



**ADDIS ABABA UNIVERSITY  
ADDIS ABABA INSTITUTE OF TECHNOLOGY  
SCHOOL OF GRADUATE STUDIES  
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING**

**EXPERIMENTAL INVESTIGATION OF USE OF GLASS CULLET AS  
ASPHALT MIXTURE AGGREGATE**

**By Tewodros Nigatu**

A Thesis Submitted to School of Graduate Studies in Partial Fulfillment of the  
Requirement for Degree of Master of Science  
In  
Road and Transport Engineering

Advisor

**Dr. Bikila Teklu**

November, 2014

Addis Ababa, Ethiopia

Addis Ababa University  
School of Graduate Studies  
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## **DECLARATION**

I, the undersigned, declare that this thesis is my original work performed under the supervision of my research advisor Dr. Bikila Teklu and has not been presented as a thesis for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

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To  
W/O Atsede Bayu

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## **ABSTRACT**

Various studies have shown that replacement of natural aggregate by crushed waste glass on the performance of asphalt concrete pavements.

This study was intended to investigate the effect of using cullet asphalt concrete aggregate, derive the maximum allowable percentage and evaluate the economic advantage. Crushed glass with different percentages by total weight of the mixture was used in the study.

Cleaned and crushed, waste glass resulted from glass bottles has been added to the asphalt mixture using a gradation of (0/4.75) mm. Marshall Method was used to determine the Optimum Binder Content (OBC) and to evaluate the properties of the glasphalt mix. Using the different glass content at their respective optimum asphalt content, specimens were prepared to investigate moisture susceptibility of asphalt mixtures. The Marshal Immersion test method was adapted to determine the moisture effect of mixtures. In total, 130 samples were prepared, 100 of which have been used to determine the OBC for each glass content, and the rest have been used to find out the moisture susceptibility of different percentages of crushed waste glass in the asphalt mixture.

The results of the experiments (Marshall Stability, flow, specific gravity & air voids) are consistent to the local and international specifications, except the marshal stability reduction at 20% replacement rate. Crushed waste glass can be used in asphalt binder course with the maximal size of 4.75mm and the optimum replacement 15% glass.

### **Key Words**

Glasphalt, Cullet, Hot Mix Asphalt, Moisture susceptibility, Stripping, Asphalt, Marshall Mix design.

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## Abbreviations

AACRA	Addis Ababa City Road Authority
AAGBF	Addis Ababa Glass Bottle Factory SC
AASHTO	American Association of State Highway and Transportation Office
ASTM	American Society of Testing and Materials
DAT	Day Light Applied Technologies PLC
$G_{mb}$	Bulk specific gravity of the mixture
HMA	Hot mix asphalt
OBC	Optimum Bitumen Content
RCS	Retained Compressive Strength
TS	Transfer Stations
$TSR$	Tensile Strength Ration
$V_a$	Air Voids
$V_b$	Volume of asphalt binder
$V_{ba}$	Absorbed asphalt content
$V_{be}$	Volume of Effective asphalt content
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate
$P_b$	Asphalt content
$P_{ba}$	Absorbed asphalt binder
$P_{be}$	Effective asphalt binder content

# **INTRODUCTION**

## CHAPTER 1

### INTRODUCTION

#### **1.1 GENERAL**

Hot mix asphalt (HMA) pavements are being increasingly constructed in Ethiopia, as the government is allocating huge amount of resources to construct and upgrade the existing road network nationwide. However, with a greater understanding of the need for sustainable development, the use of fresh (primary) aggregate in the asphalt mixture layers of a road or airfield pavement is seen as a wasteful use of a finite natural resource. Recycling materials into high value added products is most desirable if it is economically feasible. In various developed countries, researches have been conducted to produce mixes with improved properties by altering the HMA constituting ingredients.

Thus, in the HMA mix design process, care must be exercised while selecting the type of ingredient materials and their relative proportion in the mixture. This will enable the mix designer to get the desired mixture property. Hot mix asphalt mix design is the process of determining appropriate proportion of the materials that would give long lasting performance paving mixture during its service life. It is a mixture of binder, aggregate, and air in different relative proportions that determine the physical properties of the mix and, ultimately, how the mix will perform as a finished pavement. Many different, and sometimes conflicting, performance demands are placed up on the asphalt mixtures and this makes it a complex material. Thus, the design of asphalt paving mixes is largely a matter of selecting and proportioning the ingredient materials to optimize all desired properties in the finished paved road [1]. The main objective in the design of HMA mixture is to determine cost effective proportion of ingredients in the mixture having the following properties.

- i. Durability:* The mix should provide adequate durability as a paved road, where it must not suffer excessive aging and hardening during production and service life.

- ii. Stability:* The mix must provide sufficient stability under traffic loading through its service life. The stability of a mixture under traffic load is the amount of resistance to deformation.
- iii. Fatigue resistance:* The mix, as a paved road, must resist cracking effects that may induced due to repeated traffic loading over time. The cracking of mixes under repeated traffic loading over time is referred to as fatigue cracking.
- iv. Air voids content:* There must be sufficient voids in the total compacted mix to allow for a slight amount of additional compaction under traffic loading and a slight amount of asphalt expansion due to temperature increases without flushing, bleeding, and loss of stability.
- v. Low temperature cracking:* HMA pavements may be subjected to high cooling rates during low temperature seasons. The low temperature develops tensile stress due to shrinkage which eventually develops transverse cracking when the tensile stress exceeds the fracture strength of the mix.
- i. Moisture damage resistance:* HMA must be resistant to moisture induced damages. This property is mainly influenced by the characteristics of aggregate with asphalt binder and air voids. Some aggregates are characterized as more water loving (hydrophilic). Bituminous mixtures containing water loving aggregates if subjected to water or moisture, adhesion between the aggregate and asphalt binder may loose (or weaken) and finally may result stripping.
- ii. Skid resistance:* HMA designed for surfacing should provide sufficient resistance to skidding.
- iii. Workability:* The mix must be capable to provide sufficient workability and hence permit efficient placement and compaction of the mix with reasonable effort without segregation, sacrificing stability, and performance.

By considering the above control objectives during HMA mix design process, well designed bituminous mixtures can be expected to serve successfully for many years under the variety of loading and environmental conditions. The most common methods used to go about HMA mix design are the Hveem, Marshall and Super pave methods. Using either mix design method, the final goal is to select a unique design asphalt content that could achieve a

balance among the various desired objectives. This means that there is no single asphalt content that will maximize all of the above objectives; instead, asphalt content is selected on the basis of optimizing the properties necessary for the specific conditions.

The performance of bituminous surfaced roads is directly affected by the proportion and quality of ingredient materials in the mixture. Different studies revealed that certain modifications in the mixture such as, changing the type, size and gradation of aggregate, varying the filler to asphalt ratio, type and amount of filler alter the physical properties of HMA concrete. [2]

The reuse of primary aggregates and/or the use of waste (secondary) materials are seen as being of benefit to society. Of the various waste streams, recycled crushed glass (cullet) can be considered sensible alternative source of aggregate for asphalt mixture production. Quite often these materials can replace expensive, and sometimes scarce, virgin aggregates. Factors other than material properties that foster interest in recycling are environmental issues, legislative activity, economics, and construction material shortages. [3]

This study was intended to evaluate the effect of use of glass cullet as asphalt mixture aggregate at various contents. The Marshal and moisture susceptibility tests were used to investigate the mixtures in the laboratory.

Different mixtures were prepared by varying contents of cullet in accordance with the Marshal Mix design procedure. Using the Marshal Mix design criteria for heavy traffic, optimum asphalt content was selected. Further test specimens were prepared at their optimum asphalt content in order to investigate the moisture susceptibility for conditioned and unconditioned mixtures.

## 1.2 PROBLEM STATEMENT

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. 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.

Addis Ababa city solid waste is estimated about 5,612.73m<sup>3</sup>/day. Glass constitutes around 0.5% (28.1m<sup>3</sup>/day) of municipal solid [4]. But till now there is no such use of recycled glass in Ethiopia.

However the utilization of glass cullet in civil engineering applications is an emerging market, subject to variability in costs of materials and contractors' perceptions of risk associated with glass cullet construction.

This study is conducted to investigate the effect of using crushed waste glass as coarse aggregate 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 Addis Ababa.

### **1.3 RESEARCH OBJECTIVES**

#### **A. General objective**

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

#### **B. The specific objectives of the project are:**

- To design replacement rates at which glass cullet can be effectively used.
- To experimentally investigate the effect of glass on asphalt concrete using Marshall Mix design and Marshal Immersion test.
- To analyze the economic advantage of using glass as asphalt mixture aggregate.

## 1.4 IMPORTANCE OF THE STUDY

- Using waste glass as coarse sand and filler in order to improve the Marshall properties of asphalt pavement.
- Reducing the amount of waste materials and the area of land used for landfill.
- Preservation of natural aggregate.
- Creating employment opportunities.

## 1.5 SCOPE AND LIMITATION

This study had a set of limitations and criteria that were taken into account during the experimental work. These limitations include:

- The research reported herein was focused on asphalt concrete characteristics such as the Marshall properties, stripping effect of cullet in asphalt concrete.
- The materials selected for this study were collected from different sources, i.e. aggregate only from AACRA (Addis Ababa City Road Authority) construction quarry and crusher site located at 'Augesta' around old airport and glass cullet from Addis Ababa Glass Bottle Factory. All these materials were tested in the laboratory and evaluated. The mixtures were prepared using different amount cullet.
- From different mix design and moisture susceptibility tests results produced in this research were based on Marshall Mix Design and Marshall Immersion test.
- Only crushed clean glass from white, amber, and green 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 aggregate, has 4.75mm maximum sieve size.

# **LITERATURE REVIEW**

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 INTRODUCTION

Asphalt is basically a mixture of natural raw materials: coarse and fine 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. [2]

Various studies have been conducted on the properties of HMA using minor changes on the ingredients of the mixture. In general the main objectives of the researches were to understand in a better way the characteristics of bituminous mixtures and evaluate the effects of constituent ingredients on the performance.

Among the various studies conducted, many were concerned on investigating effects of using glass on bituminous mixture performance. This is as the aggregate make up 90 to 95 percent by total weight of the mixture, they are a prime suspects influencing the performance of the mixture.

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.

The research herein with concentrates and builds on the Marshal Properties and moisture susceptibility of HMA mixtures prepared using different replacement rate of cullet on asphalt concrete aggregate content.

In this chapter, review of researches conducted on the effect of glass on HMA performance will be discussed.

## 2.2 ASPHALT CONCRETE PAVEMENT

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 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.

