitable for traditional recycling processes due to small sizes and the requirement to separate glass colors for reprocessing (Neilson, A., 2009).

Waste Glass may be used in landscaping applications, tile, decorative items, abrasive, filtration, bead manufacturing (used in reflective paint for highways), brick manufacture, concrete pavements, aggregate and road use (Missouri Recycling Association, 2011).

2.3.1.1 Waste glass in the Gaza Strip

The total daily solid waste produced in the Gaza Strip is estimated about 1,300 tons/day (MoP, 2010). Studies and surveys indicate that the municipal solid waste composition in the Gaza Strip constitutes of 47.5% Organic wastes, 14.5% Paper, 12% Plastic, 11.5% Other inorganic, 8% Metals, and 6.5% Glass (Abdalqader, 2011).

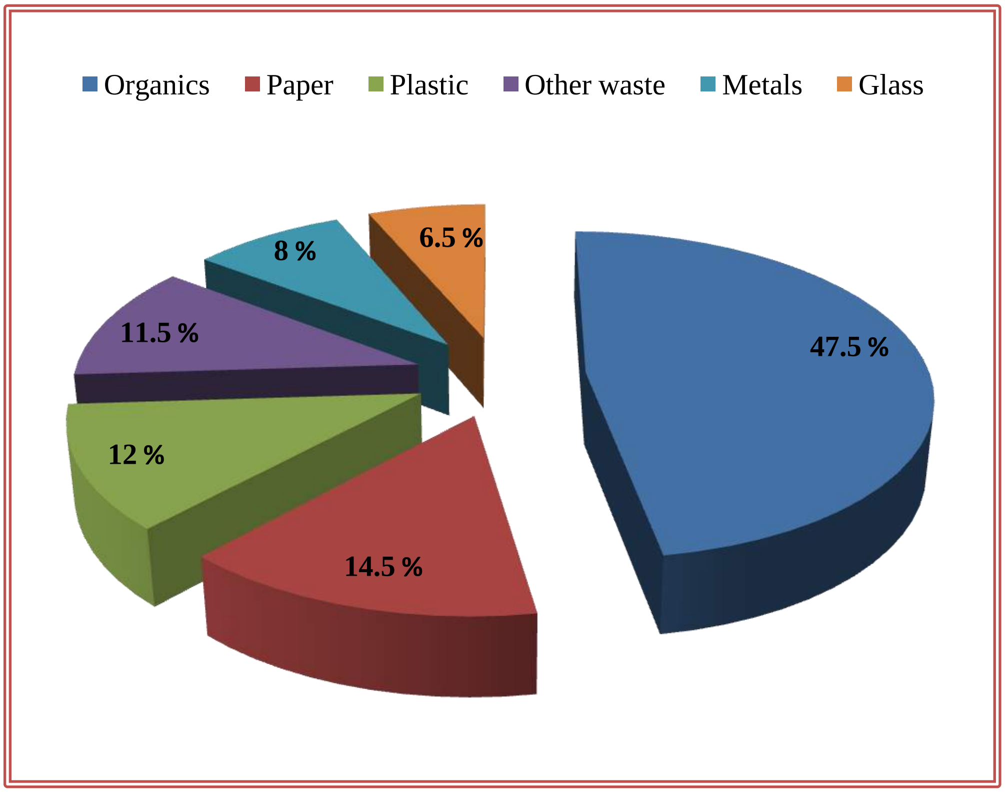

Figure (2.3): *Municipal solid waste composition in the Gaza Strip (Abdalqader, 2011)*

2.3.2 Glasphalt

The use of waste materials (recycling) in the construction of pavements has benefits in not only reducing the amount of waste materials requiring disposal but can provide construction materials with significant savings over new materials. The use of these materials can actually provide value to what was once a costly disposal problem (Jony H. *et al.*, 2011).

Asphalt with glass cullet is commonly referred to as '**Glasphalt**' (Arnold G. *et al.*, 2008). In recent years, the discovery of several economic and environmental benefits could increase the use of recycled glass in highway construction, making the evaluation of the engineering properties of glass and aggregate mixes necessary. The uses of recycled glass have varied widely, depending on the specific application. Crushed recycled glass, or cullet, has been used independently, and has also been blended with natural construction aggregate at different replacement rates (Finkle I., & Ksaibati K., 2007).

Glasphalt is used in the structural layers of the pavement below the surfacing layer to prevent the problems that occur when it is used as surfacing asphalt. These include lack of skid resistance and poor bonding of glass cullet to the bitumen in the asphalt mix, which results in stripping and raveling problems (Arnold G. *et al.*, 2008).

Su and Chen (2002) studied Marshall stability value, dry/wet moisture damage, skid resistance, light reflection, water permeability, and compaction were carried out in accordance with the ASTM and AASHTO and the test results reveal that glass waste is a viable material for asphalt concrete that has been widely used in pavement that offers profound engineering and economic advantages.

Arabani (2011) studied the behavior of Hot Mix Asphalt (HMA) in different temperature conditions depending on the variation of the admixture contents and the gradation of the aggregates. The results showed that the dynamic behavior of glasphalt mixture in comparison with HMA mixtures is improved and the higher internal friction plays an important role in increasing the stiffness of glasphalt. Glasphalt with different glass contents do not show similar responses to changes of temperature. Results also showed that glasphalt is less sensitive to the temperature changes in comparison to HMA.

2.3.3 Waste glass as aggregate in Glasphalt

Fulton (2008) carried out a laboratory testing on the basecourse aggregate with and without the added crushed glass and the results show that the use of recycled glass in aggregate is an excellent initiative to promote sustainable practices.

Finkle & Ksaibati (2007) concluded that crushed recycled glass, or cullet, can be used as a supplement to natural road base material but they recommended the use of cullet be limited to a 20% maximum replacement rate and a maximum size of 1/2". It is more feasible to use glass cullet with crushed, angular aggregate since it performs more consistently than when blended with rounded natural aggregate.

Wu *et al*. (2003) studied the performance of asphalt concrete where some of the fractional fine aggregate is substituted with crushed glass material. The research has demonstrated that the use of waste glass in asphalt concrete is feasible where waste broken glass can be used in asphalt concrete with the maximal size of 4.75mm. The optimal replacement ratio is 10% that maintain the performances such as strength index, high temperature stability and water stability achieve the standards.

Viswanathan (1996) studied the characterization of waste recycled glass as a highway material, based on the results of tests; it was found that glass cullet has properties similar to natural aggregates and could be used as a highway material.

Ouda *et al*. (2010) and Diab *et al*. (2010) At the Islamic university of Gaza, graduation projects of Bachelor Degree were carried out by some students to search the use of glass in many fields such as Man-Made Marble, Mosaic for stair, Marmarina plastering and the results indicated that the use of recycled glass improve the absorption and adsorption values.

The use of glass replacement with aggregate in Masonry Blocks, Paving Blocks and Terrazzo Tiles was also searched and the results showed that the mechanical properties were affected by the various percentage of added glass.

2.3.4 Waste Glass powder as filler in Glasphalt

Various studies have been conducted to study the properties of mineral filler and to evaluate its effect on the performance of asphalt paving mixtures in terms of mechanical properties while the use of waste glass as filler in hot mix asphalt is still not widely experimented (Jony H. *et al.*, 2011).

Pereira *et al*. (2010) studied the use of waste flat glass as a filler in asphalt mixtures and it concluded that the effect of, waste glass on the asphalt mixture does not differ from those made with conventional materials and may be used effectively in asphalt paving.

Jony *et al*. (2011) compared the effect of using different fillers with different contents, glass powder is proposed as an alternative to traditional lime stone powder and ordinary Portland cement fillers in hot asphalt mixtures. The results indicate that there is a satisfactory stability, where using glass powder filler improve the Marshall Stability values for all mixtures comparing to Portland cement or Limestone powder fillers.

2.4 Summary

As seen in the literature review, glass was used in asphalt mix as filler and as a part of granular basescourse but in the Gaza Strip it wasn't used in asphalt mix, it was used in other fields, so this research will study its use as coarse sand and filler in asphalt mix in the binder course.

Chapter 3. Materials and Experimental Program

3.1 Introduction

This chapter highlights the materials and the materials properties used during the laboratory testing such as bitumen, aggregates and waste glass. Also it illustrates how experimental work has been done to achieve the objectives of the research.

3.2 Materials

The raw materials, used for this study are natural aggregates, bitumen, and waste glass. The main and local sources of these materials are presented in the Table (3.1).

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

Material	**Source**	
	Main	***Local***
Bitumen	Egypt	Al-Farra factory (Rafah city)
Aggregates	Egypt	Al-Amal asphalt factory (Johr El-Deek- South east Gaza)
Waste Glass	MSW *****	MSW-Gaza city

* MSW= Municipal Solid Waste

3.2.1 Asphalt Cement (Bitumen)

In this research, a kind of asphalt binder with 70/80 penetration grade was used for producing all test specimens. Physical properties tests for this asphalt cement were conducted in the Materials and Soil Laboratory of the Islamic University of Gaza. Table (4.9) shows the physical properties of used bitumen.

3.2.2 Aggregates

The aggregates commonly used for asphalt mixes are natural fine and coarse aggregates. Used aggregates are divided into two types as presented in Table (3.2). Figure (3.1) shows aggregate types.

Table (3.2): *Used aggregates types*

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

* Local names of aggregates

Figure (3.1): *Types of used aggregates*

3.2.3 Aggregates properties

Laboratory tests have been conducted to evaluate the physical properties of used aggregates. Gradation tests were conducted to determine the size distribution for each aggregate type.

3.2.4 Physical properties of aggregates

Required tests were performed on the aggregate to evaluate their physical properties. The results together with the specification limits are summarized in Table (3.3):

Table (3.3): *Physical properties of used aggregates*

Test	ASTM designation	Folia 0/ 19.0	Adasia 0/ 12.5	Simsimia 0/ 9.50	Trabia 0/4.75	Sand 0/0.6	Specification limits
Bulk dry S.G	C127	2.51	2.49	2.54	2.67	2.58	-
Bulk SSD S.G		2.56	2.55	2.61	2.73	2.63	
Apparent S.G		2.66	2.65	2.73	2.85	2.72	
Effective S.G		2.58	2.57	2.64	2.76	2.65	
Absorption (%)	C128	2.38	2.49	2.79	2.46	2.02	< 5
Abrasion value (%)	C131	22.4		-	-	-	< 40

3.2.5 Sieve analysis of aggregates

A gradation test according to specification (ASTM C 136) is performed on a sample of used aggregate for each type of aggregate in a laboratory and the results are presented below in Table (3.4) and Figures (3.2 - 3.7).

Table (3.4): *Aggregates sieve analysis results*

Sieve size (mm)	Sieve #	Sample passing %				
		Folia 0/ 19.0	*Adasia 0/ 12.5*	*Simsimia 0/ 9.50*	*Trabia 0/4.75*	*Sand 0/0.6*
19	**3/4"**	100.0	99.5	100.00	100.0	100.0
12.5	**1/2"**	1.1	71.4	100.00	100.0	100.0
9.5	**3/8"**	0.5	29.8	99.50	100.0	100.0
4.75	**#4**	0.5	4.5	40.20	96.0	100.0
2.36	**#8**	0.5	2.0	6.03	67.4	100.0
1.18	**#16**	0.5	1.8	5.03	49.3	100.0
0.6	**#30**	0.5	1.5	4.02	34.6	99.0
0.425	**#40**	0.5	1.5	4.02	29.0	67.6
0.3	**#50**	0.5	1.3	3.02	25.1	18.0
0.15	**#100**	0.4	0.8	2.01	20.5	0.2
0.075	**#200**	0.2	0.3	1.01	17.3	0.0
Pan		0.0	0.0	0.00	0.0	0.0

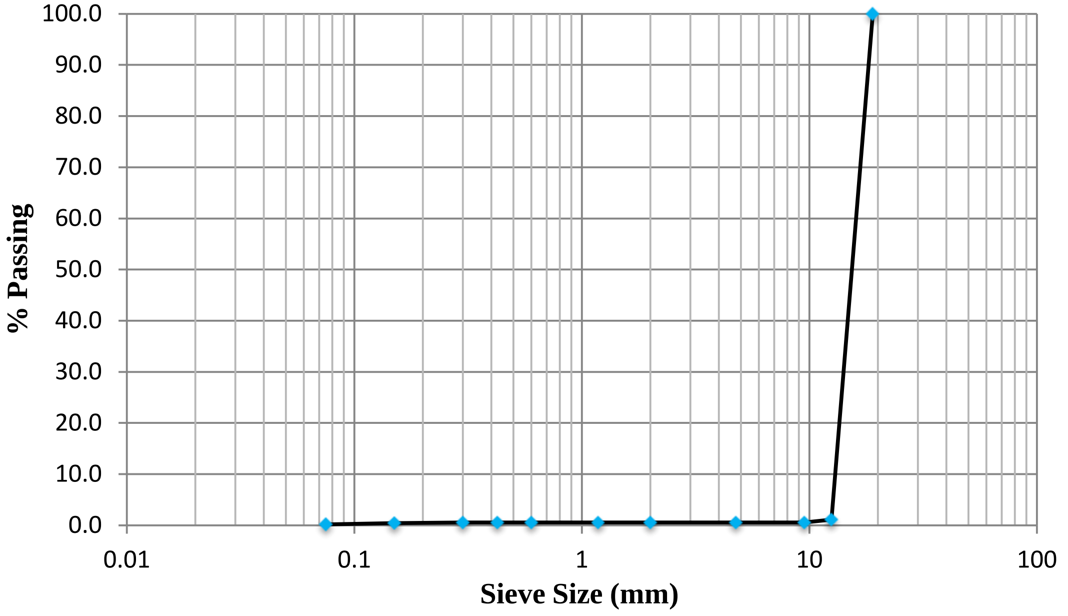

Figure (3.2): *Gradation curve for used (Folia 0/ 19.0) aggregate*

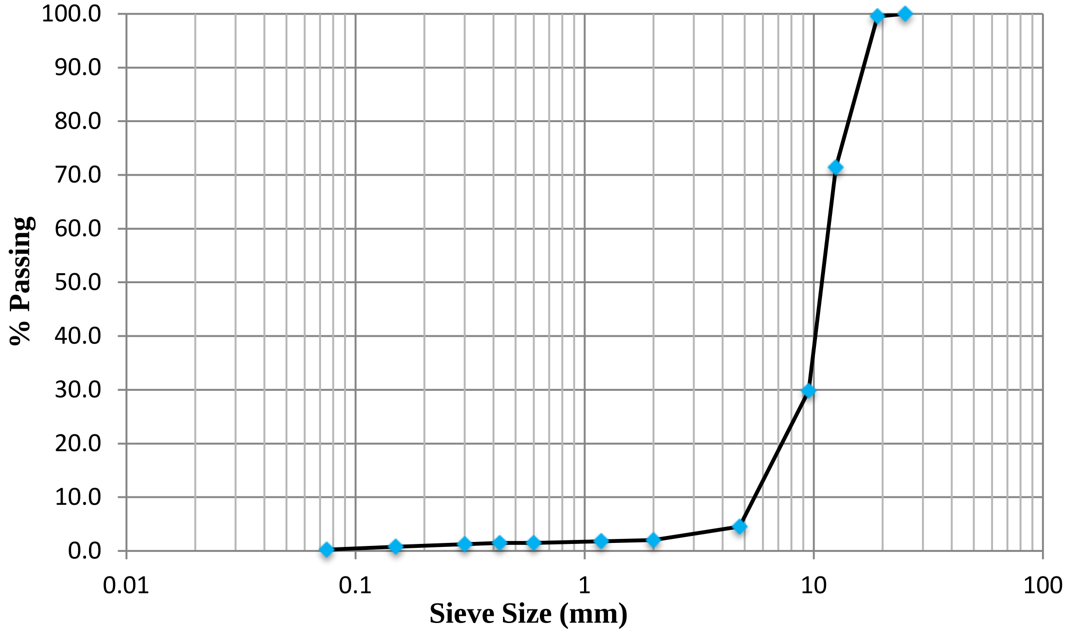

Figure (3.3): *Gradation curve for used (Adasia0/ 12.5) aggregate*

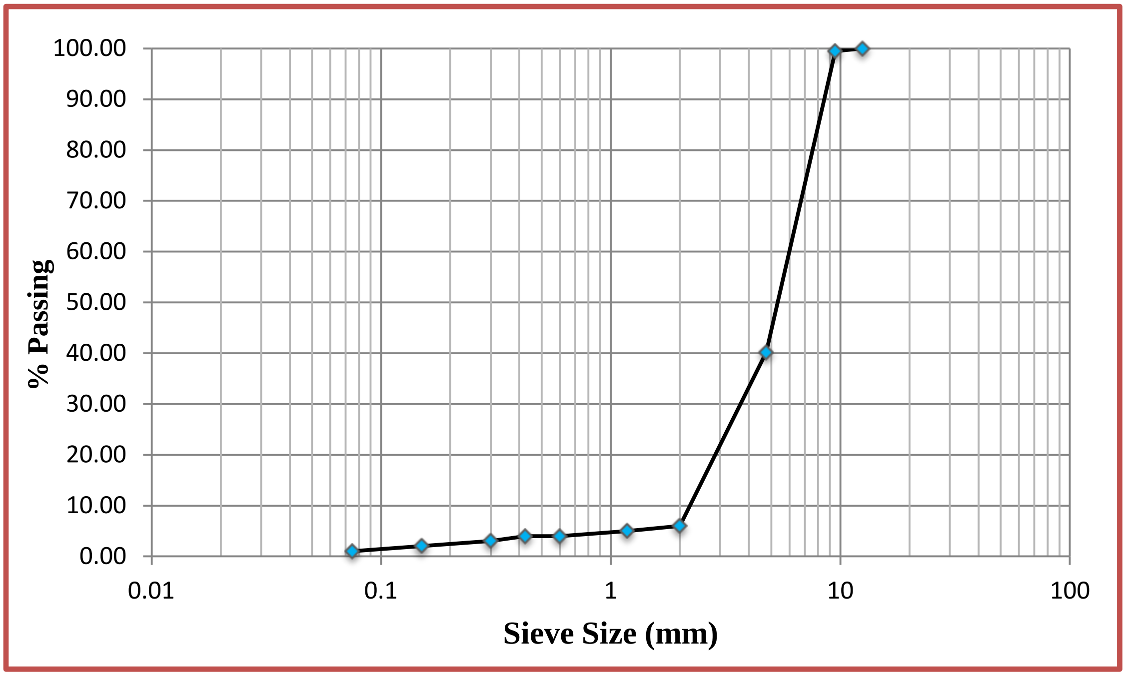

Figure (3.4): *Gradation curve for used (Simsimia 0/ 9.5) aggregate*

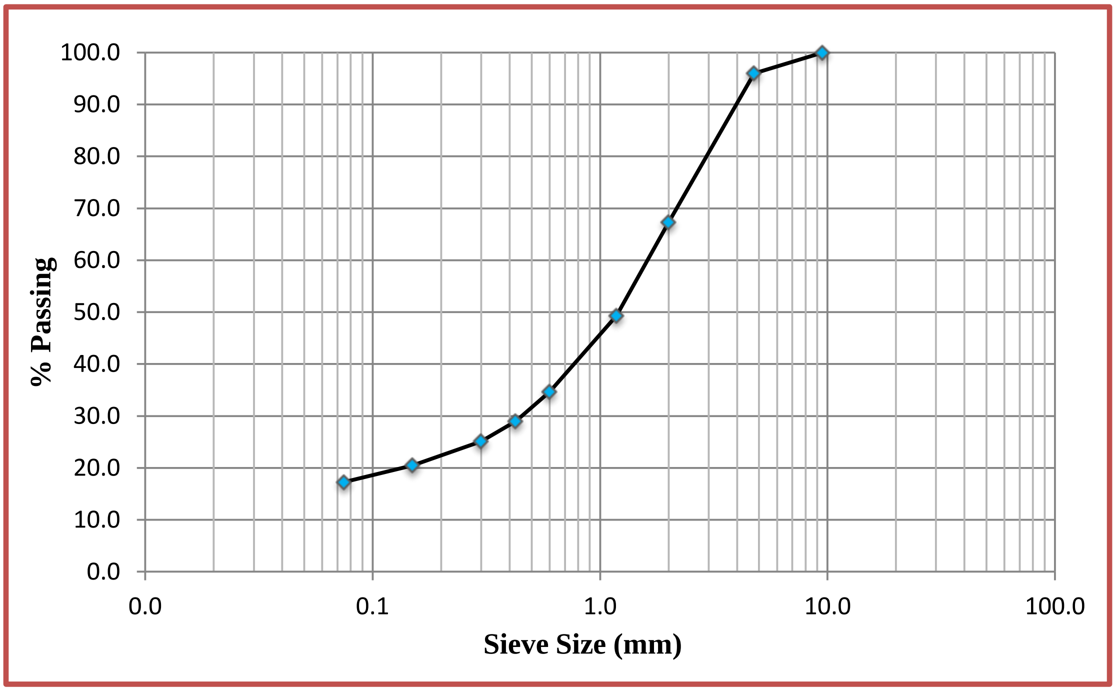

Figure (3.5): *Gradation curve for used (Trabia 0/ 4.75) aggregate*

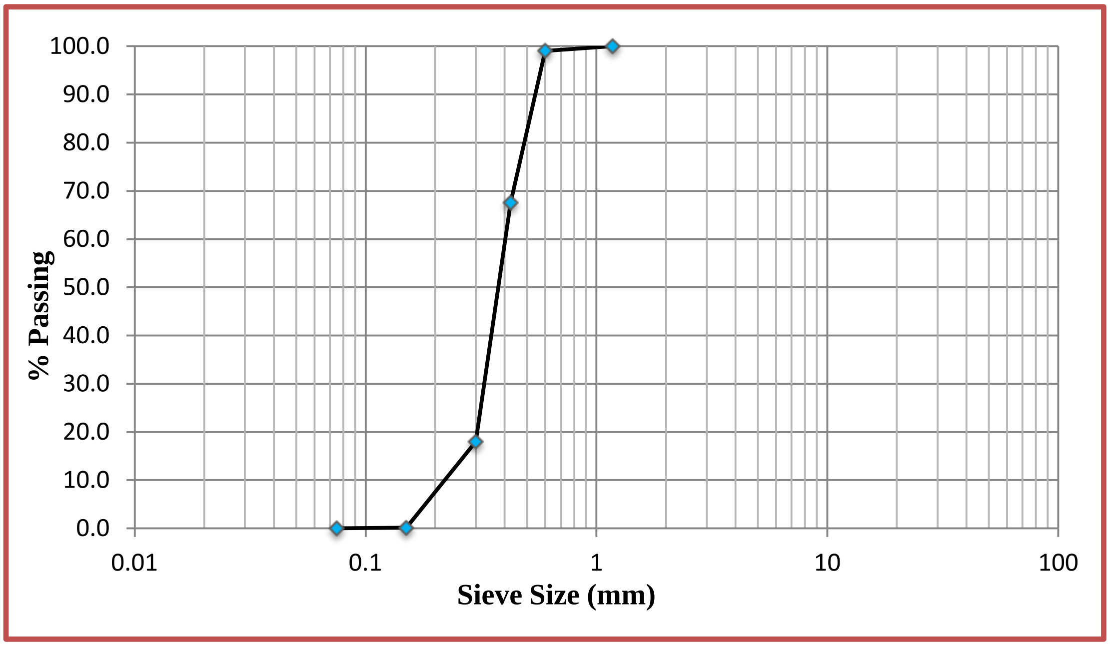

Figure (3.6): *Gradation curve for used (Sand 0/ 0.6)*

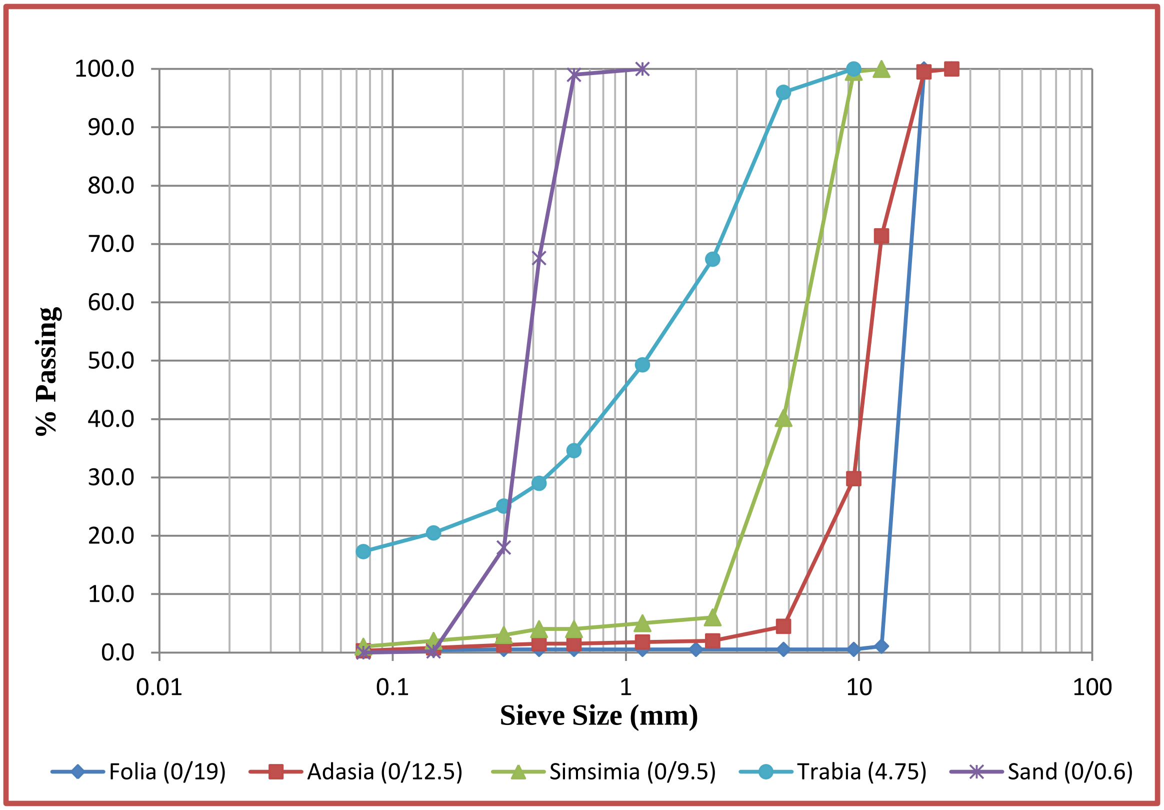

Figure (3.7): *Used aggregates gradation curves*

3.2.6 Waste Glass

The crushed waste glass, which was blended with the aggregates, was obtained from waste bottles. Bottles were cleaned before crushing and then crushed manually to get the required gradation. The crushed glass gradation was completely uniform with the grain size distribution of the Trabia (0/4.75) aggregate that was used in the asphalt mixture. Table (3.5) and Figures (3.8 - 3.11) show the gradation of used waste glass and Trabia (0/4.75) aggregate.

Table (3.5): *Used Crushed Waste Glass Gradation*

Sieve size (mm)	Sieve #	% Sample passing
4.75	**#4**	97.67
2.36	**#8**	69.33
1.18	**#16**	51.00
0.6	**#30**	36.00
0.425	**#40**	30.00
0.3	**#50**	26.00
0.15	**#100**	20.13
0.075	**#200**	16.67
Pan	**Pan**	0.00

3.2.6.1 Crushed Waste Glass Properties

Only crushed clean glass from bottles was used in this study and other types of waste glass such as sheet glass, ceramic plates, vacuum tubing, mirrors, medical or laboratory glass, and etc. are not within the concern of this study. Table (3.6) shows the properties of used crushed glass

Table (3.6): *Used Crushed Glass Properties*

Property	Detail
Glass Source	Bottles
Size (mm)	0/4.75
Density (g/cm^3)	2.52

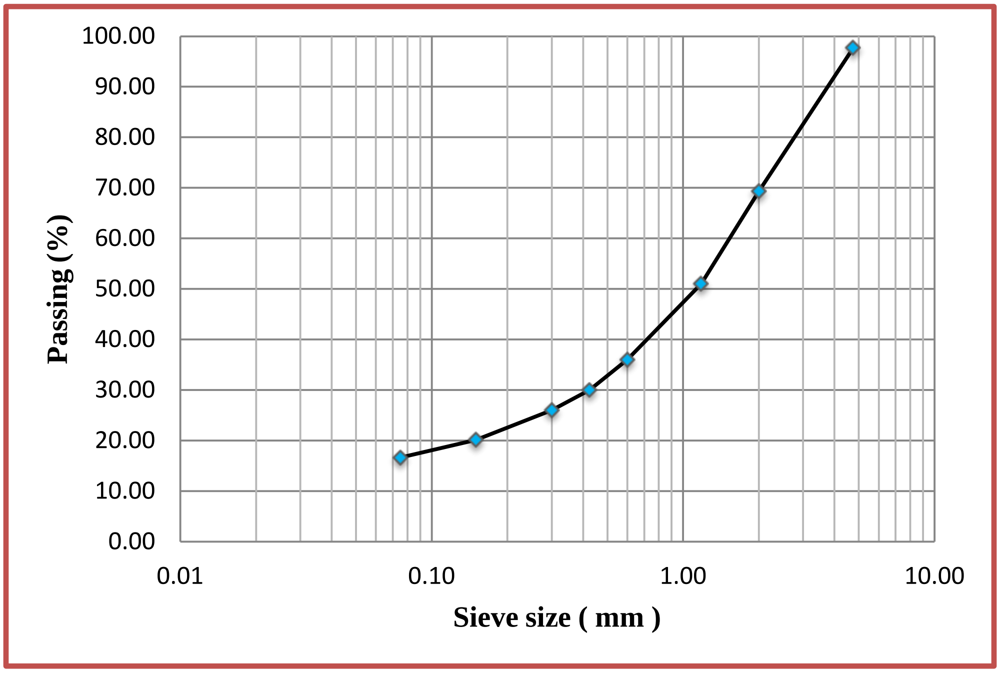

Figure (3.8): *Gradation curve of used Crushed Waste Glass*

Figure (3.9): *Used Crushed Waste glass*

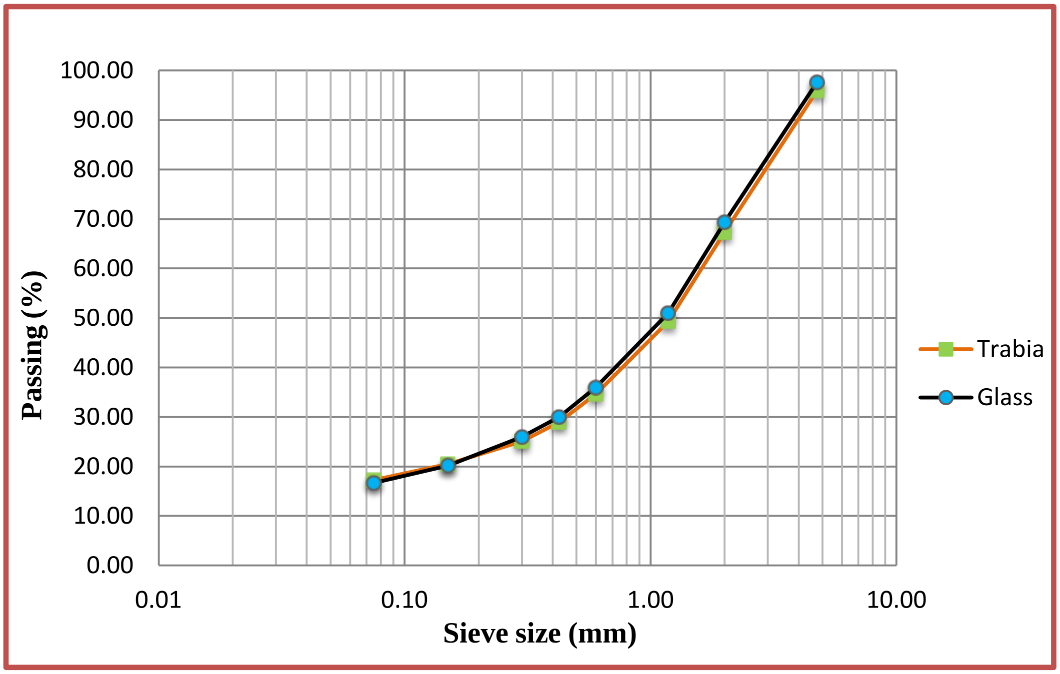

Figure (3.10): *Gradation curve of used Crushed Waste Glass & Trabia*

Figure (3.11): *Used Crushed Waste glass & Trabia*

3.3 Exprimental work

For investigating the properties of Glasphalt and to find out the suitability of using crushed waste glass in asphalt mixtures, an extensive experimental work was conducted. After evaluating the properties of used materials as bitumen, aggregates, and crushed waste glass and carrying out sieve analysis for crushed waste glass and each aggregate type, blending of aggregate carried out to obtain the binder course gradation curve which used in the preparation of the asphalt mix. After that, with different bitumen contents asphalt mixes are prepared to obtain optimum bitumen content by marshall test. Then optimum bitumen content is used to prepare asphalt mixes with various percentages of waste crushed glass. Marshall Test was used to evaluate the properties of these glasphalt mixes. Finally, laboratory tests results are obtained and analyzed. Figure (3.12) shows a flowchart of experimental work for this study.