Asphalt concrete pavements are not a thin covering of asphalt concrete over soil, they are engineered structures composed of several different layers. Figure (2.1) illustrates a vertical section of flexible pavement structure.[5]

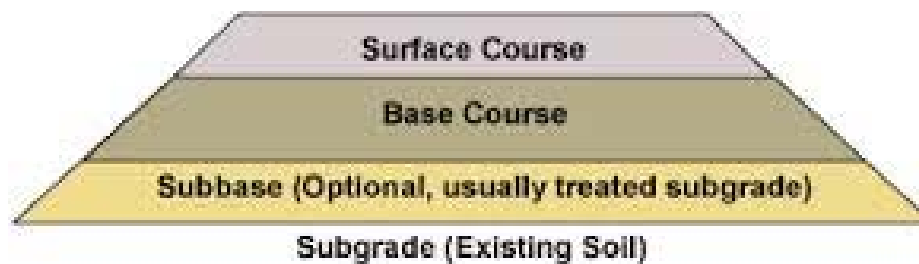


Figure 2.1 *Conventional flexible pavements*

## 2.3 BASIC PROCEDURE IN HMA MIX DESIGN

Hot-Mix-Asphalt mixture consists of two basic ingredients: mineral aggregate and asphalt binder. The process in HMA mix design involves determining what type of aggregate to use, what asphalt binder to use and what proportion of these two ingredients to use so as to achieve the desired bituminous mixture performance. HMA is a complex material where different, and sometimes conflicting, performance demands are placed. It must resist deformation and

cracking, be durable over time, resist water damage, and yet be inexpensive, readily made and easily placed.[6]

The most common methods used to go about this process are the Marshall, Hveem and Superpave methods. In general, all mix design methods involve manipulation of three basic variables: namely aggregate selection, asphalt binder choice and optimum asphalt binder content determination where they are briefly discussed under this section.

### **2.2.1 Aggregate Type and Quality Selection**

The properties of aggregates are very important to the performance of hot mix asphalt (HMA) pavements. Often pavement distress such as rutting, stripping, surface disintegration, and lack of adequate surface frictional resistance can be attributed directly to improper aggregate selection and use.

Thus, care has to be made while selecting the mineral aggregate and all quality test assurance has to be conducted to confirm whether they satisfy a definite project specification. Aggregates are deemed to give the mixture stability after various traffic loads, resistance to wear due to abrasive action of traffic, and still resistant to frost action. Thus, to obtain a mixture having good performance, evaluation of various mineral aggregate physical properties is essential. [6]

### **2.2.2 Aggregate Gradation and Size**

An aggregate's particle size distribution, or gradation, is one of its most influential characteristics. It determines almost every HMA properties including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. [7]

A study was made on effects of gradation on the asphalt content where both wearing and binder mixes were considered. Further, they have carried out regression analysis on test data to investigate the relationship between asphalt content and gradation. Their study shows that no correlation exists between asphalt content and the percent passing the 4.75mm (No. 4) and 2.36mm (No. 8) sieves for the wearing mix. On the other hand, for binder mixes there exists a

relationship between changes in gradation and measured asphalt content that shows as the mix becomes finer for the given sieve size, the asphalt content increases. [8]

In conjunction with this, care has to be taken while determining maximum aggregate size in a mixture. In HMA mixtures, instability may result from excessively small maximum sizes; and poor workability and/or segregation may result from excessively large maximum sizes. [7]

### **2.2.3 Asphalt Binder Selection**

Asphalt binder is supplied in various forms and grades having a wide range of consistency from fluid to hard and brittle for bituminous pavement construction. Asphalt binders are most commonly characterized by their physical properties. This is because an asphalt binder's physical properties directly describe how it will perform as a constituent in HMA pavement. Different quality tests were carried out on asphalt cement during this study to assess its physical properties through various laboratory steps. [9]

### **2.2.4 Optimum asphalt binder content determination**

Mix design methods are generally distinguished by the way in which they determine the optimum asphalt binder content. This process can be subdivided into:

- Make several trial mixes with different asphalt binder contents.
- Compact these trial mixes in the laboratory. This compaction is meant to be a rough simulation of actual field conditions.
- Run laboratory tests to determine key sample characteristics.
- Pick the asphalt binder content that best satisfies the mix design objectives.

The various important mixture properties which show weight-volume relationship and strength are discussed here in after. [6]

### i. Bulk Specific Gravity Determination

The bulk specific gravity test on the freshly compacted specimens may be performed as soon as when they have cooled to room temperature. This test is conducted according to ASTM D 2726, “Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-dry Specimens”.<sup>[10]</sup>

In the Marshal Mix design procedure, the density varies with asphalt content in such a way that it increases with increasing asphalt content in the mixture as the hot asphalt lubricates the particles allowing the compaction effort to force them closer together. The density reaches a peak and then begins to decrease because additional asphalt cement produces thicker films around the individual aggregates, and tend to push the aggregate particles further apart subsequently resulting lower density.

The bulk density of the compacted mixture can also be altered with the proportion of mineral filler. It is expected that the bulk density increases as the amount proportion of mineral filler increases in the mixture up to some point and then decreases. This is because an increased amount of mineral fillers will increase the amount of fines in the mix and the large amount of fine particles tend to push the larger particles apart and act as lubricating ball-bearings between these larger particles which subsequently lower the bulk density.

The voids in the mineral aggregate, VMA, is the total available volume of voids between the aggregate particles in the compacted paving mixture that includes the air voids and the effective asphalt content expressed as a percent of the total volume. It is calculated based on the bulk specific gravities of the combined aggregates and compacted paving mixture.

The VMA has two components: the volume of voids that is filled with asphalt, and air volume remaining after compaction for thermal expansion of the asphalt cement during hot weather. It is significantly important for the performance characteristics of a mixture. For any given mixture, the VMA must be sufficiently high enough to ensure there is space for the required asphalt cement, for its durability purpose, and air space. If the VMA is too small, there will be no space for the asphalt cement required to coat around the aggregates and this subsequently

results in durability problems. On the other hand, if VMA is too large, the mixture may suffer stability problems.

The available VMA will decrease as the amount of mineral fillers in the mixture increases. This can be due to both fillers can be used for filling voids or extend the asphalt binder. [9]

#### **ii. Percent Air Voids in Compacted Mixture**

The air voids,  $P_a$ , in a compacted paving mixture that consists of small air spaces between the coated aggregate particles expressed as percent of the bulk volume of the compacted paving mixture. To address this, HMA mix design seeks to adjust items such as asphalt content and aggregate gradation to produce design air voids.

#### **iii. Percent Voids Filled with Asphalt in Compacted Mixture**

The voids filled with asphalt, VFA, is a percentage of inter granular voids space between the aggregate particles (VMA) that are filled with asphalt cement. The amount of asphalt cement that fills the voids in the mixture is termed as “effective asphalt content”. It is this effective asphalt cement that provides the required asphalt film thickness around the aggregate particles, which subsequently determines the durability of the mixture.

#### **iv. Marshal Stability and Flow**

Marshal stability values can be determined by conducting a test on a prepared bituminous specimen. It is the maximum load carried by a compacted specimen tested at 60°C.

The stability value obtained is an indication of the mass viscosity of the aggregate-asphalt cement mixture. In most cases, it is affected significantly by the angle of internal friction of the aggregate and the viscosity of the asphalt cement at 60°C. Hence, one of the easiest ways to increase the stability of an aggregate-asphalt mixture is to use a higher viscosity grade of asphalt cement. It is also possible to increase the stability of the mix by selecting a more crushed angular aggregate than rounded shape aggregates.[11]

The flow is measured as the vertical deformation of the specimen in millimeter from start of loading up to the point where the stability begins to decrease. It is obtained at the same time as the Marshal Stability test is conducted. Generally, high flow values indicate a plastic mix that is more prone to permanent deformation problem due to traffic loads, whereas low flow values may indicate a mix with higher than normal voids and insufficient asphalt for durability and could result premature cracking due to mixture brittleness during the life of the pavement.

### **2.3 MOISTURE SUSCEPTIBILITY OF HOT MIX ASPHALT**

One of the desirable properties of bituminous mixtures is that the resistance to moisture induced damages. Water affects asphalt concrete in various ways. It may act directly and literally strip binder from the aggregate. However, generally, the effects are more subtle. Water weakens the structure to a point where the mix can no longer sustain the traffic it was designed to support, and finally fails under the repeated loading. The resistance to moisture damage under the presence of moisture in the mixture is a complex matter and the degree mainly depends on the properties of each ingredient materials in the mixture, type and use of mix, environment, traffic, construction practice, and the use of anti-strip additives. Among these factors, aggregate response to asphalt cement under water is primarily responsible for this phenomenon, although some asphalt cement are more subjected to stripping than others.

### **2.4 EFFECT OF CULLET ON HMA**

The use of glass cullet as an aggregate in asphalt mixtures was developed in USA in the 1960's [12]. The result -"glasphalt" - was heavily tested in the early 1970s and was generally found to be acceptable for some paving uses. [13]

The markets for glass container cullet can be broadly thought of in two main categories: (i) new glass containers, and (ii) all other uses. While the glass container manufacturers can theoretically use all the color sorted cullet collected to make new containers, for many communities, there are significant barriers of transportation cost and the problem of either marketing mixed colors, or, more recently, having them processed with electro-mechanical glass sorting equipment.

From the mid-1970's through the mid-1980's, the City of Baltimore made use of glass in its street pavement program. At least 17 streets were paved with glass to produce a "sparkle" effect, resulting from the reflection of sunlight or street lamp light off the glass pavement. [14]

However, the use of this secondary aggregate has not grown significantly due to cost, availability and performance considerations. In terms of its mechanical performance, asphalt mixtures containing glass aggregate as a replacement for primary aggregate have tended to perform slightly worse than conventional materials, depending on the replacement ratio of glass to aggregate. As glass aggregate does not absorb bitumen, stripping of glass modified asphalt mixtures is a potential concern. In addition, raveling of glass particles can be a serious safety concern. [12]

### 2.3.1 Moisture Susceptibility

Performance of building materials is one of the most important aspects that engineers must consider. When waste materials are used, the performance should be equal to or better than that of conventional materials. Since glass has a very smooth surface, the asphalt cement may fail to form a durable permanent bond, especially in the presence of water. Some of the early field projects showed stripping, which has been a concern in other studies. A recent technical assistance report showed stripping to be a major concern; therefore, any addition of a material that would result in more stripping may be undesirable. A laboratory feasibility study by Hughes in 1990 demonstrated that stripping in glasphalt may not be a problem; however the study was limited to one aggregate and only hydrated lime was used as an antistripping additive. [15]

*Tensile Strength Ratio (TSR)* test is a reliable predictor of field stripping. Because of the extremely smooth surface of glass particles, it is expected the addition of glass to have a more profound effect on stripping than was observed with the two mixes tested. The maximum allowable percentage of glass may be different for different types of mixes and particularly for other gradations of glass. [16]

Flat and elongated particles that could contribute to pavement raveling, stripping, poor skid resistance, abnormally high tire wear, and excessive glare were all identified by early researchers as potential problems. Since glass does not absorb any of the asphalt cement binder, and since

glass is also "hydrophobic," moisture damage (stripping) is a particular concern that has been identified, especially when high percentages and large gradations are introduced into a surface course mix. [17]

Then it faded into obscurity, mainly because the cost of obtaining the container scrap (cullet) was too high. Now there is Second Coming of glasphalt. Field testing is on the rise again, and by the early 1990s glasphalt could become a significant market for recycled glass bottles [18]. At the present time, the commercial use of waste glass in asphalt paving applications has been limited to communities where the quantity of waste glass produced and collected provides sufficient incentive to recycle it in pavement applications. [19]

Some Advantages of Glass Asphalt are: [20]

- The surface appears to dry faster than traditional paving after rain because the glass particles do not absorb water. Its extra heat retention could be especially beneficial when paving in a cold climate.
  - Increase road safety
- Glass asphalt surfaces are also more reflective than conventional asphalt
  - May improve night time road visibility.
- Due to its glass content will hold heat longer than conventional asphalt
  - Easier to compact and cartage benefits over longer distances
- Glass is not disposed in landfills offering environmental benefits and saving costs to local government
  - Waste reduction initiative
- There are savings with regard to input costs of raw materials which are replaced by glass.
  - Commercial benefits