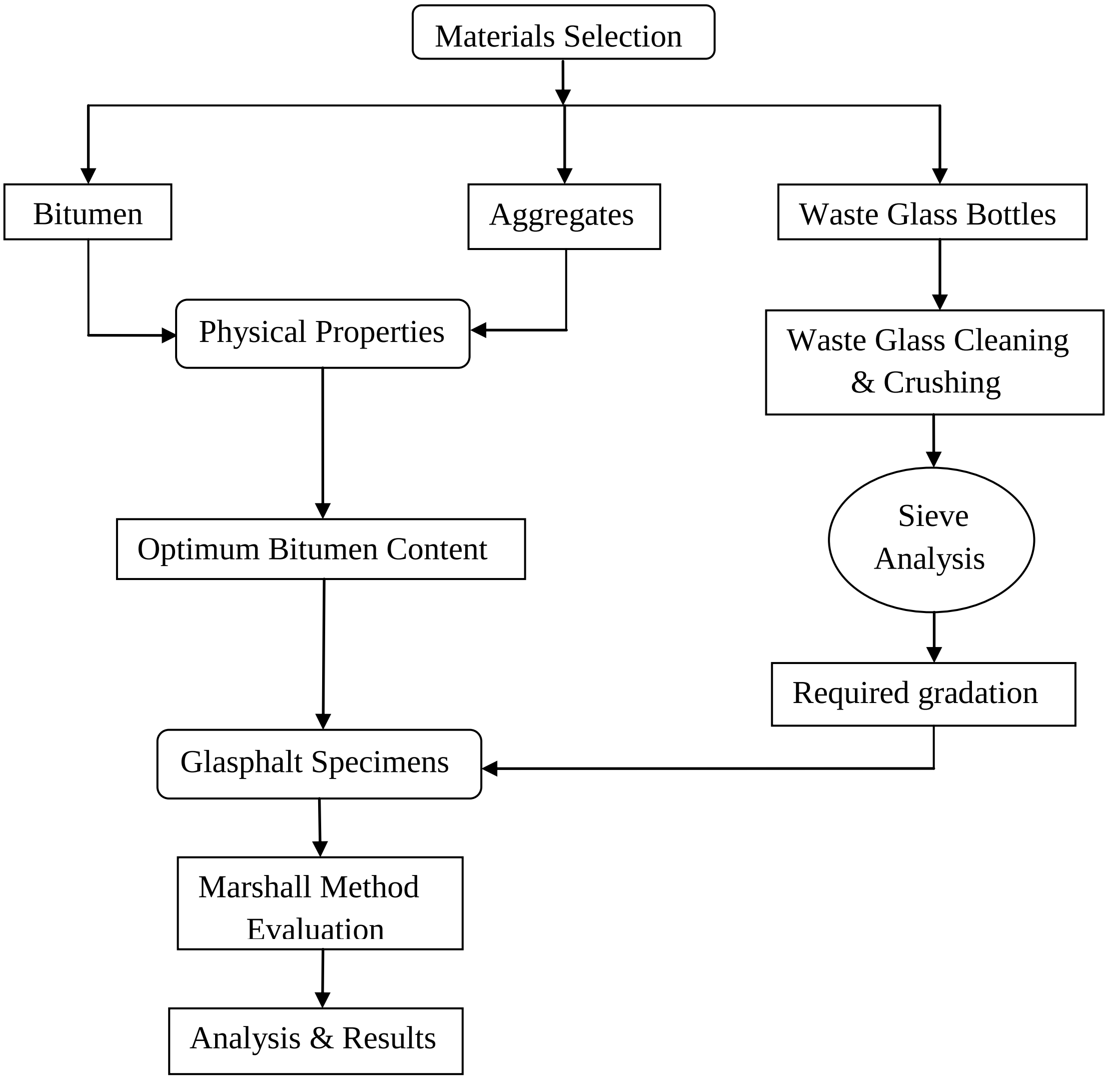

Figure (3.12): *Flowchart of experimental work*

3.3.1 Prepration of Mixtures

According to ASTM specifications using mathematical trial method, aggregates are banded together in order to get a proper gradation. Mathematical trial method depends on suggesting different trial proportions for each type of aggregate. The percentage of each type of aggregates is to be computed and compared to specification limits. If the calculated percentages for, each type of aggregate, gradation is within the specifications limits, no further adjustments need to be made; if not, an adjustment in the proportions must be made till the percentage of each size of aggregate are within the specifications limits (Jendia, 2000). Figure (3.14) shows the envelope of ASTM D 3515-01 binder dense gradation and used aggregate gradation.

Each aggregate sample was blended for each specimen separately. Aggregate are first dried to constant weight at 110±5 ºC. The aggregates are then heated to a temperature of 135 ºC before mixing with asphalt cement. Asphalt was heated up to 145 ºC prior mixing. Pre-heated asphalt was avoided and excess heated asphalt was disposed of to avoid variability in the asphalt properties. The required amount of asphalt were then added to the heated aggregate and mixed thoroughly for at least three minutes and until a homogenous mix is obtained. Standard Marshall molds were heated in an oven up to 130 ºC. The hot mix is placed in the mold and compacted with 75 blows for each face of specimen.

3.3.2 Determining the Optimum Binder Content

3.3.2.1 Marshall Test Method

Marshall Stability test is used in this study for both determining the optimum binder content (OBC) and evaluation the specimens of glasphalt. Marshall Method is essentially empirical and it is useful in comparing mixtures under specific conditions. This method covers the measurement of the resistance to plastic flow of cylindrical specimens of bituminous paving mixture loaded on the lateral surface by means of the Marshall apparatus according to ASTM D 1559-89. The prepared mixture was placed in preheated mold 4inch (101.6mm) in diameter by 2.5 inch (63.5mm) in height, and compacted with 75 blows for each face of specimen. The specimens were then left to cool at room temperature for 24 hours. Marshall stability and flow tests were performed on each specimen, where the cylindrical specimen was placed in water path at 60 ºC for 30 to 40 minutes then compressed on the lateral surface at constant rate of 2 inch/min. (50.8mm/min.) until the maximum load (failure) is reached. The maximum load resistance and the corresponding flow value are recorded. Three specimens for each combination were prepared and the average results were reported. The bulk specific gravity, density, air voids in total mix, and voids filled with bitumen percentages are determined for each specimen.

3.3.3 Optimum Binder Content

Marshall Test has been used to determine the optimum binder content. Five percentages of bitumen were examined to determine the best percentage of bitumen for the aggregates used, which include 4, 4.5, 5, 5.5 and 6% by weight of the mix with three samples for each percentage. The optimum binder content was found equal to 5.1% by weight of the total mix, which is calculated as the average of binder content values that corresponding the maximum stability, maximum density and median percent of air voids (Jendia, 2000).

$$\textbf{Optimum Bitumen Content (OBC) \%} = \frac{(\%\,\text{mb})_{\text{Stability}} + (\%\,\text{mb})_{\text{bulkdensity}} + (\%\,\text{mb})_{\text{Va}}}{3}$$

3.3.4 Optimum Crushed waste glass content

A number of laboratory investigations were performed in order to determine the mix properties of glasphalt using Marshall test procedure. All mixtures are prepared with the same binder content (5.1%). To determine the best percentage of crushed waste glass that could be used in glasphalt, six percentages of crushed waste glass were investigated which are 2.5, 5, 7.5, 10, 12.5,15 % by weight of the total aggregate with 3 samples for each percentage.

The steps of preparing Glasphalt samples can be summarized as follows:

a) Waste glass bottles have been collected, cleaned, crushed and then sieved.
b) The gradation of used crushed waste glass was uniform with the grain size distribution of the Trabia (0/4.75) aggregate was used.
c) Six percentages of crushed waste glass were investigated which were (2.5 - 15%

with 2.5 % incremental) by weight of the total aggregate with 3 samples for each percentage.

d) Crushed waste glass replaced only instead of Trabia aggregate (0/4.75) using the aforementioned percentages and mixed with other aggregates.

e) The mixed crushed waste glass and aggregates are then heated to a temperature of 135 ºC before mixing with asphalt cement.

f) Asphalt was heated up to 145 ºC prior mixing with aggregates. Pre-heated asphalt was avoided and excess heated asphalt was disposed of to avoid variability in the asphalt properties.

g) The required amount of asphalt were then added to the heated aggregate and mixed thoroughly for at least three minutes until a homogenous mix is obtained.

h) Standard Marshall molds were heated in an oven up to 130 ºC and then the hot mix is placed in the mold and compacted with 75 blows for each face of specimen.

i) Specimens are prepared, compacted, and tested according to Marshall Method designated ASTM D 1559-89. Figure (3.13) show Marshall Specimens of Glasphalt with different percentages of crushed waste glass.

Figure (3.13): *Marshall Specimens of Glasphalt*

Chapter 4. Data Analysis and Results

4.1 Introduction

Data analysis and results of laboratory investigations that conducted to study the effect of using crushed waste glass in asphalt binder course specifically, the influence of glass content on the stability, flow, and air voids content of asphalt concrete will presented in this chapter. Also this chapter will discuss in detail all results of laboratory tests that conducted on used materials such as aggregate, bitumen and crushed waste glass.

Marshall Method for designing hot asphalt mixtures was used to determine the optimum bitumen content to be added to specific aggregate blend. Also Marshall Method for designing hot asphalt mixtures was used to evaluate the specimens of glasphalt to determine the best content of glasphalt.

The results of this study only apply to the specific gradation of glass and type of mixes that were used. Other gradations of glass or source may produce different results.

4.2 Aggregates Blending

Natural fine and coarse aggregates are used in this research with physical properties presented in Table (3.4). To produce identical controlled gradation, aggregates were sieved and recombined in laboratory to meet the selected gradation which is satisfying ASTM specifications for asphalt binder course gradation. Table (4.1) shows the final proportion of each used aggregate in asphalt binder course. The selected gradation of aggregates with ASTM gradation limits is presented in Table (4.2) and Figure (4.1). For more details see Appendix (B).

Table (4.1): *Final proportion of each used aggregate*

Aggregates type	Size (mm)	Proportion of proposed mix (%)
Folia	**0/19**	14.0
Adasia	**0/12.5**	19.0
Simsimia	**0/9.5**	27.0
Trabiah	**0/4.75**	34.0
Sand	**0/0.60**	6.0
Sum		100

Table (4.2): *ASTM D 3515 dense binder gradation limits and used aggregates gradation*

Sieve size (mm)	% Passing Used gradation	ASTM specifications limits (%)	
		Min	*Max*
25	**100.00**	100	100
19	**99.93**	90	100
12.5	**80.76**	67	85
9.5	**72.65**	56	80
4.75	**50.47**	35	65
2.36	**31.04**	23	49
1.18	**24.59**	15	37
0.6	**19.21**	8	26
0.425	**15.38**	6	22
0.3	**10.75**	5	19
0.15	**7.74**	3	14
0.075	**6.24**	2	8

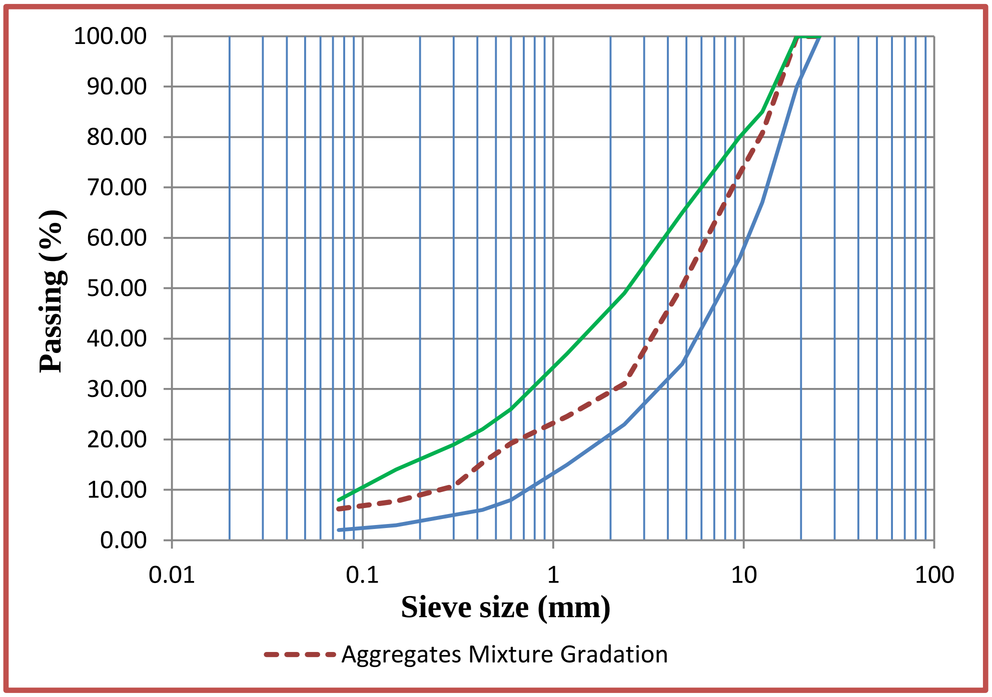

Figure (4.1): *ASTM D 3515 dense binder gradation curves limits and aggregates mixture gradation curve*

4.3 Bitumen Results

Penetration, ductility, specific gravity, softening point, flash point and fire point tests have been performed to measure the properties of asphalt binder.

4.3.1 Penetration test

According to ASTM D5-06 specification, penetration test for bitumen was performed and results presented in Table (4.3) below.

Table (4.3): *Bitumen penetration test results*

	Sample (1)			**Sample (2)**		
Trial	***1***	***2***	***3***	***1***	***2***	***3***
Penetration Value (0.1 mm)	71	69	70	69	71	72
	70			70.67		
	Average = 70.33					

4.3.2 Ductility test

According to ASTM D113-86 specification, ductility test for bitumen was performed and results presented in Table (4.4) below. Figure (4.2) show ductility test for a bitumen sample.

Table (4.4): *Bitumen ductility test results*

Sample	**Ductility (cm)**
(1)	140
(2)	149
(3)	145
Average	**144.67**

Figure (4.2): *Ductility test for a bitumen sample*

4.3.3 Specific Gravity test

According to ASTM D70 specifications, specific gravity test for bitumen was performed and results presented in Table (4.5) below.

Table (4.5): *Bitumen Specific Gravity test results*

Sample weight (gm)	145.19
Weight of Pycnometer + water at 25ºC (gm)	1783.34
Weight of Pycnometer + water at 25ºC + Sample (gm)	1786.92

$$S.G. = \frac{145.19}{(1783.34 + 145.19) - 1786.92} = 1.025 g/cm^3$$

4.3.4 Softening point test

According to ASTM D36-2002 specification, softening point test for bitumen was performed and results presented in Table (4.6) below. Figure (4.3) shows softening point test for bitumen samples.

Table (4.6): *Bitumen softening point results*

Sample	Softening point (ºC)
(1)	46.4
(2)	46.4
Average	**46.4**

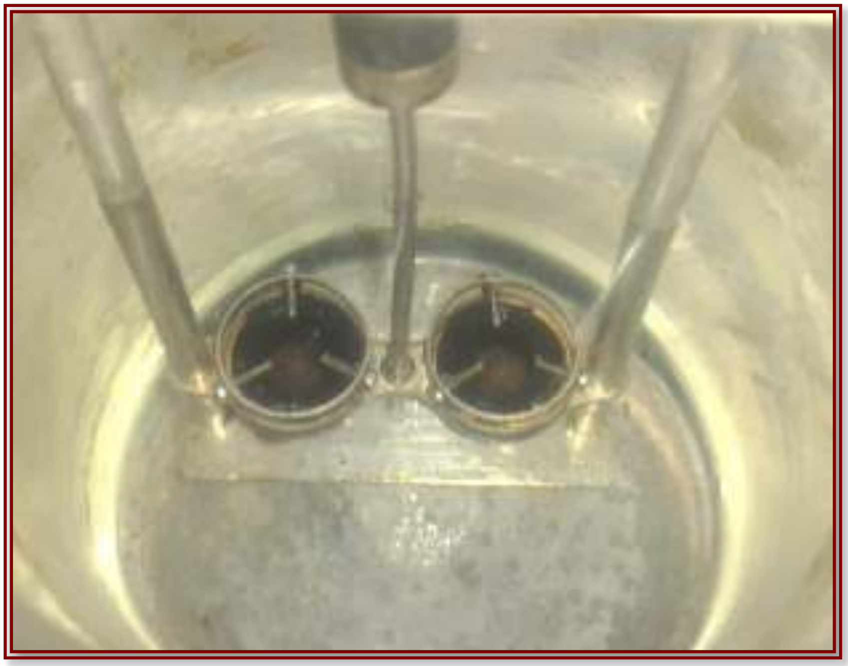

Figure (4.3): *Softening point test for bitumen samples*

4.3.5 Flash point test

According to ASTM D92-90 specification, flash point test for bitumen sample was performed and results presented in Table (4.7) below.

Table (4.7): *Bitumen flash point test results*

Flash point (ºC)	272

4.3.6 Fire point test

According to ASTM D92-90 specification, fire point test for bitumen sample was performed and results presented in Table (4.8) below.

Table (4.8): *Bitumen flash point test results*

Fire point (ºC)	286

4.3.7 Summary of physical properties of bitumen

Table (4.9): *Physical properties of used bitumen*

Test	**Unit**	**Specification**	**Test result**	**Specifications limits**
Penetration at 25 ºC	1/10 mm	ASTM D5-06	70.34	70-80
Specific Gravity at 25 ºC	g/cm^3	ASTM D70	1.025	0.97-1.06
Ductility at 25 ºC	cm	ASTM D113-86	144.67	Min 100
Softening Point	ºC	ASTM D36-2002	46.4	(45 – 52)
Flash Point	ºC	ASTM D92-90	272	Min 230 ºC
Fire Point	ºC	ASTM D92-90	286	-

4.4 Determining the Optimum Bitumen Content

Marshall test was used to examine the specimens of asphalt mixture with different percentages of bitumen content which were (4.0, 4.5, 5.0, 5.5 and 6.0%) to obtain the optimum bitumen content.

4.4.1 Marshall test results

Marshall test results of mixture with different binder content are shown in Table (4.10). The relationships between binder content and the properties of mixtures such as stability, flow, V.F.B, V.M.A.,Va, Vb and bulk density (ρ_A) are shown in Figures (4.4 – 4.9). A number of 15 samples each one of them weigh 1200 gram, were prepared using five different bitumen contents (4.0, 4.5, 5.0, 5.5 and 6.0 % by total weight) in order to determine the optimum bitumen content . Further details are presented in Appendix (C).

Table (4.10): *Marshall test results*

Bitumen (% By total weight)	Sample No.	Corrected Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	Vb (%)	VMA (%)	VFB (%)
4	1	1517.59	3.37	2.31	7.46	9.03	16.49	54.76
	2	1412.64	3.13	2.28	8.64	8.91	17.55	50.79
	3	1384.27	2.47	2.32	7.30	9.04	16.34	55.35
Average		**1438.17**	**2.99**	**2.31**	**7.80**	**9.00**	**16.79**	**53.63**
4.5	1	1550.98	3.58	2.34	5.52	9.15	14.67	62.38
	2	1384.11	2.87	2.32	6.38	9.07	15.45	58.69
	3	1443.38	2.52	2.34	5.83	9.12	14.95	60.98
Average		**1459.49**	**2.99**	**2.33**	**5.91**	**9.11**	**15.02**	**60.69**
5	1	1445.76	2.99	2.35	4.40	9.19	13.59	67.62
	2	1515.28	3.34	2.35	4.78	9.15	13.94	65.67
	3	1531.58	3.13	2.36	4.37	9.19	13.56	67.76
Average		**1497.54**	**3.15**	**2.35**	**4.52**	**9.18**	**13.70**	**67.02**
5.5	1	1608.05	3.50	2.35	4.02	9.16	13.18	69.49
	2	1355.95	3.39	2.36	3.59	9.20	12.79	71.92
	3	1257.48	2.83	2.33	4.53	9.11	13.64	66.77
Average		**1407.16**	**3.24**	**2.35**	**4.05**	**9.15**	**13.20**	**69.39**
6	1	1551.83	4.26	2.33	3.85	9.11	12.96	70.28
	2	1349.94	4.08	2.34	3.76	9.12	12.87	70.82
	3	1286.59	4.15	2.33	3.99	9.09	13.08	69.50
Average		**1396.12**	**4.18**	**2.33**	**3.87**	**9.11**	**12.97**	**70.20**

(1)	ρ_A	Bulk Density
(2)	Va%	Air voids
(3)	Vb %	Percent volume of bitumen
(4)	VMA%	Voids Mineral Aggregates
(5)	VFB%	Percent Voids Filled with Bitumen

4.4.2 Marshall stability

The stability of the specimen is the maximum load required to produce failure of the specimen when load is applied at constant rate 50 mm / min (Jendia, 2000). From figure below it is noticed that the maximum stability of asphalt mix is 1470.643 kg at 4.75 % bitumen content. Figure (4.4) shows the stability result for different bitumen contents.

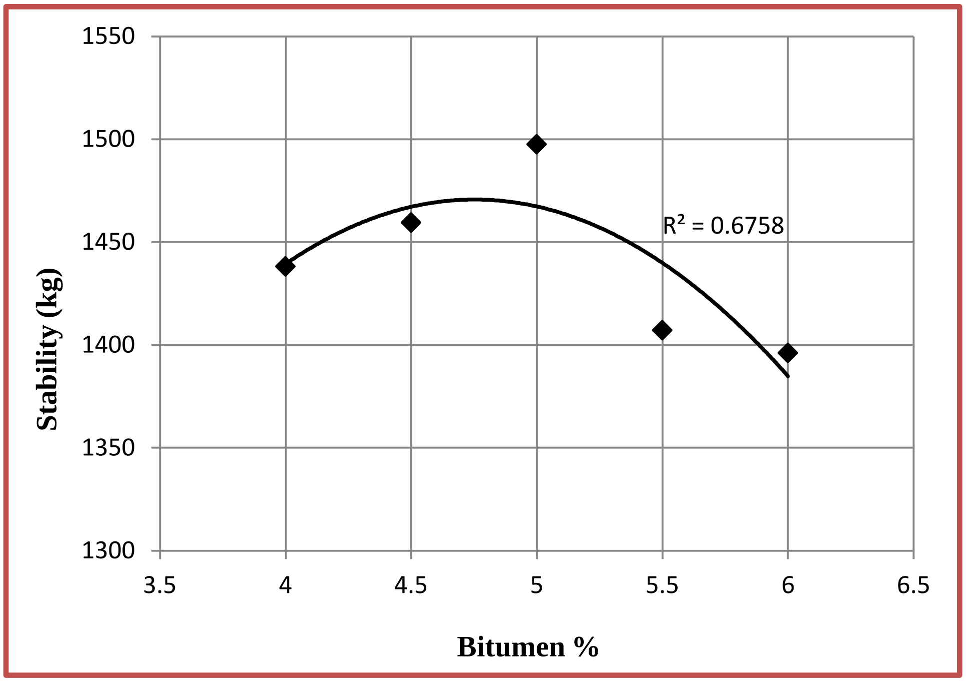

Figure (4.4): *Stability vs. bitumen content*

4.4.3 Flow

Flow is the total amount of deformation which occurs at maximum load (Jendia, 2000). From the figure below it is noticed that the maximum flow of asphalt mix is at 6% bitumen content. Figure (4.5) shows bitumen flow results for different bitumen contents.

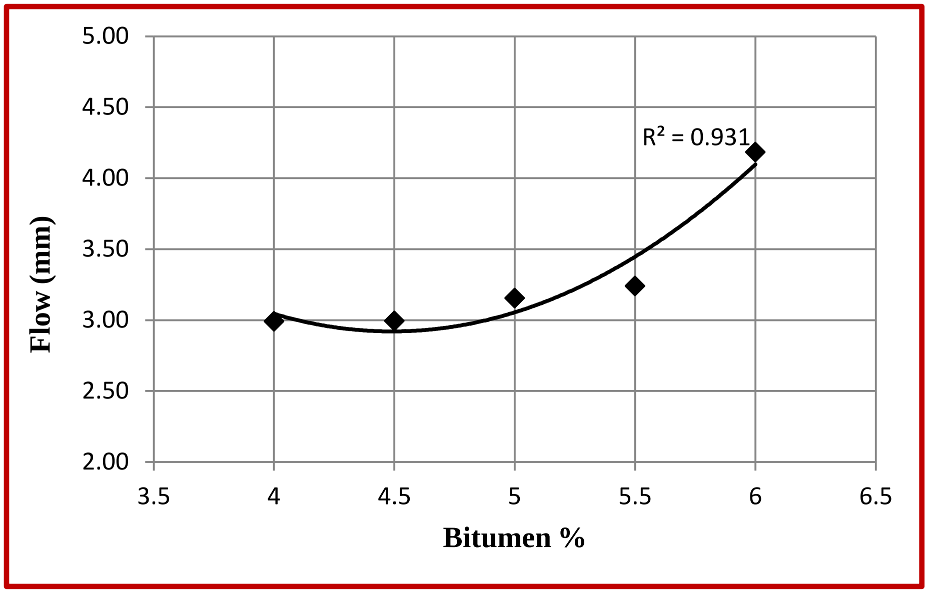

Figure (4.5): *Flow vs. bitumen content*

4.4.4 Bulk density

Bulk density is the actual density of the compacted mix. Figure (4.6) represents the bulk density results for different bitumen contents. From the figure below it's noticed that the maximum bulk density is 2.35 g/cm^3 at 5.2 % bitumen content.

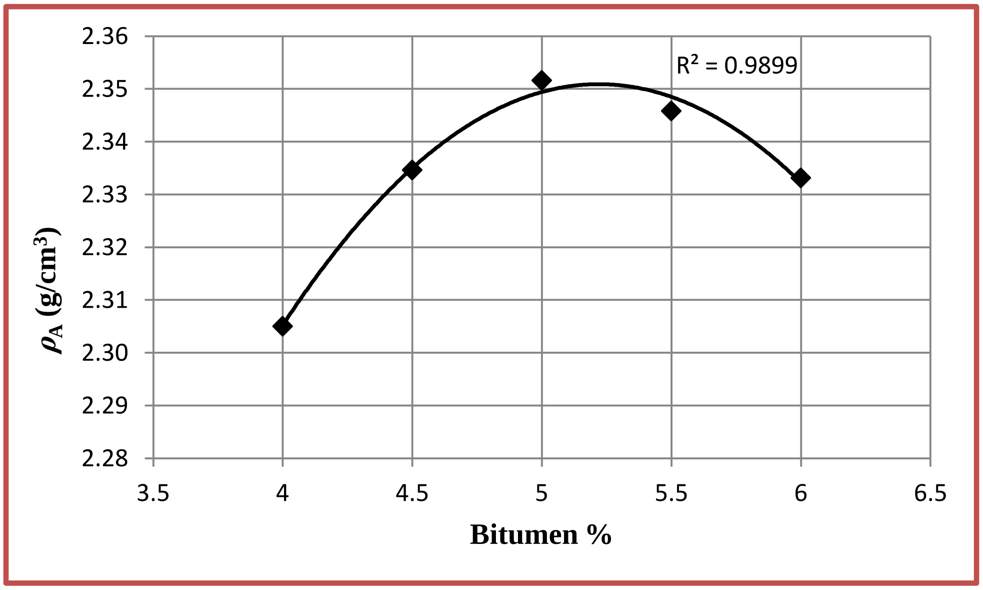

Figure (4.6): *Bulk density vs. bitumen content*

4.4.5 Air Voids content (Va)

The air voids, *Va*, is 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 (O'Flaherty, 2002). From Figure (4.7) it's noticed that the air voids content gradually decreases with increasing the bitumen content and that due to the increase of voids percentage filled with bitumen in the asphalt mix. Figure (4.7) shows results of air voids content with different bitumen contents.