Furthermore, research carried out previously demonstrated that the braking and speed increasing process of the vehicles improved by using crushed glass in pavements because of its all-around fracture strength and greater internal friction. On the other hand, the glass particles are so smooth and their silica content is so high that they become like hydrophilic materials. In this way, glass-asphalt pavements must be strengthened against water susceptibility. [21]

However, the cohesion between bitumen and stone aggregates can be easily destroyed because of the smooth surface of the glass particles in certain circumstances and can result in asphalt pavement stripping. Additives, like hydrated lime, are usually used to prevent the harmful phenomenon of glass–asphalt mixtures while retaining their useful characteristics. Because of the small ratio of absorbed bitumen, the glass particles would have a slight coating of bitumen on their surfaces, which results in small fractioning strength in the joint surface area of glass and asphalt particles. [22]

Thus, the fractioning strength of glass–asphalt mixtures is less than that of traditional asphalt concretes. As stated before, this deficiency of glass–asphalt mixtures can be avoided by adding 1–2% of lime to the mixture. Moreover, it was indicated by previous investigations that a higher percentage of lime would result in higher flexibility strength. Satisfactory performance of glass–asphalt pavements containing 10–15% glass cullet content by weight of mix occurs in surface coating mixtures. In addition, considering the limits and allowable technical properties including safety issues (skin cutting and tire puncturing), usually a maximum size of 4.75 mm can be used as the maximum allowable glass particle dimension in pavements. In this research 2% of a type of lime (by weight of mixture) was used as anti-stripping agent. [19]

A recent study on the dynamic characteristics of asphalt mixtures containing waste glass aggregates and conventional asphalt concrete mixtures showed an increase in the stiffness modulus of glass–asphalt pavements in comparison with conventional asphalt-mix. Three percent of hydrated lime was used as an anti-stripping agent additive, and the results were compared with those of a specimen without antistripping. [23]

A disadvantage observed on a glassphalt test strip in Montreal is that rutting may occur when studded tires are used. And also the crushing process can generate dust if not monitored adequately. [24]

Most installations of glassphalt have been designed to meet the standards of The Asphalt Institute for medium traffic asphalt, which specify a maximum speed limit of 40 mph. These standards include requirements for stability, flow, voids in mineral aggregate, percentage of air

voids in the mix, and unit weight. The most common applications are as surface pavement (surface coarse) for residential streets, secondary roads, parking lots, sidewalks, and curbing.

## 2.5 PRACTICAL USE OF WASTE GLASS FOR URBAN PAVING

Over the past few decades, another market for cullet has been developing within many states of United States of America, including Texas, Minnesota, California, Connecticut, Washington, Oregon, New York, and several others. The use of glass cullet as a construction aggregate is becoming more widespread as the results of research and laboratory testing studies on glass cullet become better known. [25]

Several towns in Connecticut have taken to the streets in an effort to put unmarketable, mixed, broken glass to use. Since 1988, a number of towns around Long Island Sound have experimented with “glasphalt” pavements, in which glass is used as a fine aggregate in bituminous concrete. To really get the show on the road, all these towns need now is a nod from the state’s Department of Transportation (ConnDOT). [26]

New York City uses glass in 10% of the total aggregate, which comes out to about 7.6% of the total mix. Using a 10% mix saves the city about \$1 per ton. The asphalt plant receives the glass, which is crushed by the sanitation department, at no cost. [25]

Experience with glasphalt in New York City has been positive. According to a consultant’s report, the New York Department of Transportation successfully placed various experimental glass pavements in 1988 on E. 19<sup>th</sup> Street, E. 108<sup>th</sup> Street, W. 45<sup>th</sup> Street, and various streets around the Plaza Hotel at 59<sup>th</sup> Street, primarily for aesthetic reasons. [26]

In 1983, Christman Associates, Inc. (Chester, Conn.), a pavement engineering consulting firm, worked with Baltimore to design a surface course glasphalt mixture that contained 50% graded broken glass. The 50% crushed glass mixture was tested and found to be below conventional skid tests. It was then decided to lower the glass content to between 20% and 25%. To date, according to a 1991 Christman report, the glass pavements have been providing “acceptable serviceability” with no liability due to the glass. [26]

## 2.6 SUMMARY

As seen in the literature review, glass was used in asphalt mix as filler and coarse aggregate in the USA, But not in Ethiopia. Some researchers also indicate some worst effect of glass in hot mix asphalt especially on moisture susceptibility. So this research will study its use as coarse sand and filler in asphalt mix in the binder course.

# **MATERIALS AND METHODS**

## **CHAPTER 3**

### **MATERIALS AND METHODS**

#### **3.1. INTRODUCTION**

This study involved investigating the Marshal properties and moisture susceptibility of bituminous mixtures prepared in the laboratory using different replacement rate of glass cullet ranging from 0-20%.

This study involves collecting of materials for the preparation of bituminous mixtures. The materials used in the mixture includes: coarse and fine aggregates, glass cullet, and asphalt binder.

The crushed stone coarse and fine aggregates are collected from AACRA construction quarry and crusher site located at 'August' around Addis Ababa old airport . The cullet was collected from Addis Ababa Glass Bottle Factory. The asphalt cement of 80/ 100 penetration grade was also obtained from AACRA batching plant.

These ingredient materials were subjected to various laboratory tests in order to determine their physical properties whether they can meet common specification limits. These quality assurance tests conducted on the aggregates include: gradation, Los Angeles abrasion, soundness, flakiness, aggregate crushing value, asphalt affinity, specific gravity and water absorption tests. The tests carried out on the asphalt cement sample include: penetration, flash point, ductility, durability, purity and specific gravity. The results obtained are indicated in Table-3.1, 3.2, 3.3 and 3.4 in comparison with the common specifications.

Test specimens were then prepared using different amount of cullet based on the rate of replacement proportion by weight of aggregate in the mix. In accordance with the Marshal Mix design procedure and criteria different mixture properties were obtained and the optimum asphalt binder content was determined.

Finally, mixtures were prepared using different amount of cullet at their respective optimum asphalt binder content to investigate the mixture resistance to moisture damages using the Marshal immersion test method .

## **3.2. CHARACTERISTICS OF MATERIALS**

### **3.2.1 Mineral Aggregate**

The mineral aggregates used in the research were subjected to various tests in order to assess their physical characteristics and suitability in the road construction. Natural fine and coarse aggregates are used in this research with physical properties presented in Table (3.1). 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 average gradation. The coarse and fine aggregate particles were separated into different sieve size and proportioned to obtain the desired gradation for bituminous mixtures of ASTM 3515 for 12.5 mm nominal maximum aggregate size. Table (3.2) and Figure (3.1) shows the final proportion of each used aggregate in asphalt binder course.

**Table 3.1** *Aggregate Physical Properties*

S/N	Test Description	Test Method	Result	Specification Requirements (ERA Pavement Design Manual, 2002)
1	Cleanliness and Deleterious Materials, %	AASHTO T176	51	>40
2	Los Angeles Abrasion, %	AASHTO T96	10.76	<30
3	Soundness, %	AASHTO T104	4.7	<12
4	Specific Gravity (Bulk) i. Coarse Aggregate ii. Fine Aggregate	AASHTO T85 AASHTO T84	2.85 2.59	-
5	Particle Shape, Flakiness, %	BS 812, Part 105	27	<45
6	Aggregate Crushing Value, ACV, %	BS 812, Part 110	17	<25
7	Water Absorption, %	ASTM C 127	0.6	<2
8	Affinity for Asphalt (Coating and Stripping), %	AASHTO T - 182	99	>95

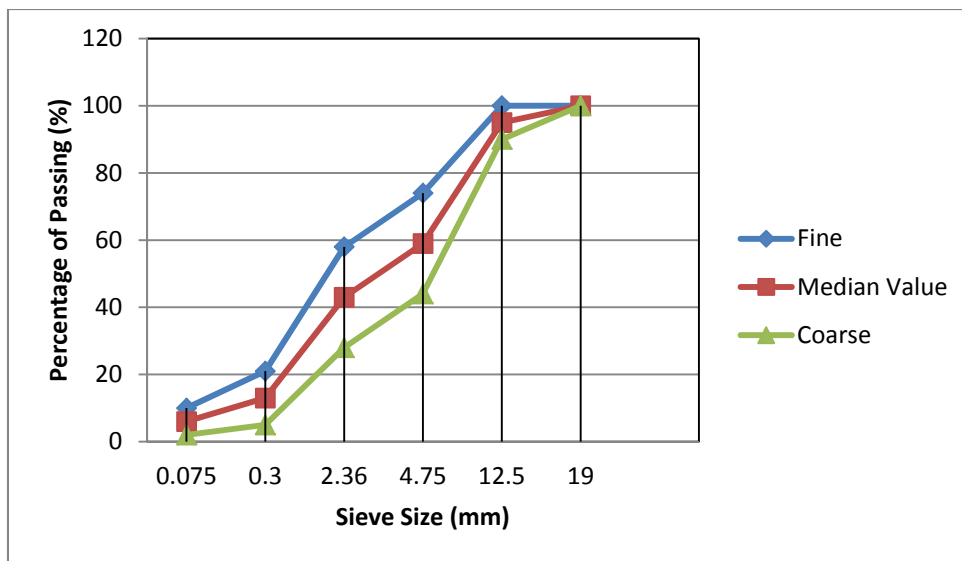


Figure 3.1 Aggregate Gradation Curve

Table 3.2 Aggregate proportion [ASTM D3515] [10]

Sieve Size (mm)	Percentage of passing (%)			
	Fine	Average	Coarse	Specification
19.0	100	100	100	100
12.5	100	95	90	90 – 100
9.50	-	-	-	-
4.75	74	59	44	44 – 74
2.36	58	43	28	28 – 58
0.30	21	13	5	5 – 21
0.075	10	6	2	2 - 10

### 3.2.2 Asphalt binder

Asphalt is the most commonly used material in pavement construction today because of its high engineering performance capabilities such as elasticity, adhesion and water resistance. Asphalt is known to be a complicated colloidal system of hydrocarbon materials which are composed of asphaltenes, resins and oils. Today's asphalt is produced mainly by the refining of crude oil and the physical and chemical properties can be altered or improved by blending, air blowing, additives etc. The interface between the asphalt and aggregate has been much focused in order to determine the chemical factors that influence bonding between the two materials. [20]

An asphalt binder of grade 80/ 100 penetration was used in the preparation of mixtures since it is widely used and acceptable for temperature condition like Addis Ababa. It was then subjected to various tests in the laboratory to determine its physical properties, where the summary of test results is shown in table 3.3 below.