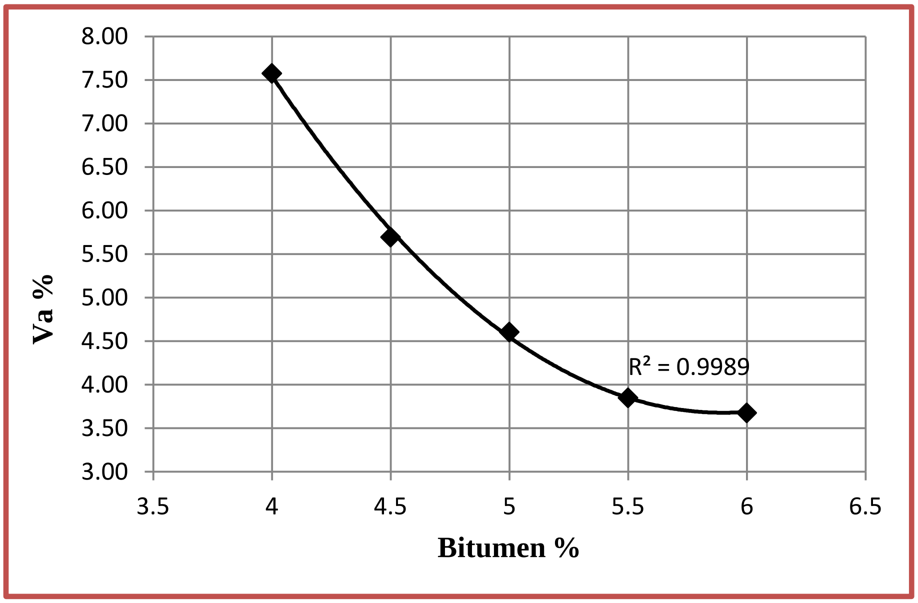

Figure (4.7): *Mix air voids proportion vs. bitumen content*

4.4.6 Voids in Mineral Aggregates (VMA)

The voids in the mineral aggregate, VMA, are defined as the intergranular void space between the aggregate particles in a compacted paving mixture that includes the air voids and the effective bitumen content, expressed as a percent of the total volume (O'Flaherty, 2002). From Figure (4.8) it's noticed that the VMA decrease gradually as bitumen content increase. Figure (4.8) shows results of VMA for different bitumen contents.

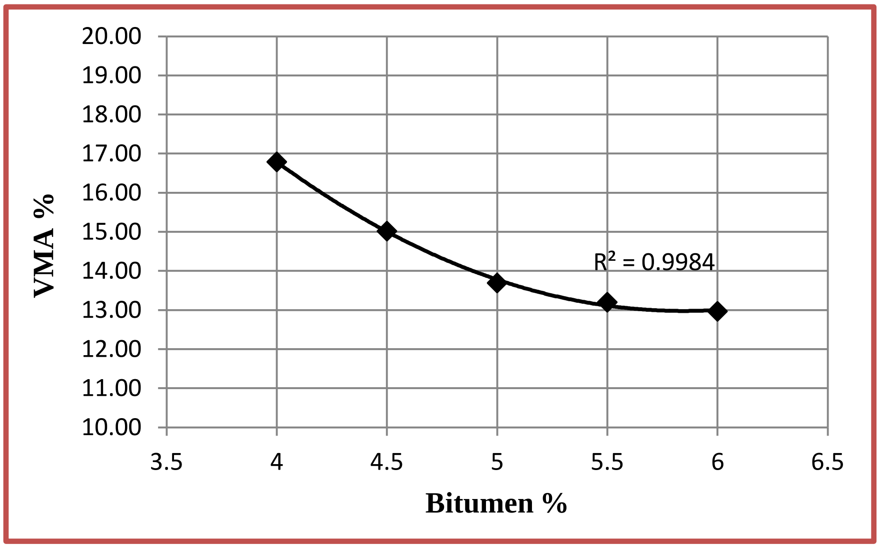

Figure (4.8): *Voids of mineral aggregates proportion vs. bitumen content*

4.4.7 Voids Filled with Bitumen (VFB)

The voids filled with bitumen, VFB, is the percentage of the intergranular void space between the aggregate particles (VMA) that are filled with bitumen (O'Flaherty, 2002). From Figure (4.9) it's noticed that the VFB% increase gradually as bitumen content increase and that due to the increase of voids percentage filled with bitumen in the asphalt mix. Figure (4.9) shows results of VFB with different bitumen contents.

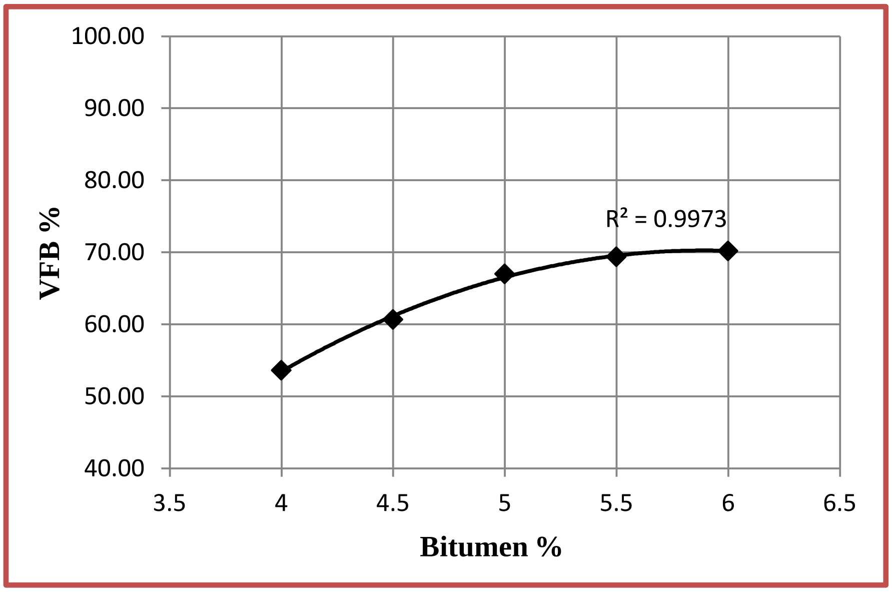

Figure (4.9): *Voids filled with bitumen proportion vs. bitumen content*

4.4.8 Optimum bitumen content (OBC)

The optimum bitumen content was found equal to 5.1% by weight of the total mix which is calculated as the average of bitumen content values that corresponding the maximum stability, maximum density and median of the air voids. Figures (4.4, 4.6 and 4.7) are utilized to find the three values.

- Bitumen content at the maximum stability = 4.75 %
- Bitumen content at the maximum value of bulk density = 5.2%
- Bitumen content at the median percent of air voids = 5.35%

$$\textbf{Optimum Bitumen Content (OBC)} = \frac{4.75+5.2+5.35}{3} = 5.10\ \%$$

At 5.1% bitumen content it's found from Figures (4.4 - 4.9) that all test values consistence with the specifications limits. Table (4.11) presents the properties of asphalt mix at 5.1% bitumen content and the specifications limits.

Table (4.11): *Properties of the asphalt mix at 5.1% bitumen content*

Test	Test Result	International Specifications (Asphalt Institute, 1997)		Local Specifications (Municipality of Gaza, 1998)	
		Min	***Max***	***Min***	***Max***
Stability (Kg)	1464	817	*	900	*
Flow (mm)	3.1	2	3.5	2	4
Bulk density (gm/cm^3)	2.35	2.3	*	2.3	*
Air voids (%)	4	4	5	3	7
Voids in mineral aggregates (%)	13.8	13	*	13.5	*

4.5 Glasphalt results

As discussed in chapter three, there were 18 of Marshall samples of glasphalt each one of them weigh 1200 gm were prepared using six different crushed glass content (2.5, 5, 7.5, 10, 12.5, and 15) by the weight of total aggregates and 5.1% bitumen content (by the weight of total mix). Marshall Test also was used to evaluate the specimens with different percentages of crushed waste glass and the results are presented in Table (4.12). Further details are presented in Appendix (D).

Table (4.12): *Mechanical properties of asphalt mixes with crushed waste glass & 5.1% bitumen content*

Glass (% from aggregates weight)	Sample No.	Corrected Stability (Kg)	Flow (mm)	ρA (g/cm3)	Va (%)	Vb (%)	VMA (%)	VFB (%)
0 (See Table 4.11)		**1464**	**3.1**	**2.35**	**4**	**11.63**	**13.8**	**67.33**
2.5	**1**	1419.70	2.73	2.35	4.54	11.62	16.16	71.90
	2	1271.61	3.08	2.33	5.44	11.51	16.95	67.91
	3	1284.56	3.38	2.32	5.68	11.48	17.16	66.92
Average		**1325.29**	**3.06**	**2.33**	**5.22**	**11.54**	**16.76**	**68.91**
5	**1**	1319.34	2.81	2.35	3.62	11.64	15.27	76.26
	2	1390.21	2.48	2.37	2.94	11.73	14.66	79.97
	3	1299.60	3.17	2.36	3.45	11.66	15.12	77.17
Average		**1336.39**	**2.82**	**2.36**	**3.34**	**11.68**	**15.02**	**77.80**
7.5	**1**	1479.67	4.08	2.35	3.61	11.64	15.25	76.31
	2	1405.01	2.72	2.34	3.95	11.60	15.55	74.59
	3	1508.99	4.14	2.33	4.32	11.55	15.88	72.78
Average		**1464.56**	**3.65**	**2.34**	**3.96**	**11.60**	**15.56**	**74.56**
10	**1**	1269.24	2.80	2.35	3.29	11.66	14.95	77.97
	2	1344.54	2.84	2.36	3.05	11.69	14.74	79.28
	3	1380.54	2.59	2.36	3.11	11.68	14.79	78.98
Average		**1331.44**	**2.74**	**2.36**	**3.15**	**11.68**	**14.83**	**78.75**
12.5	**1**	1257.09	2.52	2.36	2.97	11.68	14.64	79.75
	2	1268.68	3.22	2.38	2.10	11.78	13.88	84.87
	3	1359.12	2.89	2.38	1.90	11.80	13.70	86.17
Average		**1294.96**	**2.88**	**2.37**	**2.32**	**11.75**	**14.07**	**83.59**
15	**1**	1300.82	2.19	2.37	1.81	11.71	13.52	86.63
	2	1227.55	2.74	2.37	1.63	11.73	13.37	87.78
	3	1300.24	2.69	2.35	2.31	11.65	13.96	83.46
Average		**1276.20**	**2.54**	**2.36**	**1.92**	**11.70**	**13.62**	**85.96**

4.5.1 Marshall stability – Glass content relationship

From Figure (4.10) it's noticed that that all values of stability with different glass content achieve the local and international specification requirements, where the solid line represent the local minimum required value of stability and the dash line represent the minimum international requirement. Figure (4.10) shows that the stability of Glasphalt mixes increase as the glass content increases till it reaches the maximum stability at 7.5 % glass content then it start to decline.

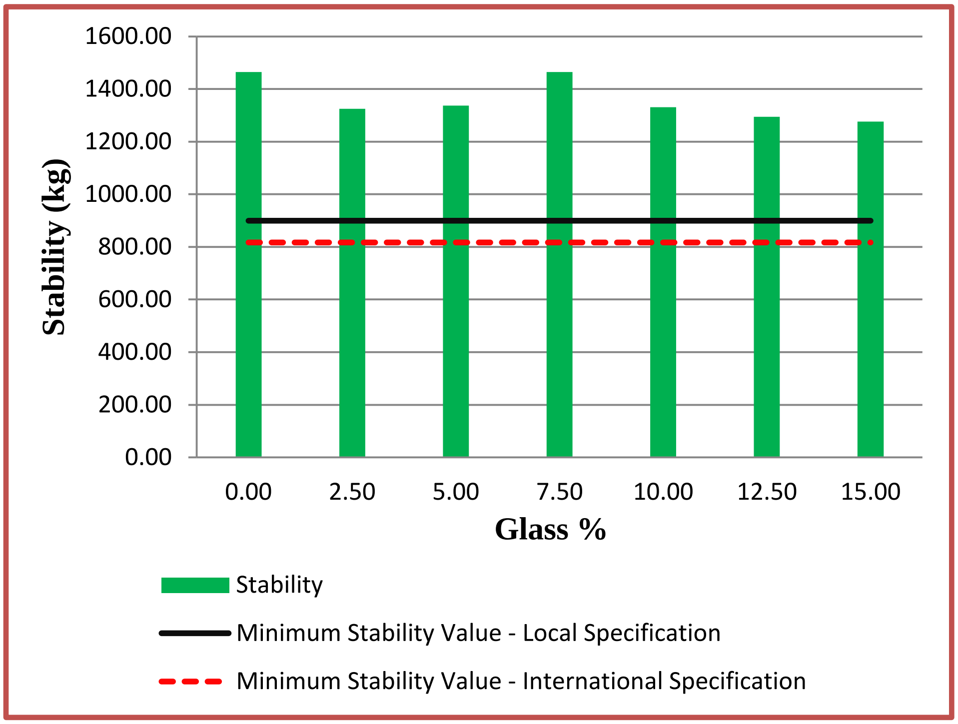

Figure (4.10): *Asphalt mix Stability – Glass content relationship*

4.5.2 Flow – Glass content relationship

The flow of Glasphalt mixes oscillate around the value of conventional mix which is 3.1mm and still in the range of local and international specifications at all different glass content. Figure (4.11) shows flow results of glasphalt at different glass content.

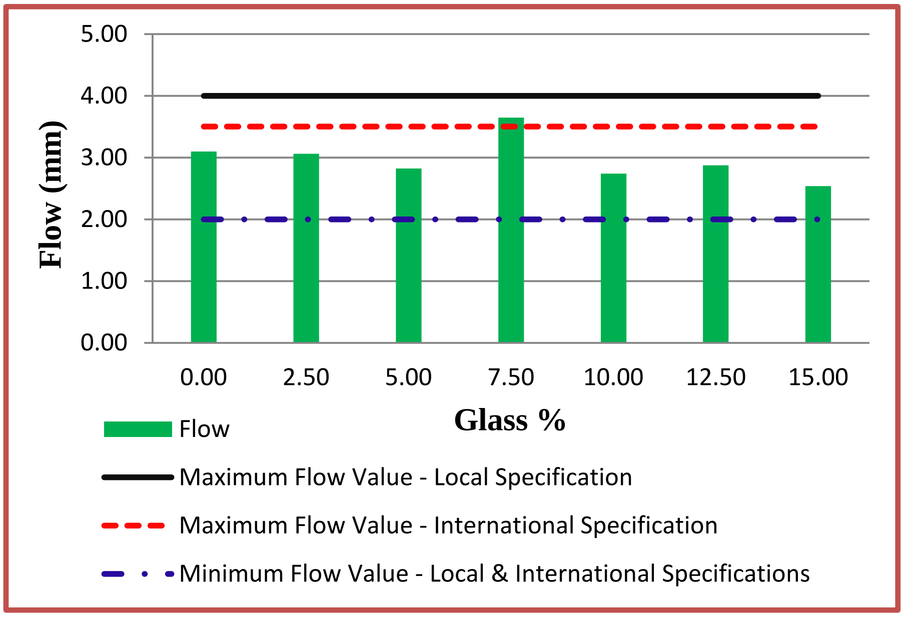

Figure (4.11): *Asphalt mix flow – Glass content relationship*

4.5.3 Bulk density – Glass content relationship

The bulk density of glasphalt mixes with the different percentages of glass content achieves the local and international specification value which is 2.3 g/cm^3. The general trend shows that the bulk density increases as the glass content increases. Figure (4.12) represents asphalt mix bulk density at different glass content.

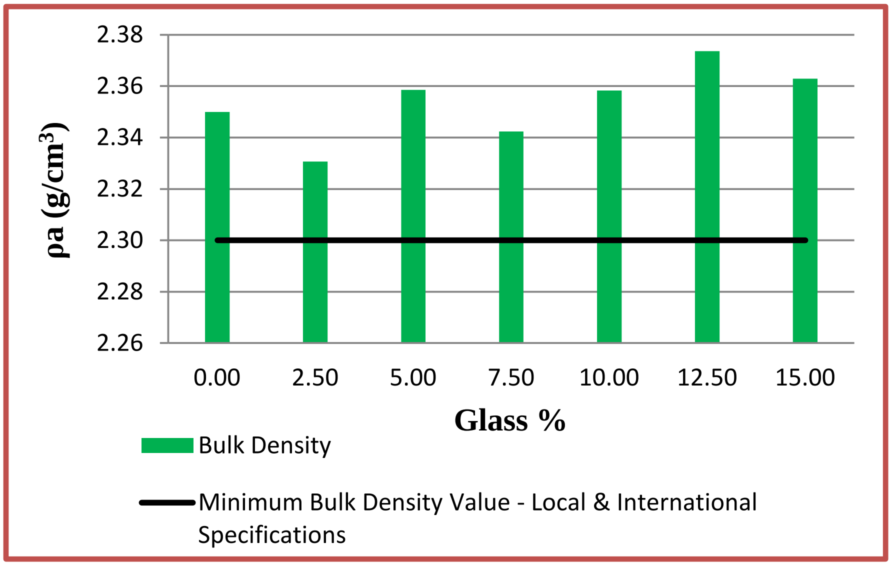

Figure (4.12): *Asphalt mix bulk density – Glass content relationship*

4.5.4 Air voids (Va) – Glass content relationship

The air voids of Glasphalt mixes decreases gradually as the glass content increase. This decline in air voids in Glasphalt mixes return to the reduction in internal pores of glass than trabia (0/4.75) aggregate. It's noticed from the Figure (4.13) that at 7.5% glass content the air voids percentage is 4% which is the median value of international specification. Figure (4.13) represents the air voids of asphalt mixes at different glass content.