**Table 3.3** *Physical properties of used bitumen*

No.	Test Description	Test Method	Recommended	Result
1	Penetration at 25°C, 100g, 5	AASHTO T49	85 – 100	90
2	Flash Point (Cleveland), °C	AASHTO T48	450+	590
3	Ductility at 25°C, cm	AASHTO T 51	min. 100	100+
4	Loss on Heating,%	AASHTO T 47	-	-0.2
5	Solubility in Trichloro Ethylene ,%	AASHTO T44	99.5+	99.8
6	Specific Gravity at 25°C (Kg/m <sup>3</sup> )	AASHTO T228 -06	-	1011
7	Penetration of residue percent of original ,at 25°C, 100g, 5 Sec	AASHTO T49	47+	89

### 3.2.3 Glass

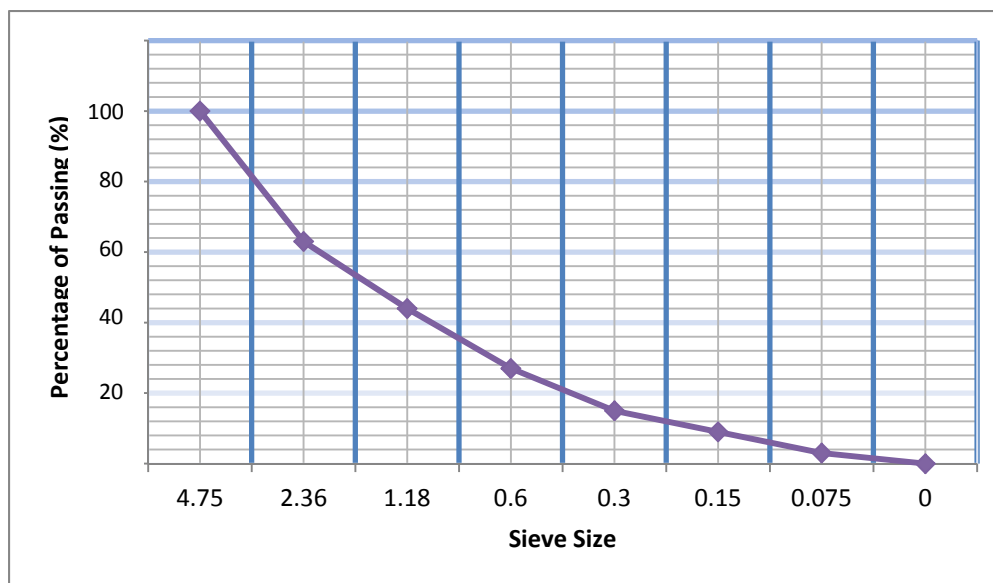
Ordinary glass is rigid and brittle and easy to crush to form satisfactory particles for asphalt concrete applications. The broken glass used in asphalt concrete is characterized by: [17]

- *Numerous long and flat particles* (especially for big broken glass particles). This may cause problems like stripping of the asphalt film from glass particles surfaces, infirm skid resistance, abrasion of tires, too high reflectance etc.
- *The surface of broken glass particles is exceeding smooth and the silica content is relatively high*, making glass particles a hydrophilic acid aggregate. Pavements with glasphalt may then be sensible to water damage (especially when glass particle size is increased or vast dosage).
- The angularity and friction angle afford insufficient transverse stability (at braking or start-up).
- Low asphalt absorption ratio and density may cause bleeding problems.
- Excellent light reflection properties assure safe nighttime driving, but when glass particle size is increased there is a risk of dazzling.
- Volume stability is good because of the inflation coefficient when heated is small (about  $8.8 \times 10^{-6} \text{cm/cm/}^\circ\text{C}$  -  $9.2 \times 10^{-6} \text{cm/cm/}^\circ\text{C}$  when the temperature is below  $700^\circ\text{C}$ ). This is beneficial to the resistance of low temperature cracking.
- The asphalt absorption ratio is near upon zero which is unfavorable to the adhesion of the asphalt film to the broken glass particles.

The waste broken glass used in the study is reclaimed beer and soft drink bottles that were factitious crushed into required particles. The crushed glass gradation was completely uniform with maximum glass particles size is 4.75mm and is adaptive to AC type gradation. Table 3.4 and Figure 3.2 show the gradation curve of the broken glass particles. Bottles were cleaned before crushing and then crushed mechanically and sieved to get the required gradation.

**Table 3.4** *Gradation of Broken Glass Particles*

Sieve Size (mm)	Specification
4.75	100
2.36	62
1.18	42
0.600	23
0.300	14
0.150	12
0.075	4



**Figure 3.2** *Sieving Curve of Broken Glass Particles*

### 3.2.3.1 Material Processing Requirements

- **Cleaning**

When used in asphalt concrete, glass processing must include the removal of ferrous and nonferrous metal, plastic, and paper. In most waste glass processing plants this requires screening, magnetic and eddy metal current (non-ferrous metal) separation, air classification, and/or handpicking operations. Although 100-percent removal of all paper, plastic, and debris from postconsumer glass streams is unlikely, an acceptable glass product can be achieved in most instances, particularly if mix designs limit glass to 10 to 15 percent of the mix. [19]

- **Crushing and Screening**

Crushing and screening are required to achieve proper sizing and to eliminate flat and/or elongated and sharp-edged glass particles.

- **Engineering Properties**

Some of the glass properties that are of particular interest when glass is used as aggregate in asphalt paving include gradation, specific gravity, and durability.

*Gradation:* Waste glass used in asphalt surface pavements should be processed to a fine aggregate size (less than 4.75 mm (No. 4 sieve) and blended with conventional aggregates to conform to gradation requirements in accordance with ASTM D3515.

*Durability:* Glass is a brittle material and coarse particles greater than 4.75 mm (3/8 in) in size can be expected to break down during handling. Consequently, it is preferable to process (crush and screen) waste glass into a fine aggregate size,

which is minus 4.75 mm (No. 4 sieve), prior to its use in surface course asphalt paving mixes.

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 (3.4) shows the properties of used crushed glass

**Table 3.5** *Used Crushed Glass Properties*

<b>Property</b>	<b>Detail</b>
<b>Glass Source</b>	Bottles
<b>Size (mm)</b>	4.75
<b>Density (gm/cm<sup>3</sup>)</b>	2.52

### 3.3 EXPERIMENTAL 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 was carried out to obtain the binder average gradation curve which used in the preparation of the asphalt mix. After that, with different bitumen and cullet contents asphalt mixes are prepared to obtain optimum bitumen content by marshall test. Then optimum bitumen content with their respective cullet ratio is used to prepare asphalt mixes. Marshall Test was used to evaluate the properties of these glasphalt mixes. Finally, laboratory tests results are obtained and analyzed. Figure (3.3) shows a flowchart of experimental work for this study.

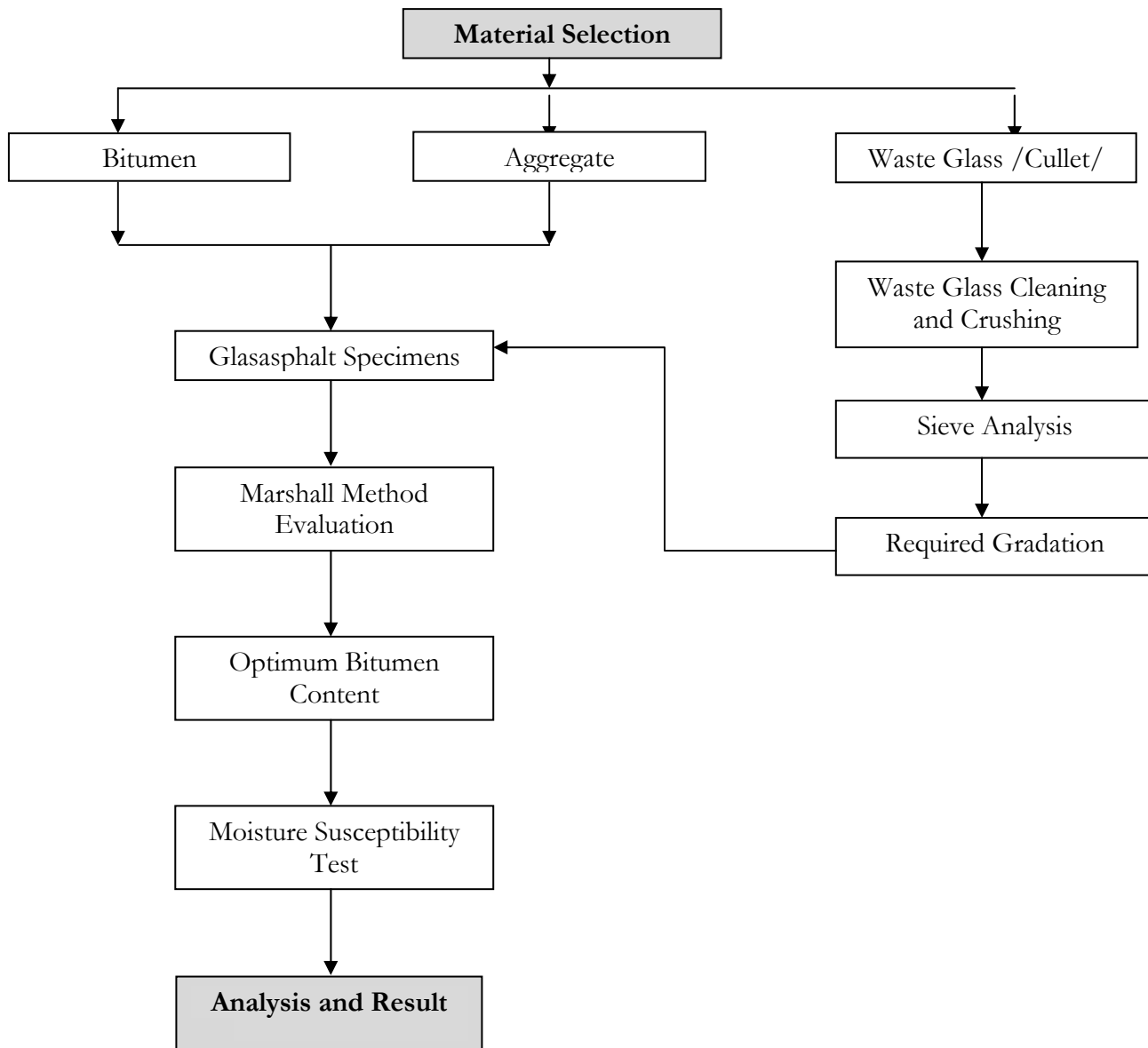


Figure 3.3 Flowchart of experimental work

### 3.4 MARSHAL MIX DESIGN

Marshal Mix Design method was used to determine the optimum asphalt content and evaluate the stability of the mixtures in the laboratory. An aggregate weighing about 1200gm and the 80/100 grade asphalt were heated to a temperature of 180°C and 130°C, respectively. Also cullet with different percent of replacement from 0 to maximum 20% of aggregate weight with 5% increment heated to a temperature 180°C is used. Then, these ingredients were mixed at a temperature of 135°C. The percent by weight of asphalt content for all mixes was taken with respect to the total weight of the mixture. The mixture was then placed in the preheated mold and compacted using 75 blows on either sides of the specimen. After compaction, the specimen were allowed to cool for 24 hours and removed from the mold by means of an extrusion jack. In accordance with the Marshal procedure, each compacted test specimens were subjected to determination of unit weight, void analysis, stability and flow tests. Then, plots were made to determine values of each respective specimen prepared using different cullet replacement rate.

#### 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 procedure for determining for optimum asphalt content for a particular mixture under evaluation was adopted from the publication by the Asphalt Institute [23], where both the American Society for Testing and Materials given by ASTM D1559 and American Association of State Highway and Transportation Officials given by AASHTO R-12 standardized it. Accordingly, the optimum binder content is calculated as the average of binder content values that corresponding the maximum stability, maximum density and median percent of air voids.

$$\text{Optimum Binder Content (OBC) \%} = \frac{[\%mb]Stability + [\%mb]Bulk\ Density + [\%mb]Va}{3} \dots \dots \dots \text{Eq 3.1}$$

Thus, all the calculated and measured mix properties for the average asphalt content is compared with criteria for acceptability given in Table 3.5 and 3.6. The Marshall properties of individual mixes, prepared using different amount of cullet, obtained at their optimum binder content was evaluated and will be discussed in chapter 4.