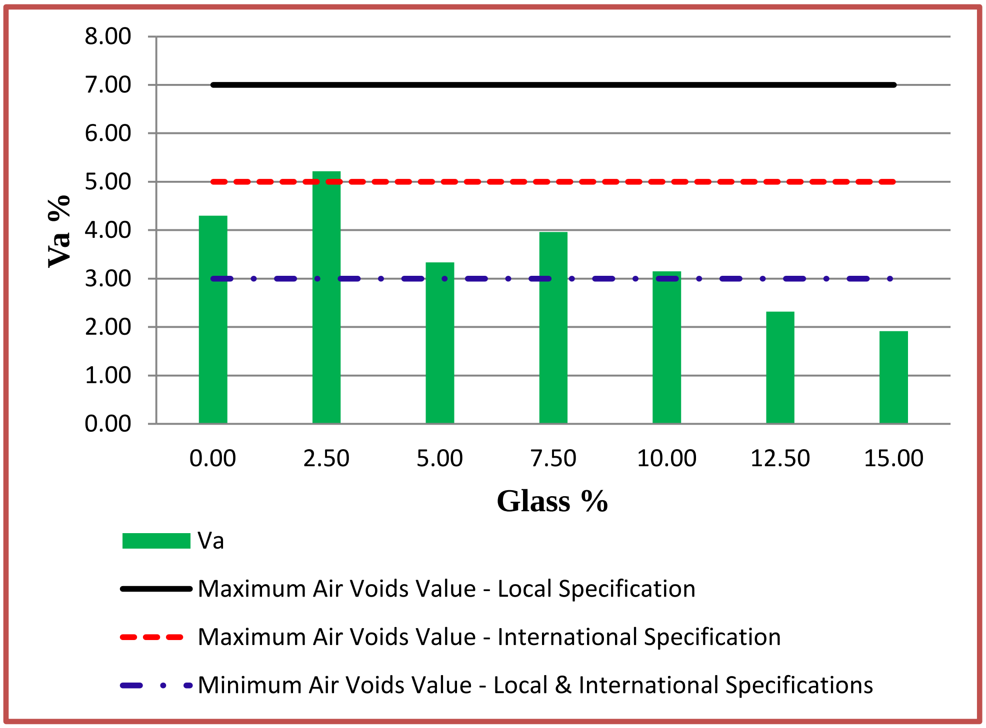

Figure (4.13): *Asphalt mix air voids – Glass content relationship*

4.5.5 Summary of Glasphalt properties

Table (4.13) summarizes the properties of glasphalt with different glass content.

Table (4.13): *Properties of mixtures with different glass content*

Property	Glass content %					
	2.5	5	7.5	10	12.5	15
Stability (KN)	1325.29	1336.39	1464.56	1331.44	1294.96	1276.20
Flow (mm)	3.06	2.82	3.65	2.74	2.88	2.54
Bulk Density (gm\cm^3)	2.33	2.36	2.34	2.36	2.37	2.36
% of Voids in Total Mix (Va %)	5.22	3.34	3.96	3.15	2.32	1.92
% of Voids in Mineral Agg. (V.M.A %)	16.76	15.02	15.56	14.83	14.07	13.62
% of Voids Filled with Binder (V.F.B%)	68.91	77.80	74.56	78.75	83.59	85.96

4.6 Optimum Glass Content

From Figure (4.10) it’s noticed that all values of Marshall Stability for different glass content satisfy the local and international specifications which are (900-817) kg respectively and the maximum stability corresponds 7.5% glass content. Figure (4.13) represents the air voids percentage at different glass content. And it’s noticed from the figure that at 7.5% glass content the corresponding air voids value -which is 4%- is very close to the median air voids in the specifications and it’s the same as the air voids value that is used to determine the OBC. From Figure (4.12) it’s noticed that all the values of bulk density at different glass content are very close to each other and all of them achieve the local and international specifications requirements. Table (4.14) illustrates a comparison of the mechanical properties of glasphalt containing 7.5% glass content with the local specifications -Municipality of Gaza (MOG)- and the international specifications -Asphalt Institute.

Table (4.14): *Comparison of Glasphalt mix with optimum content and specifications range*

Property	**Glass content 7.5 %**	**Local Spec. (MOG, 1998)**		**International Spec. (Asphalt Institute, 1997)**	
		Min	***Max***	***Min***	***Max***
Stability (KN)	1464.56	900	*	817	*
Flow (mm)	3.65	2	4	2	3.5
Bulk Density (gm\cm^3)	2.34	2.3	*	2.3	*
% of Voids in Total Mix (Va %)	3.96	3	7	3	5
% of Voids in Mineral Agg. (V.M.A %)	15.56	13.5	*	13	*

As obviously shown in Table (4.14) the glasphalt mix with optimum glass content 7.5% by weight of aggregates satisfies the requirements of Municipality of Gaza (MOG) specifications, and Asphalt Institute specifications for all tested properties.

Chapter 5. Conclusion and Recommendation

5.1 Conclusion

The objective of this study is to investigate the effect of using crushed waste glass as coarse sand and filler in the Asphalt Binder Course, where the results can be concluded as the following:

- The existence of crushed glass in the asphalt binder course mixture is considered as an eco-friendly material and it can be utilized as a sustainable management of waste glass.
- Crushed waste glass can be used in asphalt binder course with the maximal size of 4.75mm and the optimum replacement 7.5% of trabia (0/4.75) aggregate.
- The results of Marshall stability, flow, bulk density and air voids of glasphalt are consistent with the specifications range at the different percentages of glass contents (2.5% - 15%), except the flow values at 12.5 and 15 % its below the minimum specifications limit.
- Marshall Stability and the bulk density achieve the local and international specifications requirements with 7.5% glass content.
- At 7.5% glass content the value of flow consistent with the local specification and slightly higher than the maximum limit of the international specification.
- Air voids will be within the local and international specifications at 7.5% glass content.
- The results of this study apply only to the specific gradation and the type of glass that were used. Other gradations of glass or resources may produce different results.

5.2 Recommendations

- Further studies are needed using various glass gradation and different percentages of glass content.
- More studies are needed to study the effect of glass in base course and wearing course layers of asphalt pavement.
- It’s recommended to evaluate using crushed waste glass from other products like cathode ray tubes, fluorescent light tubes and laboratory glassware etc.
- Investigate the effects of using waste glass incorporate with other waste material

such as plastic or iron filings on the asphalt pavement properties.

- It is recommended for the local authorities to permit using crushed waste glass in asphalt pavements depending on the results of this research and other researches, and to encourage using recycled materials in construction fields.
- It's recommended to encourage the field application and evaluation to find out the performance of hot mix asphalt containing waste materials.

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Appendices

Appendix (A)

Physical properties and sieve analysis of aggregates

Aggregates physical properties

1. Specific gravity (ASTM C127) and absorption (ASTM C128)

Where,

A = Weight of oven-dry sample in air, gram

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

C = Weight of saturated sample in water, gram

- ***Coarse aggregate (Folia 0/19)***

$$\boldsymbol{A = 395.2\ gram},\ \ \boldsymbol{B = 4045.34\ gram}\ \&\ C = 2468.13\ gram$$

  - Bulk dry S.G $= \frac{A}{B-C} = 2.51$
  - SSD S.G $= \frac{B}{B-C} = 2.56$
  - Apparent S.G $= \frac{A}{A-C} = 2.66$
  - Effective S.G $= \frac{Bulk(dry) + Apparent}{2} = \frac{2.51 + 2.66}{2} = 2.58$
  - Absorption $= \frac{(B-A)}{A} * 100 = 2.38\%$

- ***Coarse aggregate (Adasia 0/12.5)***

$$\boldsymbol{A = 3154.8\ \ gram},\ \ \boldsymbol{B = 3233.27\ gram}\ \&\ C = 1965.03\ gram$$

  - Bulk dry S.G $= \frac{A}{B-C} = 2.49$
  - SSD S.G $= \frac{B}{B-C} = 2.55$

- $\text{Apparent S.G} = \frac{A}{A-C} = 2.65$
- $\text{Effective S.G} = \frac{Bulk(dry) + Apparent}{2} = \frac{2.51+2.66}{2} = 2.57$
- $\text{Absorption} = \frac{(B-A)}{A} * 100 = 2.49\%$

- ***<u>Coarse Aggregate (Simsimia 0/9.5)</u>***

$$\boldsymbol{A = 1014.1\ gram},\ \boldsymbol{B = 1042.1\ gram}\ \&\ C = 642.86\ gram$$

- $\text{Bulk dry S.G} = \frac{A}{B-C} = 2.54$
- $\text{SSD S.G} = \frac{B}{B-C} = 2.61$
- $\text{Apparent S.G} = \frac{A}{A-C} = 2.73$
- $\text{Effective S.G} = \frac{Bulk(dry) + Apparent}{2} = \frac{2.51+2.66}{2} = 2.64$
- $\text{Absorption} = \frac{(B-A)}{A} * 100 = 2.79\%$

2. <u>Abrasion value (ASTM C131)</u>

Grade (B)

Passing sieve 19mm (3/4”) Retained on 12.5 mm (1/2”) = 2500 gr

Passing seive 12.5mm (1/2”) Retained on 9.5mm (3/8”) = 2500 gr

A = Original sample weight = 5000 gr

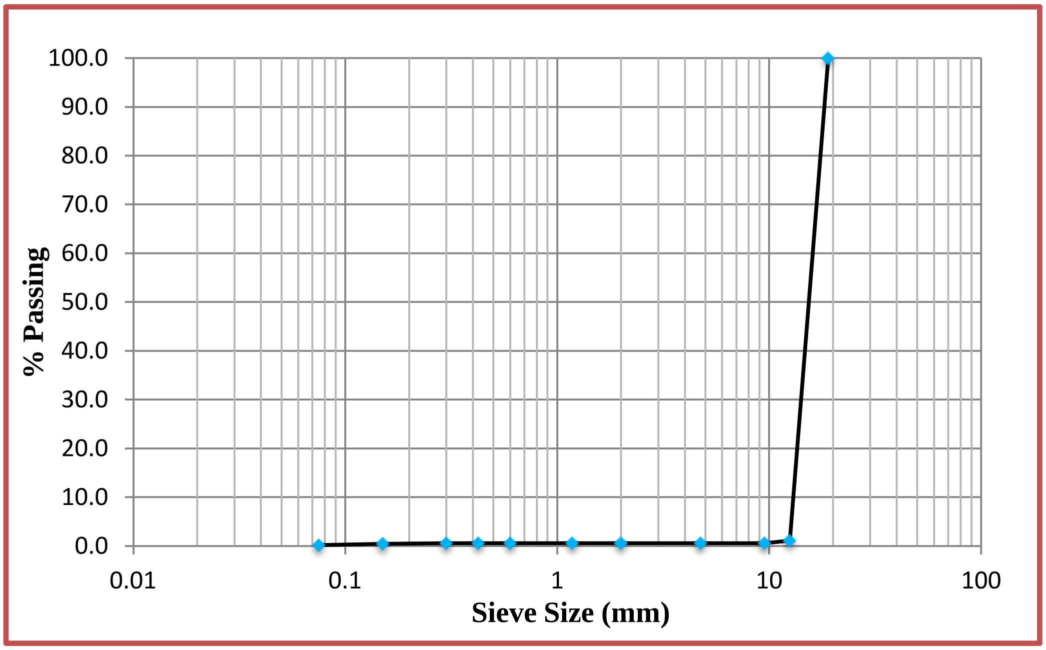
B = Weight retained on the 1.7mm sieve = 3880 gr

$$\text{A.V} = \frac{A-B}{A} * 100 = 22.4\%$$

Aggregates Sieve analysis

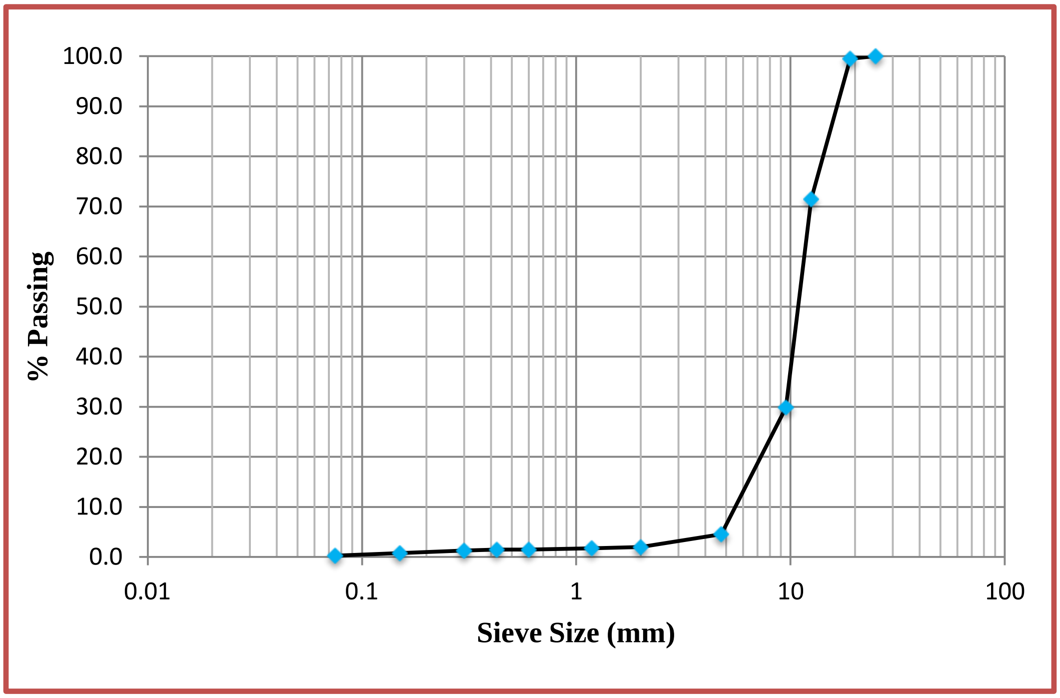
Folia (0/19)

Sieve size (mm)	Sieve #	Cumulative retained (g)	Cumulative retained (%)	Sample passing (%)
25	**1"**	0	0.0	100.0
19	**3/4"**	0	0.0	100.0
12.5	**1/2"**	1810	98.9	1.1
9.5	**3/8"**	1820	99.5	0.5
4.75	**#4**	1820	99.5	0.5
2	**#8**	1820	99.5	0.5
1.18	**#16**	1820	99.5	0.5
0.6	**#30**	1820	99.5	0.5
0.425	**#40**	1820	99.5	0.5
0.3	**#50**	1820	99.5	0.5
0.15	**#100**	1822	99.6	0.4
0.075	**#200**	1827	99.8	0.2
Pan	**Pan**	1830	100.0	0.0