**Table 3.6** Suggested Marshall Criteria for Asphalt Concrete Mix Design Based on ERA Manual [26]

Marshall Method Mix Criteria	Light Traffic		Medium Traffic		Heavy Traffic	
	Surface – Base		Surface – Base		Surface – Base	
	Min	Max	Min	Max	Min	Max
Compaction, number of blows each end of specimen	35		50		75	
Stability (KN at 60°C)	3.5	-	6	-	7	-
Flow, (mm)	2	-	2	-	2	-
Percent Air Voids	3	5	3	5	3	5
Percent Voids filled with Asphalt (VFA)	70	80	65	78	65	75
Percent VMA (for 4% air voids and Nom. Max, Particle size of 19mm)	13	-	13	-	13	-

**Table 3.7** *Suggested Marshall Criteria for Asphalt Concrete Mix Design Based on AACRA Manual [27]*

Marshall Method Mix Criteria	Nominal Size of Mix	
	14mm	
	Min	Max
Bitumen Content	4.6	6.1
Percent Air Voids	4	6
Stability (KN at 60°C)	6.5	-
Percent VMA	14	-

### 3.5 MOISTURE SUSCEPTIBILITY OF MIXTURES

The performance of hot-mix asphalt in the presence of water is a complex issue where it depends on various variables. Among the various types of quantitative tests, the Marshall Immersion test, whose conditioning process is similar to that of the Immersion compression test standardized in ASTM D1075-94 and AASHTO T165-97, is used for evaluating all the Marshall specimens prepared using different cullet amount. The Marshall Immersion test uses the compressive strength done as per AASHTO T167-97 as a strength parameter. [17]

Two groups of six compacted specimens are used in this test method for each glass content. One group is submerged in a 49°C water bath for 4 days for conditioning, and the other group is maintained dry in air bath for 4 hours at 25°C. An alternative approach to conditioning is to immerse the test specimens in water for 24 h at 60°C and 2 hours at 25°C where this is adopted in this study. The retained stability expressed as a percentage of the ratio of conditioned stability to controlled stability.

$$\text{Index of retained strength \%} = \frac{S_1}{S_2} \dots\dots\dots \text{Eq 3.2}$$

Where: S1 = compressive strength of immersed specimens

S2 = compressive strength of dry specimens

The results obtained from investigations conducted on all bituminous mixtures prepared using different glass content as described on preceding sections were evaluated. The evaluation of the results was made in a way that could direct to interpret and give conclusive statements on the objective of the study.

The test results are tabulated and plotted for mixtures prepared using respective cullet content. The mixture properties assessed include Marshal Properties and moisture susceptibility.

# **RESULTS AND DISCUSSION**

## CHAPTER 4

### RESULTS AND DISCUSSION

#### **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 be presented in this chapter. 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 glass content in 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. EFFECT OF GLASS ON MARSHAL PROPERTIES OF BITUMINOUS MIXTURES**

The results of Marshal Tests on bituminous mixes prepared at various glass contents by total weight of mix. From the test results, optimum asphalt content was determined for all respective mixtures using different amount of cullet. Table 4-1 indicates the properties of mixtures at their various asphalt content for mixes with different glass content. The effect of cullet on various properties of the asphalt mixtures will be discussed under subsequent sections. The discussion is made taking the general trend of the curves. But on some diagrams there are some irregularities which occur due to laboratory work limitations like difficulty to have consistent mixing temperature and minor aggregate loss at the time of mechanical mixing.

Table 4-1 Marshall Properties of Bituminous Mixture at Various Asphalt Content

0% Glass											
P <sub>b</sub>	V <sub>b</sub>	V <sub>ba</sub>	V <sub>be</sub>	P <sub>be</sub>	P <sub>ba</sub>	G <sub>mb</sub>	V <sub>a</sub> , %	VMA, %	VFA, %	STABLITY	FLOW
4	9.049	1.213	7.835	3.464	0.536	2.287	8.115	15.361	47.197	11.360	2.390
4.5	10.380	1.685	8.695	3.770	0.730	2.332	5.200	14.143	63.287	11.370	2.530
5	11.701	2.147	9.554	4.082	0.918	2.366	3.506	13.349	73.924	11.690	2.220
5.5	12.993	2.607	10.386	4.397	1.103	2.388	2.238	12.993	83.021	12.210	3.290
6	14.169	3.033	11.135	4.715	1.285	2.387	2.113	13.484	84.333	11.050	3.440
5% Glass											
P <sub>b</sub>	V <sub>b</sub>	V <sub>ba</sub>	V <sub>be</sub>	P <sub>be</sub>	P <sub>ba</sub>	G <sub>mb</sub>	V <sub>a</sub> , %	VMA, %	VFA, %	STABLITY	FLOW
4	8.949	1.217	7.733	3.456	0.544	2.262	7.977	16.290	51.045	9.960	2.240
4.5	10.216	1.680	8.536	3.760	0.740	2.295	5.583	15.497	64.063	10.220	2.580
5	11.638	2.177	9.461	4.065	0.935	2.353	2.395	13.817	82.761	11.600	2.400
5.5	12.812	2.616	10.196	4.377	1.123	2.355	2.119	14.206	85.412	10.580	3.120
6	13.965	3.049	10.915	4.690	1.310	2.353	1.874	14.731	87.299	10.400	4.280
10% Glass											
P <sub>b</sub>	V <sub>b</sub>	V <sub>ba</sub>	V <sub>be</sub>	P <sub>be</sub>	P <sub>ba</sub>	G <sub>mb</sub>	V <sub>a</sub> , %	VMA, %	VFA, %	STABLITY	FLOW
4	8.846	0.634	8.213	3.713	0.287	2.236	8.664	29.295	60.978	8.980	2.230
4.5	9.922	-0.081	10.003	4.537	-0.037	2.229	8.153	53.661	84.807	9.360	2.680
5	11.153	0.355	10.798	4.841	0.159	2.255	5.723	53.366	89.279	10.300	3.010
5.5	12.394	0.802	11.592	5.144	0.356	2.278	3.955	53.137	92.559	10.880	3.670
6	13.547	1.248	12.298	5.447	0.553	2.283	2.992	53.295	94.391	10.470	4.030

Table 4-1 Cont...

15% Glass											
P <sub>b</sub>	V <sub>b</sub>	V <sub>ba</sub>	V <sub>bc</sub>	P <sub>bc</sub>	P <sub>ba</sub>	G <sub>mb</sub>	V <sub>a</sub> ,%	VMA, %	VFA, %	STABLITY	FLOW
4	8.703	1.105	7.598	3.492	0.508	2.200	10.796	21.261	49.225	7.370	2.180
4.5	9.840	1.533	8.307	3.799	0.701	2.211	9.656	21.281	54.629	7.560	2.840
5	11.040	1.982	9.058	4.102	0.898	2.232	7.717	20.928	63.131	8.210	3.060
5.5	12.307	2.457	9.850	4.402	1.098	2.262	5.308	20.292	73.850	8.030	4.230
6	13.565	2.917	10.648	4.710	1.290	2.286	3.802	19.891	80.891	7.840	4.520
20% Glass											
P <sub>b</sub>	V <sub>b</sub>	V <sub>ba</sub>	V <sub>bc</sub>	P <sub>bc</sub>	P <sub>ba</sub>	G <sub>mb</sub>	V <sub>a</sub> ,%	VMA, %	VFA, %	STABLITY	FLOW
4	8.728	1.107	7.621	3.493	0.507	2.206	10.648	21.034	49.468	6.120	1.890
4.5	9.897	1.547	8.350	3.797	0.703	2.224	8.832	20.823	57.605	6.780	2.370
5	11.139	2.026	9.113	4.091	0.909	2.252	5.844	20.223	71.106	7.020	2.830
5.5	12.349	2.484	9.864	4.394	1.106	2.270	4.344	20.020	78.321	6.840	3.310
6	13.559	2.949	10.610	4.695	1.305	2.285	2.901	19.924	86.688	6.430	3.920

### 4.3 EFFECT ON UNIT WEIGHT

The effect of cullet content on the unit weight of compacted mixes is shown in Figure 4-1. Almost all Mixes with variable glass content showed a trend of increase in unit weight as asphalt content increases. It is shown that at 0% glass content, mixes made with 5.5% asphalt possessed highest unit weight (2388.31 Kg/m<sup>3</sup>) and mix made with 15% glass and 4.0% asphalt has lowest unit weight value for mixes (2199.77 Kg/m<sup>3</sup>). The reduction on the bulk unit weight for mix with 0% to 5% glass content is not large as compared to remaining contents. This may be due to that effect of glass at lower content is insignificant. The results obtained show a wide variability in unit weight for respective glass content, and hence it would be difficult to give an explanation.

In fact, the effect of glass content on unit weight, for mixes made by glass replacement on total aggregate in mix from 5% – 20%, is that the values decrease. This is because while glass content increases in the mix, since glass had lower unit weight hence decreases unit weight. As the bulk unit weight decreases with increasing glass content the air void in the total mix ( $V_a$ ) will increase and reduce the performance.

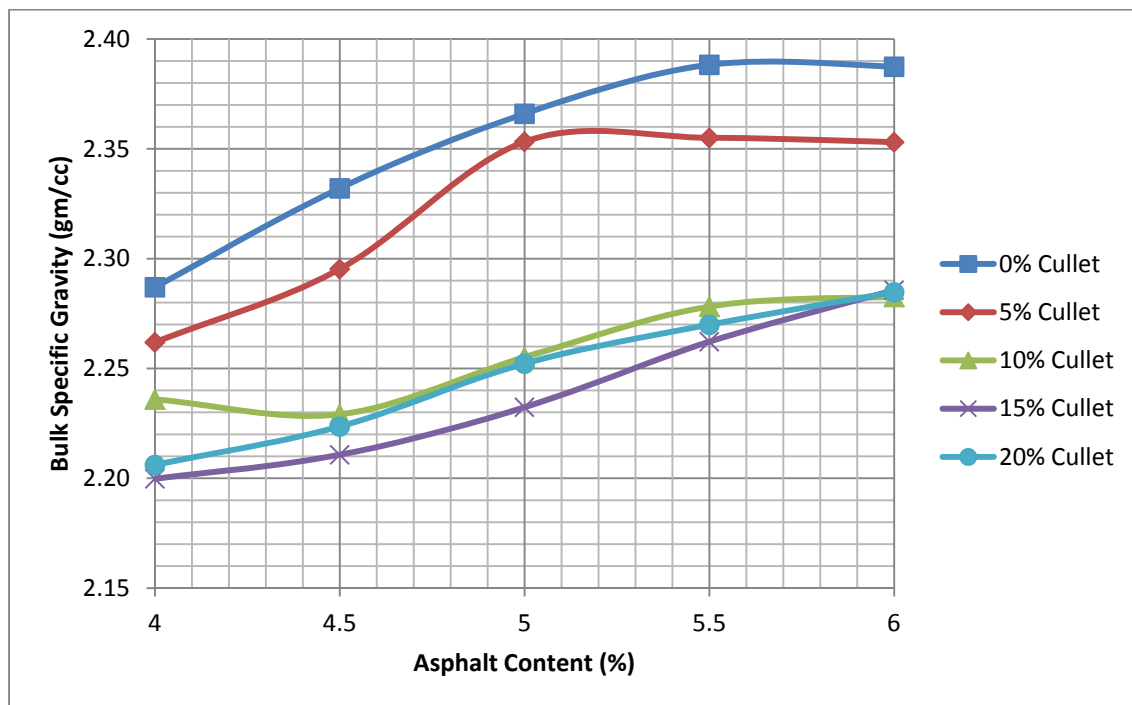


Figure 4-1- Effect of Cullet content on unit weight at various Asphalt Content

#### 4.4 EFFECT ON MARSHAL STABILITY

The stability of the specimen is the maximum load required to produce failure of the specimen when load is applied at constant rate. Figure 4-2 demonstrates the effect of glass contents on Marshal Stability. All cullet content have similar trend on their effect on Marshal stability by content, i.e., as asphalt content in the mixes increase, Marshal Stability also increases up to maximum then decreases. This is due to the fact that voids at lower asphalt content is too high and the void will be filled with asphalt as asphalt content increases, after maximum stability it

reduce due to additional asphalt tends to separate aggregate interlock hence effect tend to reduce the stability values.

Thus, a small addition of glass in the mixture reduces the Marshal stability. The test results obtained for individual glass content revealed that addition of more cullet is finer than the control one (the glass has 4.75mm of nominal maximum sieve size). Thus the finer the material the more it modifies the asphalt mixtures by extending the asphalt binder, hence would rather give lower stability values. On the other hand, surface smoothness of glass produce lower stability on the total mixture.

The figure can illustrate the above theory, where addition of glass could decrease the stability of the mixture, also higher replacement could reduce the stability by acting like an asphalt extender. This is why mixtures prepared using glass content of 15% and 20%, have lower stability. The stability of mixture with 20% cullet shows values below the minimum with in all asphalt content.

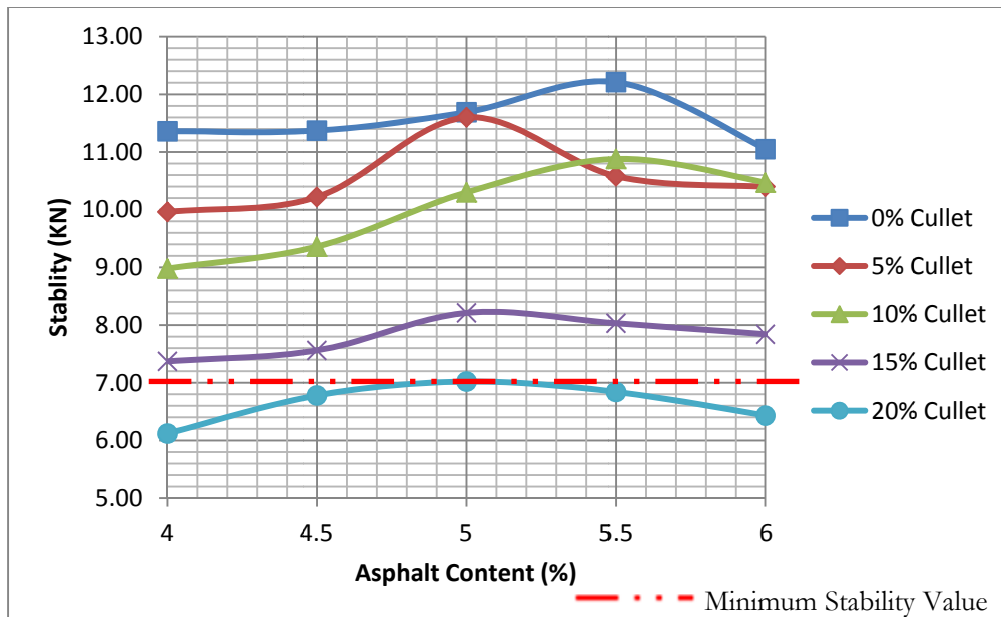


Figure 4-2- Effect of Cullet Content on Stability at Various Asphalt Content

#### 4.5 EFFECT ON FLOW

Flow refers that the vertical deformation of the sample (measured from start of loading to the point at which stability begins to decrease) in 0.25mm. High flow values generally indicate a

plastic mix that will experience permanent deformation under traffic, whereas low flow values may indicate a mix with higher than normal voids and insufficient asphalt for durability and one that may experience premature cracking due to mixture brittleness during the life of the pavement

The flow of Glasphalt mixes is above 2mm and still in the range of local and international specifications at all different glass content. Figure (4-3) shows flow results of glasphalt at different glass content. For all glass content the flow increases as asphalt content increase. Similarly flow number shows increment as the glass replacement rate increase. The increased flow number out of the required specification range exposed the HMA for permanent deformation during their time of service.

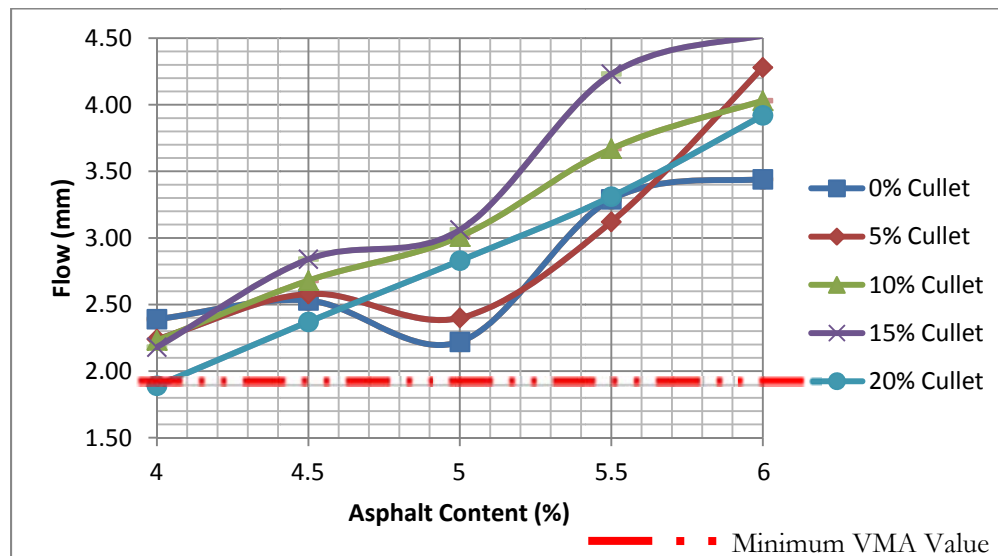


Figure 4-3- Effect of Cullet Content on Flow at Various Asphalt Content

#### 4.6 EFFECT ON AIR VOIDS ( $V_a$ )

Total void in the mix refers that the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as percent of the bulk volume of the compacted paving mixture.

The air voids of Glasphalt mixes increases gradually as the glass content increase. It's noticed from the Figure (4-4) that control mix attains the average specification (4% air void) at lower

asphalt content than other mixes with glass. Figure (4.4) represents the air voids of asphalt mixes at different glass and asphalt content.

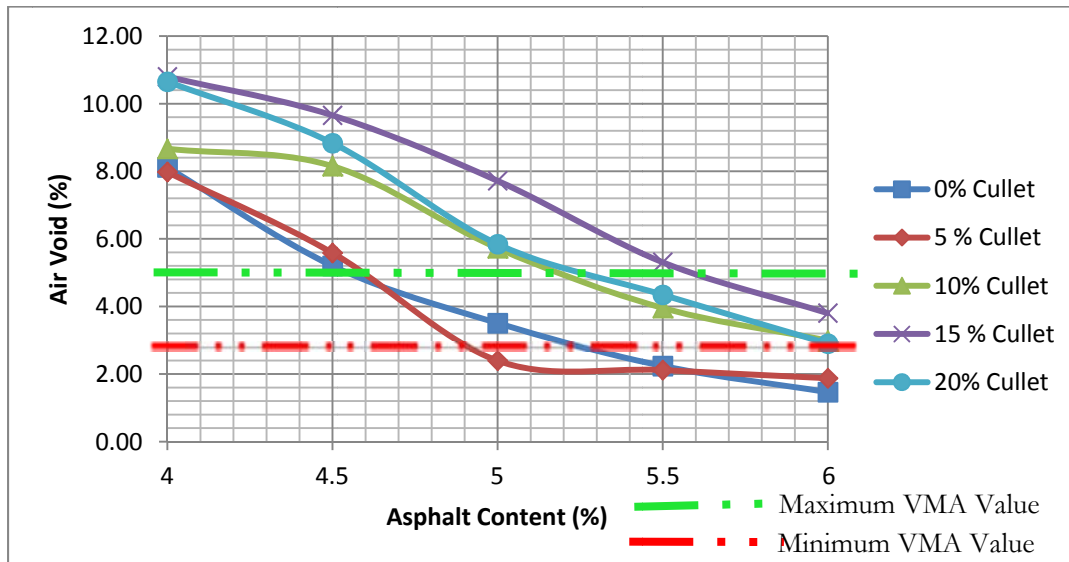


Figure 4-4- Effect of Cullet Content on Air Void at Various Asphalt Content

#### 4.7 EFFECT ON VOIDS IN MINERAL AGGREGATE (VMA)

The effect of different fillers on voids in mineral aggregate was also evaluated and the results are shown in Figure 4-5. It is a common trend that, as glass content in the mixes increase, the voids in mineral aggregate increase. Minimum VMA is necessary in mixtures to accommodate enough asphalt content, so that aggregate particles can be coated with adequate asphalt film thickness. This consequently results in a durable asphalt paving mixtures. It can be seen from the figure that lower VMA is in mixtures with no glass and hence, results lower effective asphalt content (see figure 4-5). These mixes could be less durable than that of containing higher glass content. Higher voids in mineral aggregate were obtained from mixes prepared by 15% and 20% glass replacement, results higher effective asphalt content. This may result due to lower asphalt absorption of glass.