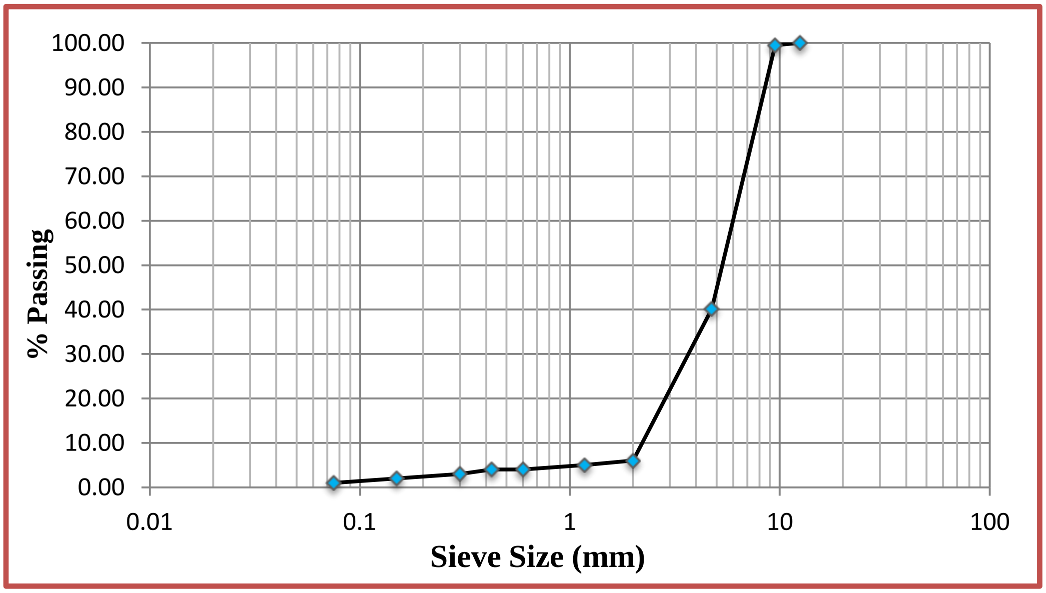
Adasia (0/12.5)

Sieve size (mm)	Sieve #	Cumulative retained (g)	Cumulative retained (%)	Sample passing (%)
25	**1"**	0	0.0	100.0
19	**3/4"**	10	0.5	99.5
12.5	**1/2"**	570	28.6	71.4
9.5	**3/8"**	1400	70.2	29.8
4.75	**#4**	1905	95.5	4.5
2	**#8**	1955	98.0	2.0
1.18	**#16**	1960	98.2	1.8
0.6	**#30**	1965	98.5	1.5
0.425	**#40**	1965	98.5	1.5
0.3	**#50**	1970	98.7	1.3
0.15	**#100**	1980	99.2	0.8
0.075	**#200**	1990	99.7	0.3
Pan	**Pan**	1995	100.0	0.0



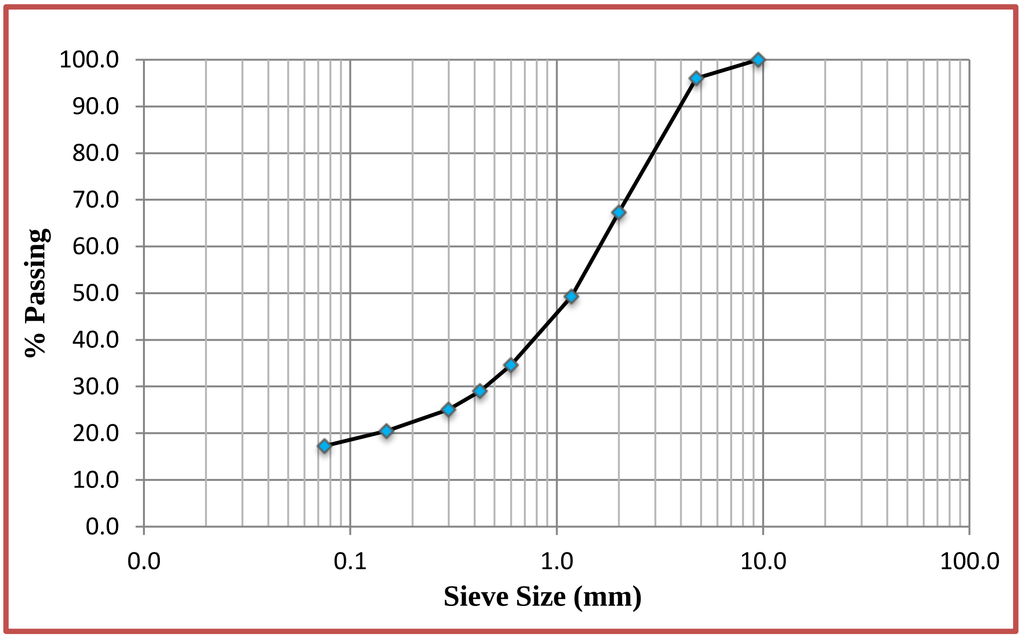
Simsimia (0/12.5)

Sieve size (mm)	Sieve #	Cumulative retained (g)	Cumulative retained (%)	Sample passing (%)
25	**1"**	0	0.0	100.00
19	**3/4"**	0	0.0	100.00
12.5	**1/2"**	0	0.0	100.00
9.5	**3/8"**	5	0.5	99.50
4.75	**#4**	595	59.8	40.20
2	**#8**	935	94.0	6.03
1.18	**#16**	945	95.0	5.03
0.6	**#30**	955	96.0	4.02
0.425	**#40**	955	96.0	4.02
0.3	**#50**	965	97.0	3.02
0.15	**#100**	975	98.0	2.01
0.075	**#200**	985	99.0	1.01
Pan	**Pan**	995	100.0	0.00



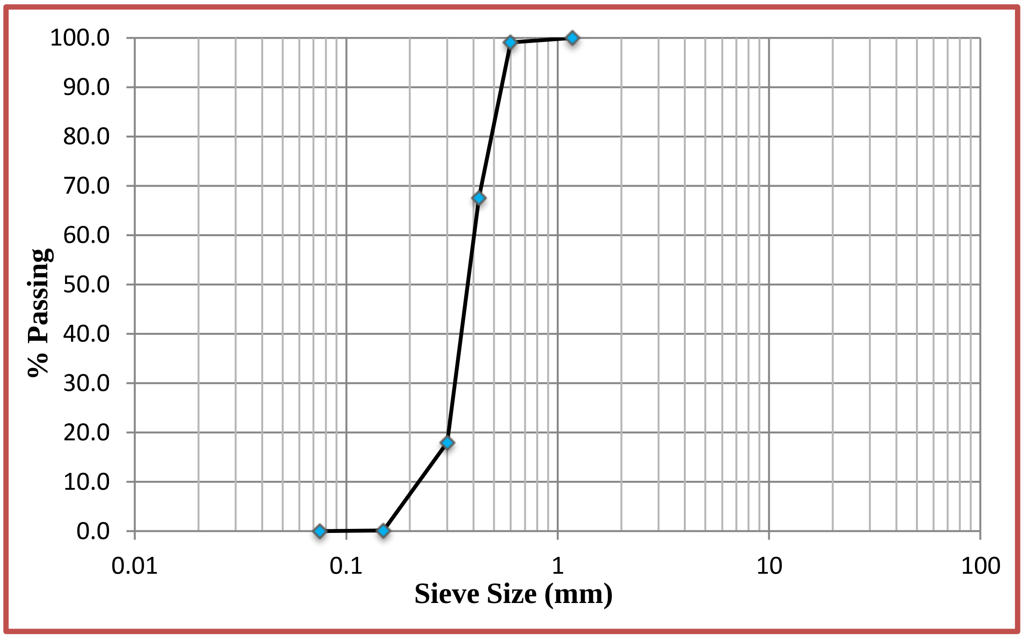
Trabia (0/4.75)

Sieve size (mm)	Sieve #	Cumulative retained (g)	Cumulative retained (%)	Sample passing (%)
25.0	**1"**	0.0	0.0	100.0
19.0	**3/4"**	0.0	0.0	100.0
12.5	**1/2"**	0.0	0.0	100.0
9.5	**3/8"**	0.0	0.0	100.0
4.75	**#4**	28.1	4.0	96.0
2.00	**#8**	228.7	32.6	67.4
1.180	**#16**	354.9	50.7	49.3
0.60	**#30**	457.8	65.4	34.6
0.425	**#40**	497.5	71.0	29.0
0.300	**#50**	524.8	74.9	25.1
0.150	**#100**	557.1	79.5	20.5
0.075	**#200**	579.4	82.7	17.3
Pan	**Pan**	700.5	100.0	0.0



Sand (0/0.6)

Sieve size (mm)	Sieve #	Cumulative retained (g)	Cumulative retained (%)	Sample passing (%)
25	**1"**	0.0	0.0	100.0
19	**3/4"**	0.0	0.0	100.0
12.5	**1/2"**	0.0	0.0	100.0
9.5	**3/8"**	0.0	0.0	100.0
4.75	**#4**	0.0	0.0	100.0
2	**#8**	0.0	0.0	100.0
1.18	**#16**	0.0	0.0	100.0
0.6	**#30**	4.8	1.0	99.0
0.425	**#40**	162.0	32.4	67.6
0.3	**#50**	409.8	82.0	18.0
0.15	**#100**	499.0	99.8	0.2
0.075	**#200**	499.6	100.0	0.0
Pan	**Pan**	499.8	100.0	0.0



Appendix (B)

Aggregates Blending

Suggested percentages for binder course aggregates mix

Aggregate	**Grain size (mm)**												**Suggested percent for final agg. mix**
	<0.075	**0.075/0.15**	**0.15/0.3**	**0.3/0.425**	**0.425/0.6**	**0.6/1.18**	**1.18/2.36**	**2.36/4.75**	**4.75/9.5**	**9.5/12.5**	**12.5/19**	**19/25**	
Filler	61.4	34.6	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Sand (0/0.6)	0.0	0.1	17.8	49.6	31.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0
	0.0	0.0	1.1	3.0	1.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	
Trabia (0/4.75)	17.3	3.2	4.6	3.9	5.7	14.7	18.0	28.6	4.0	0.0	0.0	0.0	34.0
	5.9	1.1	1.6	1.3	1.9	5.0	6.1	9.7	1.4	0.0	0.0	0.0	
Simsimia (0/9.5)	1.0	1.0	1.0	1.0	0.0	1.0	1.0	34.2	59.3	0.5	0.0	0.0	27.0
	0.3	0.3	0.3	0.3	0.0	0.3	0.3	9.2	16.0	0.1	0.0	0.0	
Adasia (0/12.5)	0.3	0.5	0.5	0.3	0.0	0.3	0.3	2.5	25.3	41.6	28.1	0.5	19.0
	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.5	4.8	7.9	5.3	0.1	
Folia (0/19)	0.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.5	98.8	0.0	14.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	13.8	0.0	
Sum	6.2	1.5	3.0	4.6	3.8	5.4	6.4	19.4	22.2	8.1	19.2	0.1	100.0
% passing	6.24	7.74	10.75	15.38	19.21	24.59	31.04	50.47	72.65	80.76	99.93	100.00	
Sieve size (mm)	0.075	0.15	0.3	0.425	0.6	1.18	2	4.75	9.5	12.5	19	25	ASTM Specifications D 3515 - 01
Binder 0/19 (min)	2	3	5	6	8	15	23	35	56	67	90	100	
(max)	8	14	19	22	26	37	49	65	80	85	100	100	

Appendix (C)

Binder Course Job Mix

Used Equations to calculate the mechanical properties of asphalt mix

$$V_a = \frac{\rho_{bit} - \rho_A}{\rho_{bit}} \times 100\%$$

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

$$\% VMA = V_a + V_b$$

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

Where,

V_b : Percent bitumen volume.

V_a : Air voids contents in total mix.

m_b : Percent of Bitumen.

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

d_{25} : Density of Bitumen at 25^{o}C.

ρ_{bit} : Max. Theoretical density.

VMA : Voids in mineral Aggregates.

VFB : Voids filled with bitumen

Marshal tests results with different bitumen contents

- Bitumen content = 4.0 % (By weight of the mix)
- Number of blows on each side : 75 blow
- Mixing temperature : 150 ºC
- Bitumen grade: 70/80

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1209.14	1208.07	1211.51	1209.57
Weight in water (gm)	692.2	685.7	696.5	691.47
SSD weight (gm)	1214.84	1214.61	1219.25	1216.23
Bulk volume (cm3)	522.64	528.91	522.75	524.77
Density of compacted mix ρA (g/cm3)	2.31	2.28	2.32	2.31
Max. theoretical density ρbit (g/cm3)	2.50	2.50	2.50	2.50
Average sample hight (mm)	66.3	67.7	66.7	66.9
Stability read value	1314	1263	1210	1262.33
Stability (Kg)	1629.36	1566.12	1500.4	1565.29
Stability correction factor	0.9314	0.902	0.9226	0.919
Corrected stability (Kg)	1517.59	1412.64	1384.27	1438.17
Flow (mm)	3.37	3.13	2.47	2.99
Stiffness (Kg/mm)	450.58	451.15	559.75	480.87
Air voids content in total mix Va (%)	7.46	8.64	7.30	7.80
Percent bitumen volume Vb (%)	9.03	8.91	9.04	9.00
Voids in mineral Agg. (VMA) (%)	16.49	17.55	16.34	16.79
Voids fill with bitumen (VFB) (%)	54.76	50.79	55.35	53.63

- Bitumen content = 4.5 % (By weight of the mix)
- Number of blows on each side : 75 blow
- Mixing temperature : 150 ºC
- Bitumen grade: 70/80

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1203.47	1212.18	1202.77	1206.14
Weight in water (gm)	694.71	694.91	690.9	693.51
SSD weight (gm)	1208.04	1216.73	1205.66	1210.14
Bulk volume (cm3)	513.33	521.82	514.76	516.64
Density of compacted mix ρA (g/cm3)	2.34	2.32	2.34	2.33
Max. theoretical density ρbit (g/cm3)	2.48	2.48	2.48	2.48
Average sample hight (mm)	65.3	66.0	65.0	65.4
Stability read value	1310	1190	1210	1236.67
Stability (Kg)	1624.4	1475.6	1500.4	1533.47
Stability correction factor	0.9548	0.938	0.962	0.952
Corrected stability (Kg)	1550.98	1384.11	1443.38	1459.49
Flow (mm)	3.58	2.87	2.52	2.99
Stiffness (Kg/mm)	432.78	481.60	571.91	487.50
Air voids content in total mix Va (%)	5.52	6.38	5.83	5.91
Percent bitumen volume Vb (%)	9.15	9.07	9.12	9.11
Voids in mineral Agg. (VMA) (%)	14.67	15.45	14.95	15.02
Voids fill with bitumen (VFB) (%)	62.38	58.69	60.98	60.69

- Bitumen content = 5.0 % (By weight of the mix)
- Number of blows on each side : 75 blow
- Mixing temperature : 150 ºC
- Bitumen grade: 70/80

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1214.31	1219.87	1199.10	1211.09
Weight in water (gm)	703.1	702.14	691.17	698.80
SSD weight (gm)	1218.82	1222.32	1200.29	1213.81
Bulk volume (cm3)	515.72	520.18	509.12	515.01
Density of compacted mix ρA (g/cm3)	2.35	2.35	2.36	2.35
Max. theoretical density ρbit (g/cm3)	2.46	2.46	2.46	2.46
Average sample hight (mm)	66.0	66.3	64.7	65.7
Stability read value	1243	1312	1274	1276.33
Stability (Kg)	1541.32	1626.88	1579.76	1582.65
Stability correction factor	0.938	0.9314	0.9695	0.946
Corrected stability (Kg)	1445.76	1515.28	1531.58	1497.54
Flow (mm)	2.99	3.34	3.13	3.15
Stiffness (Kg/mm)	483.48	453.04	489.53	474.72
Air voids content in total mix Va (%)	4.40	4.78	4.37	4.52
Percent bitumen volume Vb (%)	9.19	9.15	9.19	9.18
Voids in mineral Agg. (VMA) (%)	13.59	13.94	13.56	13.70
Voids fill with bitumen (VFB) (%)	67.62	65.67	67.76	67.02