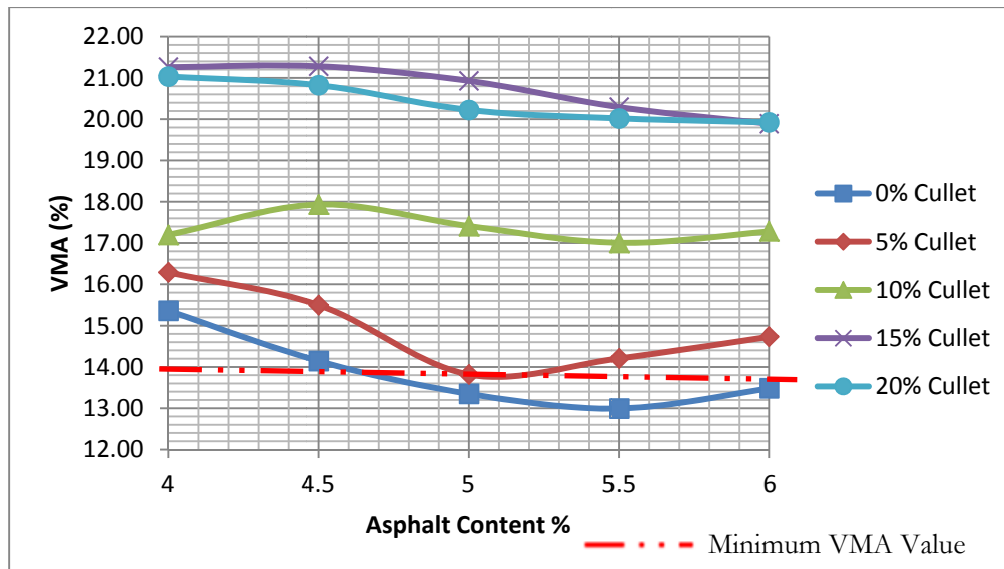
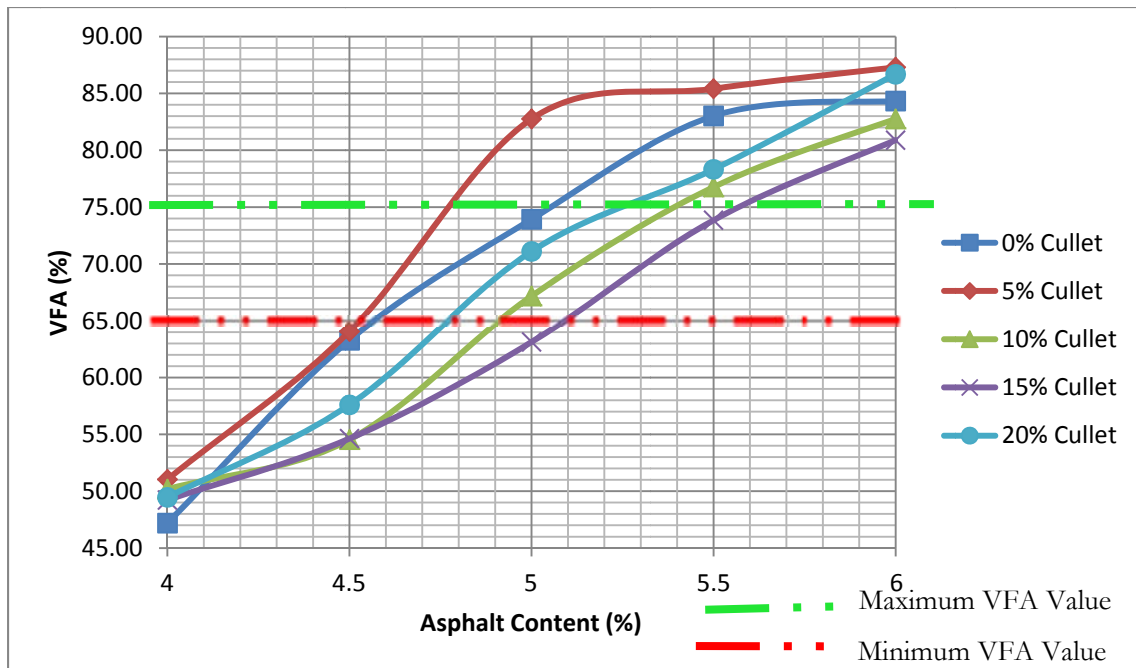


Figure 4-5- Effect of Cullet Content on VMA at Various Asphalt Content

#### 4.8 EFFECT ON VOIDS FILLED WITH ASPHALT (VFA)

Effect of glass content on the voids filled with asphalt property of the mixture is indicated on Figure 4-6. Voids filled with asphalt values are greater than 45% for all glass contents, where the Marshal Criteria for VFA is 65% - 75%. This criterion is important for the durability of mixes and is related to the effective asphalt content in the mix. If the percentage of voids filled with asphalt is lower than the limit indicated, there will be less asphalt film around the aggregate particles. Lower asphalt films are more subjected to moisture and weather effects where they can be detached from the aggregate particles and subsequently lower performance. On the other hand, if the limit is exceeded, more voids are filled with asphalt than required for durability. This can be explained as the asphalt film around aggregate particles is thicker and lower voids than required are left. This increased amount of effective asphalt results bleeding and lower stiffness of the mix.

Since VFA depends on both VMA and  $V_a$ , the cumulative effects of these two variables are shown on Figure 4-6. For mixtures prepared by 0% and 5% glass content shows relatively higher voids filled with asphalt compared with other mixes almost in all asphalt content. VFA decreases as glass content increases in the mixture.



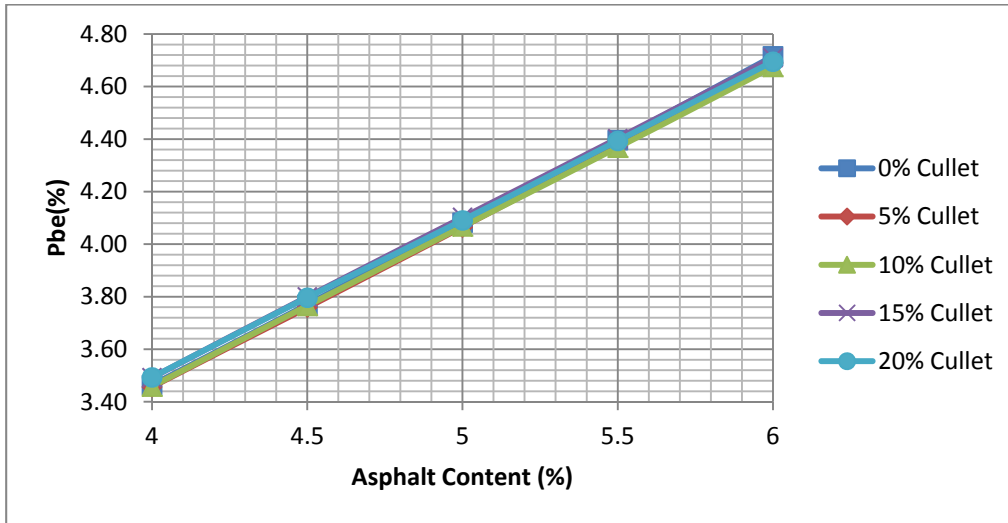
**Figure 4-6-** *Effect of Cullet Content on VFA at Various Asphalt Content*

#### 4.9 EFFECT ON EFFECTIVE ASPHALT CONTENT

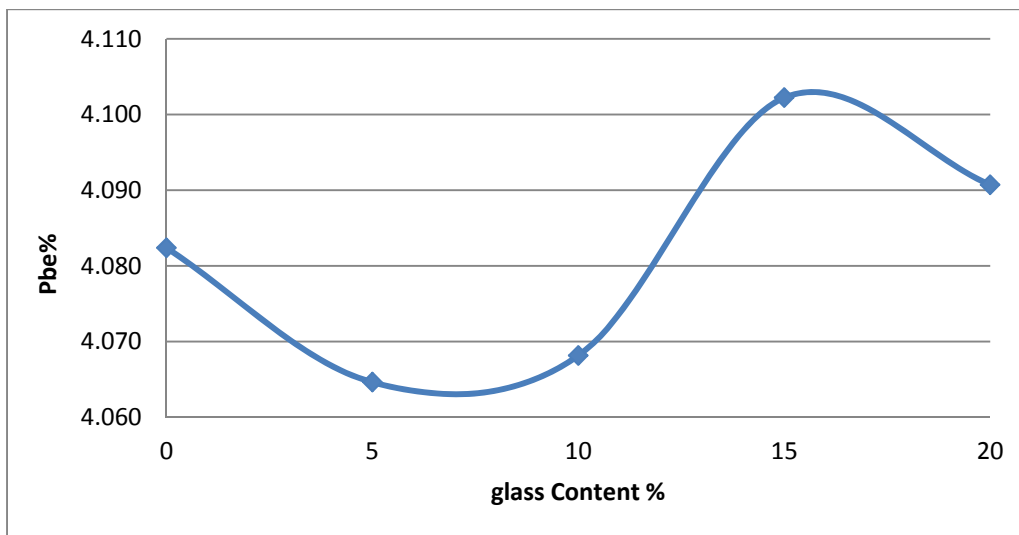
It is considered that the effective asphalt content in the mixture determines the performance of mixtures. This can be explained as that it is the effective asphalt binder content that makes the asphalt film around the aggregate particles. If the asphalt film thickness around the aggregate particles is thick enough, various desirable characteristics such as better durability, more fatigue resistance, and higher resistance to moisture induced damage can be achieved from bituminous mixtures. But, there should be a maximum limit where up on an increase in temperature and loading, the asphalt content in the mix gets increased and results bleeding on the surface of paved road.

Figure 4-7 is plotted for the effective asphalt content that is present in mixes for respective cullet content. The figure shows that there exists a common trend among all glass content with respect to their content in the mixture. That is, the effective asphalt content increases as the glass content in the mix. This is probably because reduction of asphalt absorption by glass, which results higher total asphalt content, and hence higher effective asphalt.

It is the effective asphalt content that determines the available asphalt film thickness around aggregate particles, i.e. thick film thickness is obtained with higher effective asphalt content in the mixture. Thick asphalt films do not age or harden as rapidly as thin ones do and consequently, retain its original characteristics longer. This makes mixtures having thick film of asphalt around aggregates more durable over time. Thus, mixtures containing lower glass replacement rate are less durable than the others.



**Figure 4-7-** *Effect of Cullet Content on Effective Asphalt Content at Various Asphalt Content*



**Figure 4-8-** *Effect of Cullet Content on Effective Asphalt Content at 5% Asphalt Content*

#### 4.10 EFFECT ON OPTIMUM ASPHALT CONTENT

As indicated in Figure 4-9 below, the optimum bitumen content (OBC) of mixtures, prepared with different glass amount, vary over a wide range. The OBC obtained using varying amount of glass exhibit irregular trend that is as glass content in the mixture increases, the OBC decreases for glass content greater than 10%. This is due to the fact that, an increased amount of glass content in the mixture fills the voids in the aggregate. This, subsequently, decreases the voids in the mineral aggregate, as a result, lower space is available for asphalt.

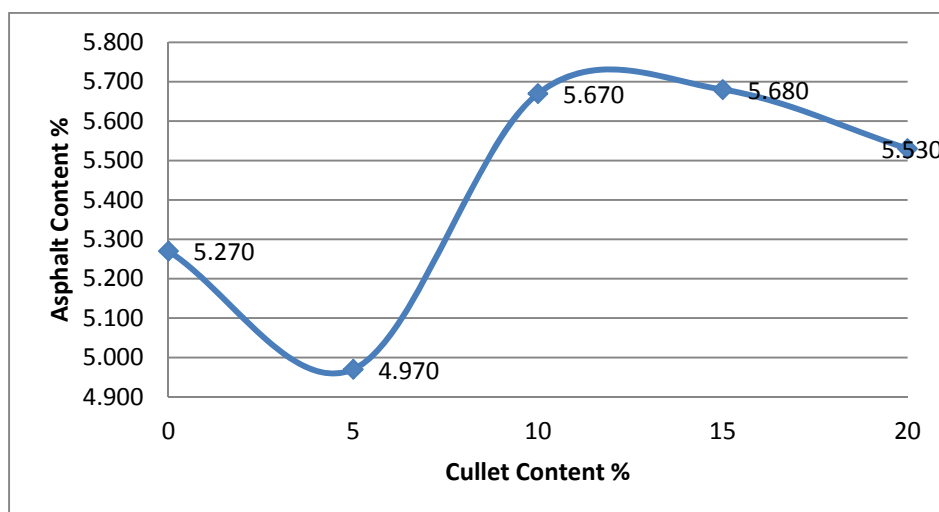


Figure 4-9- *Effect of Cullet Content on Optimum Asphalt Content at Various Asphalt Content*

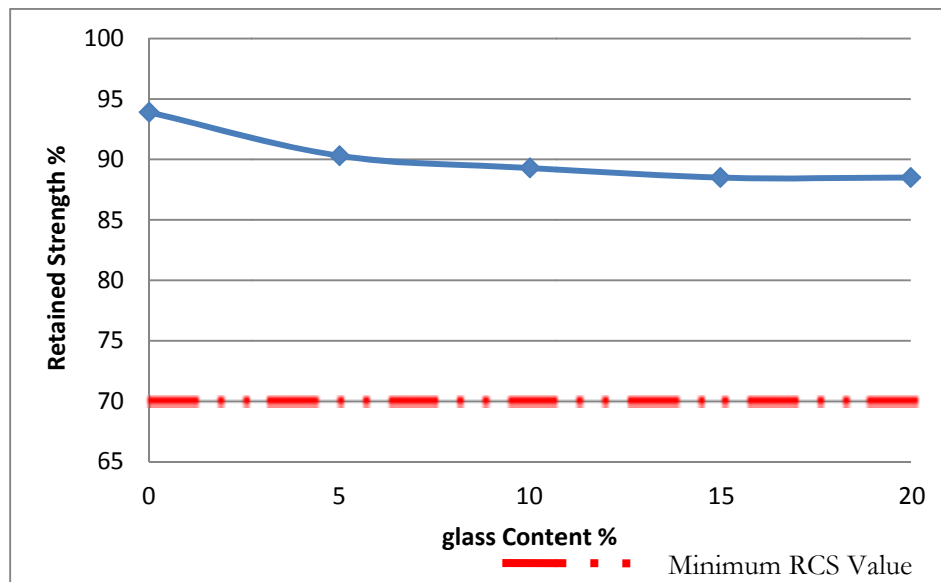
#### 4.11 EFFECT ON MOISTURE SUSCEPTIBILITY OF HMA

From the marshal immersion test conducted for mixtures prepared at their optimum asphalt content, the retained strength values are obtained as a ratio of conditioned stability to controlled stability. Mixtures prepared at various glass content were evaluated to indicate the effect used in the mixes.