- Bitumen content = 5.5 % (By weight of the mix)
- Number of blows on each side : 75 blow
- Mixing temperature : 150 ºC
- Bitumen grade: 70/80

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1223.80	1198.31	1200.15	1207.42
Weight in water (gm)	704.46	691.25	688.12	694.61
SSD weight (gm)	1226	1199.65	1202.32	1209.32
Bulk volume (cm3)	521.54	508.4	514.2	514.71
Density of compacted mix ρA (g/cm3)	2.35	2.36	2.33	2.35
Max. theoretical density ρbit (g/cm3)	2.44	2.44	2.44	2.44
Average sample hight (mm)	65.7	63.9	64.7	64.8
Stability read value	1372	1105	1046	1174.33
Stability (Kg)	1701.28	1370.2	1297.04	1456.17
Stability correction factor	0.9452	0.9896	0.9695	0.968
Corrected stability (Kg)	1608.05	1355.95	1257.48	1407.16
Flow (mm)	3.50	3.39	2.83	3.24
Stiffness (Kg/mm)	459.92	399.89	444.07	434.36
Air voids content in total mix Va (%)	4.02	3.59	4.53	4.05
Percent bitumen volume Vb (%)	9.16	9.20	9.11	9.15
Voids in mineral Agg. (VMA) (%)	13.18	12.79	13.64	13.20
Voids fill with bitumen (VFB) (%)	69.49	71.92	66.77	69.39

- Bitumen content = 6.0 % (By weight of the mix)
- Number of blows on each side : 75 blow
- Mixing temperature : 150 ºC
- Bitumen grade: 70/80

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1197.17	1199.55	1203.64	1200.12
Weight in water (gm)	685.1	686.8	688.18	686.69
SSD weight (gm)	1198.13	1200.34	1204.73	1201.07
Bulk volume (cm3)	513.03	513.54	516.55	514.37
Density of compacted mix ρA (g/cm3)	2.33	2.34	2.33	2.33
Max. theoretical density ρbit (g/cm3)	2.43	2.43	2.43	2.43
Average sample hight (mm)	63.3	64.0	64.4	63.9
Stability read value	1245	1103	1062	1136.67
Stability (Kg)	1543.8	1367.72	1316.88	1409.47
Stability correction factor	1.0052	0.987	0.977	0.990
Corrected stability (Kg)	1551.83	1349.94	1286.59	1396.12
Flow (mm)	4.26	4.08	4.21	4.18
Stiffness (Kg/mm)	364.42	330.98	305.41	333.74
Air voids content in total mix Va (%)	3.85	3.76	3.99	3.87
Percent bitumen volume Vb (%)	9.11	9.12	9.09	9.11
Voids in mineral Agg. (VMA) (%)	12.96	12.87	13.08	12.97
Voids fill with bitumen (VFB) (%)	70.28	70.82	69.50	70.20

Determination of the maximum theoretical density for the asphalt mix

Calculation of the theoretical asphalt mix density it can be done by using the Pycnometer or by calculation using specific gravities for all aggregates. In this research the calculation method was used to find out the theoretical density of the asphalt mix.

Calculation method:

$$\boxed{\rho_{\min} = \frac{100}{\frac{m_1}{\rho_{\min 1}} + \frac{m_2}{\rho_{\min 2}} + \ldots\ldots + \frac{m_n}{\rho_{\min n}}}} \qquad \boxed{\rho_{bit} = \frac{100}{\frac{m_b}{d_{25}} + \frac{100 - m_b}{\rho_{\min}}}}$$

Where,

ρ_{bit} : Max. Theoretical density.

m_b : % of bitumen by total mix.

d_{25} : Density of bitumen.

m_1 : The percentage of aggregate type (1) in the aggregates blend.

$\rho_{\min 1}$: Density of aggregate type (1).

Aggregate type	Percentage in aggregate mix m %	Aggregate density ρ_{min} (g/cm^3)	m / ρ_{min}
Folia (0/19)	14.0	2.58	12.32
Adasia (0/12.5)	19.0	2.57	2.26
Simsimia (0/9.5)	27.0	2.64	10.23
Trabiah (0/4.75)	34.0	2.76	7.39
Sand (0/0.6)	6.0	2.65	5.43
Sum			**37.63**

- ***Effective Specific gravity for aggregate mix ρ_{min} = 100 / 37.63 = 2.66 (g/cm^3)***

Bitumen percentage *mb* %	Bitumen density d_{25} (g/cm^3)	Aggregate blend density ρ_{min} (g/cm^3)	Max. Theoretical density ρ_{bit} (g/cm^3)
4	1.025	2.66	2.50
4.5	1.025	2.66	2.48
5	1.025	2.66	2.46
5.5	1.025	2.66	2.44
6	1.025	2.66	2.43

Appendix (D)

Glasphalt mix tests results

Marshal tests results with different glass contents

- Glass content = 2.5% (By weight of total aggregates)
- No. of blows on each side : 75 blow
- 3/4" binder course mix
- Bitumen = 5.1 % (By total weight)
- Mixing temperature: 150 ºC

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1195.53	1203.30	1202.16	1200.33
Weight in water (gm)	688.08	687.7	686.65	687.48
SSD weight (gm)	1197.4	1205.2	1204.95	1202.52
Bulk volume (cm3)	509.32	517.5	518.3	515.04
Density of compacted mix ρA (g/cm3)	2.35	2.33	2.32	2.33
Max. theoretical density ρbit (g/cm3)	2.46	2.46	2.46	2.46
Average sample hight (mm)	64	65	65.7	64.9
Stability read value	1160	1066	1096	1107.33
Stability (Kg)	1438.4	1321.84	1359.04	1373.09
Stability correction factor	0.987	0.962	0.9452	0.965
Corrected stability (Kg)	1419.7	1271.61	1284.56	1325.29
Flow (mm)	2.73	3.08	3.38	3.06
Stiffness (Kg/mm)	519.79	413.41	379.92	437.71
Air voids content in total mix Va (%)	4.54	5.44	5.68	5.22
Percent bitumen volume Vb (%)	11.62	11.51	11.48	11.54
Voids in mineral Agg. (VMA) (%)	16.16	16.95	17.16	16.76
Voids fill with bitumen (VFB) (%)	71.9	67.91	66.92	68.91

- Glass content = 5.0 % (By weight of total aggregates)
- No. of blows on each side : 75 blow
- 3/4" binder course mix
- Bitumen = 5.1 % (By total weight)
- Mixing temperature: 150 ºC

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1195.16	1195.49	1199.12	1196.59
Weight in water (gm)	688.35	691.55	682.7	690.87
SSD weight (gm)	1196.59	1196.33	1201.71	1198.21
Bulk volume (cm3)	508.24	504.78	509.01	507.34
Density of compacted mix ρA (g/cm3)	2.35	2.37	2.36	2.36
Max. theoretical density ρbit (g/cm3)	2.44	2.44	2.44	2.44
Average sample hight (mm)	64	63.7	64.3	64
Stability read value	1078	1127	1070	1091.67
Stability (Kg)	1336.72	1397.48	1326.8	1353.67
Stability correction factor	0.987	0.9948	0.9795	0.987
Corrected stability (Kg)	1319.34	1390.21	1299.60	1336.39
Flow (mm)	2.81	2.48	3.17	2.82
Stiffness (Kg/mm)	469.25	559.47	409.52	479.41
Air voids content in total mix Va (%)	3.62	2.94	3.45	3.34
Percent bitumen volume Vb (%)	11.64	11.73	11.66	11.68
Voids in mineral Agg. (VMA) (%)	15.27	14.66	15.12	15.02
Voids fill with bitumen (VFB) (%)	76.26	79.79	77.17	77.80

- Glass content = 7.5 % (By weight of total aggregates)
- No. of blows on each side : 75 blow
- 3/4" binder course mix
- Bitumen = 5.1 % (By total weight)
- Mixing temperature: 150 ºC

Test	**Samples Results**			**Average**
	1	**2**	**3**	
Weight of sample in air (g)	1191.97	1197.28	1202.04	1197.10
Weight in water (gm)	686.8	687.75	688.6	687.72
SSD weight (gm)	1193.83	1198.84	1203.7	1198.79
Bulk volume (cm3)	507.03	511.09	5015.1	511.07
Density of compacted mix ρA (g/cm3)	2.35	2.34	2.33	2.34
Max. theoretical density ρbit (g/cm3)	2.44	2.44	2.44	2.44
Average sample hight (mm)	64	64	65	64.3
Stability read value	1209	1148	1265	1207.33
Stability (Kg)	1499.16	1423.52	1568.6	1497.09
Stability correction factor	0.987	0.987	0.962	0.979
Corrected stability (Kg)	1479.67	1405.01	1508.99	1464.56
Flow (mm)	4.08	2.72	4.14	3.65
Stiffness (Kg/mm)	362.73	516.15	364.63	414.50
Air voids content in total mix Va (%)	3.61	3.95	4.32	3.96
Percent bitumen volume Vb (%)	11.64	11.60	11.55	11.60
Voids in mineral Agg. (VMA) (%)	15.25	15.55	15.88	15.56
Voids fill with bitumen (VFB) (%)	76.31	74.59	72.78	74.56

- Glass content = 10 % (By weight of total aggregates)
- No. of blows on each side : 75 blow
- 3/4" binder course mix
- Bitumen = 5.1 % (By total weight)
- Mixing temperature: 150 ºC

Test	**Samples Results**			**Average**
	1	**2**	**3**	
Weight of sample in air (g)	1199.67	1200.05	1204.24	1200.32
Weight in water (gm)	691.64	692.86	692.7	692.40
SSD weight (gm)	1201.1	1201.22	1201.85	1201.39
Bulk volume (cm3)	509.46	508.36	509.15	508.99
Density of compacted mix ρA (g/cm3)	2.35	2.36	2.36	2.36
Max. theoretical density ρbit (g/cm3)	2.44	2.44	2.44	2.44
Average sample hight (mm)	64.3	64.3	64	64.2
Stability read value	1045	1107	1128	1039.33
Stability (Kg)	1295.8	1372.68	1398.72	1355.73
Stability correction factor	0.9759	0.9759	0.987	0.982
Corrected stability (Kg)	1269.24	1344.54	1380.54	1331.44
Flow (mm)	2.8	2.84	2.59	2.74
Stiffness (Kg/mm)	453.76	472.84	533.96	486.85
Air voids content in total mix Va (%)	3.29	3.05	3.11	3.15
Percent bitumen volume Vb (%)	11.66	11.69	11.68	11.68
Voids in mineral Agg. (VMA) (%)	14.95	14.74	14.79	14.83
Voids fill with bitumen (VFB) (%)	77.97	79.28	78.98	78.75

- Glass content = 12.5 % (By weight of total aggregates)
- No. of blows on each side : 75 blow
- 3/4" binder course mix
- Bitumen = 5.1 % (By total weight)
- Mixing temperature: 150 ºC

Test	**Samples Results**			**Average**
	1	**2**	**3**	
Weight of sample in air (g)	1204.70	1196.15	1195.62	1198.82
Weight in water (gm)	694.8	694.57	695.19	694.85
SSD weight (gm)	1025.71	1197.37	1196.72	1199.93
Bulk volume (cm3)	510.91	502.8	501.53	505.08
Density of compacted mix ρA (g/cm3)	2.36	2.38	2.38	2.37
Max. theoretical density ρbit (g/cm3)	2.43	2.43	2.43	2.43
Average sample hight (mm)	64.3	63	63	63.4
Stability read value	1035	1010	1082	1042.33
Stability (Kg)	1283.4	1252.4	1341.68	1292.49
Stability correction factor	0.9795	1.013	1.013	1.002
Corrected stability (Kg)	1257.09	1268.68	1359.12	1294.96
Flow (mm)	2.52	3.22	2.89	2.88
Stiffness (Kg/mm)	499.82	393.59	470.47	454.63
Air voids content in total mix Va (%)	2.97	2.1	1.9	2.32
Percent bitumen volume Vb (%)	11.68	11.78	11.8	11.75
Voids in mineral Agg. (VMA) (%)	14.64	13.88	13.70	14.07
Voids fill with bitumen (VFB) (%)	79.75	84.87	86.17	83.59

- Glass content = 15 % (By weight of total aggregates)
- No. of blows on each side : 75 blow
- 3/4" binder course mix
- Bitumen = 5.1 % (By total weight)
- Mixing temperature: 150 ºC

Test	Samples Results			Average
	1	2	3	
Weight of sample in air (g)	1207.00	1203.46	1204.18	1204.88
Weight in water (gm)	697.54	696.24	694.08	695.95
SSD weight (gm)	1207.8	1204.1	1205.76	1205.89
Bulk volume (cm3)	510.26	507.86	511.68	509.93
Density of compacted mix ρA (g/cm3)	2.37	2.37	2.35	2.36
Max. theoretical density ρbit (g/cm3)	2.41	2.41	2.41	2.41
Average sample hight (mm)	64.3	64	65	64.4
Stability read value	1071	1003	1090	1054.67
Stability (Kg)	1328.04	1243.72	1351.6	1307.76
Stability correction factor	0.9795	0.987	0.962	0.976
Corrected stability (Kg)	1300.82	1227.55	1300.24	1276.20
Flow (mm)	2.19	2.74	2.69	2.54
Stiffness (Kg/mm)	595.26	447.85	483.29	508.80
Air voids content in total mix Va (%)	1.81	1.63	2.31	1.92
Percent bitumen volume Vb (%)	11.71	11.73	11.65	11.70
Voids in mineral Agg. (VMA) (%)	13.52	13.37	13.96	13.62
Voids fill with bitumen (VFB) (%)	86.63	87.78	83.46	85.96

Determination of the maximum theoretical density for the Glasphalt mix

Pycnometer method

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

(W_s) = Weight of the asphalt sample

(W_{s+P+W}) = Weight of Pycnometer filled with water and the crushed sample

$$\rho_{bit} = \frac{W_s}{W_s - (W_{s+p+w} - W_{p+w})}$$

% Glass	W_{P+W} (g)	W_s (g)	W_{s+P+W} (g)	ρ_{bit} (g/cm^3)
2.5	1783.34	450.73	2050.75	2.46
5	1783.34	475.63	2064.07	2.44
7.5	1783.34	475.38	2063.84	2.44
10	1783.34	452.40	2050.65	2.44
12.5	1783.34	478.00	2065.33	2.43
15	1783.34	464.09	2054.47	2.41

Appendix (E)

Photos

Figure (F.1): *Aggregates source* **-** *Al-Amal Factory*

Figure (F.2): *Used waste glass source*

Figure (F.3): *Waste glass sieve analysis*

Figure (F.4): *Used Aggregates*

	
Figure (F.5): *Marshal Samples*	**Figure (F.6):** *Removing Marshal samples molds after compaction*
	
Figure (F.7): *Marshal Samples weighting in air*	**Figure (F.8):** *Marshal Samples weighting in water*

	
Figure (F.9): *Glasphalt Marshal Samples*	**Figure (F.10):** *Water bath for Marshal Samples*
	
Figure (F.11): *Testing Marshal Samples for stability and flow*	**Figure (F.12):** *Measuring the theoretical density of asphalt mix using Pycnometer*