The test results are tabulated and plotted as shown in Table 4-2 and Figure 4-10 respectively. The figure is provided here for comparison between values obtained using different glass content in the mix. The figure indicates that mixes prepared using 0% glass provide highest retained strength as compared to mixes prepared with glass. This indicates that mixes prepared without using glass provide better resistance to moisture effects for the sample test.

**Table 4-2** Retained Compressive Strength at Various glass Content

Glass Content %	OBC %	Compressive Strength (Mpa)		Retained Strength %
		Control	Conditioned	
0	5.27	3.3	3.1	93.9
5	4.97	3.1	2.8	90.3
10	5.67	2.8	2.5	89.3
15	5.68	2.6	2.3	88.5
20	5.53	2.6	2.3	88.5



**Figure 4-10-** Effect of Cullet Content on moisture susceptibility at OBC

**4.12 MAXIMUM GLASS CONTENT**

It's noticed that all values of Marshall Stability for different glass content satisfy the local specifications (6.5-7) KN and the maximum stability corresponds 0% glass content. As shown in Figure (4-2) other glass replacement rates have stability values greater than the minimum specification values except for 20% glass replacement. Figure (4-4) represents the air voids percentage at different glass content. And it's noticed from the figure that all glass replacement

rates have air voids value of 4%. Which is the median air voids in the specifications and it's the same as the air voids value that is used to determine the OBC. But 4% air void is attained in higher asphalt content for higher glass contents. From Figure (4-1) it's noticed that all the values of bulk density at different glass content are very close to each other except for 0% and 5% glass contents with a little higher value. But all of them achieve the local and international specifications requirements. Therefore it is more advisable to use glass with maximum replacement rate of 15%. Table (4-3) illustrates a comparison of the mechanical properties of glasphalt containing 15% glass content with the local specifications AACRA and ERA manual. As obviously shown in Table (4-3) the glasphalt mix with maximum glass content 15% by weight of aggregates satisfies the requirements AACRA specifications for all tested properties.

**Table 4-3** Comparison of Glasphalt mix with maximum glass content and specifications range

Property	Glass Content (15%) At 5.68 OBC	AACRA Manual		ERA Manual	
		Min.	Max.	Min.	Max.
Stability (KN)	7.9	6.5	-	7	-
Flow (mm)	4.4	-	-	2	-
% of Voids in the Total Mix (Va)	3.8	4	6	3	5
% of Voids in Mineral Aggregate (VMA)	20.03	14	-	13	-
% of Voids filled with Asphalt (VFA)	78.4	-	-	65	75

# **ECONOMIC ANALYSIS**

## CHAPTER 5

### ECONOMIC ANALYSIS

#### **5.1 INTRODUCTION**

The increasing quantity and changing character of solid wastes generated in Addis Ababa each year have resulted in a need to develop improved means for processing and disposing of these wastes. Recycling and reuse of materials have been suggested as a solution to this problem.

The rationale for recycling generally includes reduction of the volume of the waste stream destined for final disposal as well as conservation of resources. Factors of importance when considering a recycling program for any waste component are, therefore, the volume or size of the fraction of the waste stream constituted by a particular type of waste, and the nation's source of raw materials from which the item or group of items were made. Obstacles to recycling are the heterogeneity of wastes, high transportation costs if reclaimed materials cannot be used in the area where they are generated, lack of stable markets and prices for salvageable materials, and absence of a suitable technology for separating and treating mixed refuse. All these factors have been considered in the development of a new means for recycling one of the waste components, glass.

The diminishing natural aggregate supplies in some urban areas further enhance this concept since aggregate costs increase with increasing haul distances. The volume of waste glass is small when compared to the amounts of aggregate required for highway construction; consequently, it is not expected that glass will comprise a significant percentage of the aggregate used for this purpose. However, this use has the potential for utilizing all of the waste glass that can be economically separated from refuse in urban areas of the Ethiopia.

## 5.2 CURRENT MANAGEMENT OPTIONS

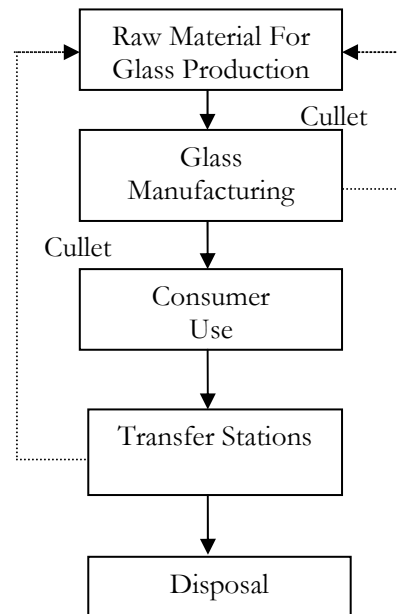
Addis Ababa city produces 5,612.73m<sup>3</sup> solid waste per day where 0.5% is glass waste (28.1m<sup>3</sup>/day). Even though percentage of glass waste is the lowest it is advantageous to set different recycling option for the future growth.

**Table 5.1** *Addis Ababa City Solid Waste types and amount* [4]

Solid waste type	Daily Contribution (m <sup>3</sup> )	Percentage (%)
Factories by products	235.7	4.2
Paper	140.3	2.5
Plastic/ Tyre	162.8	2.9
Wood	129.1	2
Animal Skeleton	61.7	1.1
Textile	134.7	2.4
Metal	84.2	0.9
Glass	28.1	0.5
Plant Leaf	847.5	15.1
Rock	140.3	2.5
Soil, Sand and Other...	3648.3	65
Total	5612.7	100

Currently, Addis Ababa City Administration Sanitation Agency collects solid waste and dump in Repi /Koshe/ Sanitary Landfill. On this site there is no noticeable and organized recycling of glass. But there are a lot of attempts to collect and sell recyclable plastic bags and bottles. The agency is planning to modernize the waste collection and recycling methods. There are five transfer station construction projects near to all five gates of the city and change the sanitary landfill location to off city center. The transfer stations sort recyclable and degradable wastes. The quality of waste glass obtained from TSs can vary widely and can contain dirt, paper, and plastics. In most cases, mixed-colored waste glass can be obtained by contacting the municipality that is responsible for the collection of recyclables or the TS operator. Figure 5.1 provides a schematic representation of the flow of

container glass in the Addis Ababa along with potential recycling options.



**Figure 5.1** *General overview of glass cycle in Addis Ababa*

### 5.3 GLASS RECYCLING

Recycling is the process by which waste materials are diverted from the waste stream. The products are sorted and used to produce new materials. There are environmental, economic and social advantages to recycling. These advantages include:

- Conserving valuable natural resources and raw materials used in industry. By making products from recycled materials instead of virgin materials, we conserve land and reduce the need to drill for oil and dig for minerals.
- Generating civic pride and environmental awareness.
- Glass in particular, can be recycled an infinite number of times without any loss of quality.
- Preventing environmental pollution. In most cases, making products from recycled materials creates less air pollution and water pollution than making products from virgin materials.

- Saving energy reduces acid rain, global warming and air pollution. Making products from recycled ingredients often uses much less energy than producing the same product from raw materials.
- Saving landfill space. When the materials that you recycle are used to make new products, they don't go into landfills, so landfill space is conserved.

In Addis Ababa glass bottles of soft drinks and beer are returned to retailers. But still there are more waste glasses used for cosmetics, beverages and food container in the house hold level and defected glasses from industries. Transfer Stations are facilities that are designed to sort, store, and market municipal solid waste recyclables that are collected from localities.

Addis Ababa has only two glass bottle factories, Addis Ababa Glass Bottle Factory SC (AAGBF) and Day Light Applied Technologies PLC (DAT) with current production and Cullet generation rate as shown on table 5.2. AAGBF produces all flint, amber and green bottles, But DAT only flint bottle.

As the table 5.2 shows AAGBF uses 40% cullet from which 15% is obtained from cullet produced in the production process whereas the remaining 25% is from defected bottles collected from soft drink and beer factories. DAT produce 18% cullet in the production process but recycle only 15% which left 3% cullet/day from the total daily production.

**Table 5.2** *Glass factories production and recycling rate*

	Addis Ababa Glass Factory S.C.	Day light Applied Technologies PLC
Current Glass Production capacity (Ton/day)	30	18
Cullet Production Rate (%)	15%	18%
Cullet Recycling Rate (%)	40%	15%



Figure 5.2.A *Addis Ababa Glass Bottle Factory*  
*Cullet Stock*

Figure 5.2.B *Day Light Applied Technologies*  
*Cullet Stock*

At Addis Ababa Glass Bottle Factory S.C waste glass is hand-sorted by color (white, amber, and green), and crushed for size reduction (generally to less than 50 mm in size). Crushed (color-sorted) glass, which is commonly referred to as cullet, is showered to remove contaminants before reused to glass production. Glass recycling involves the collection and sorting of glass by color for use in the manufacture of new glass containers. Recycling postconsumer glass from the municipal solid waste stream for use as a raw material in new glass products is limited, however, by the high cost of collection and processing (hand sorting) of waste glass, and specifications that limit impurities (e.g., ceramics, ferrous metal, paper, plastics and mixed-colored cullet) in the glass production process.



Hand Sorting

Washing



Crushing

Recycling

**Fig 5.3** *Cullet recycling cycle in Addis Ababa Glass Factory*

## 5.4 ECONOMIC ANALYSIS

Economic analysis is a very wide and complex task. It needs to determine direct and indirect tangible cost and benefits of using crushed glass. The economic feasibility of using waste glass as an aggregate is dependent upon several factors which include the cost of disposing of waste by conventional methods of disposal such as sanitary land filling or incineration, the cost of separating refuse into recyclable components and the cost of conventional aggregates.

For this paper both qualitative and simple quantitative measures are used for evaluation.

### *Qualitative analysis*

- Benefit (direct and secondary benefits)
  - Saving in land fill space
  - Saving in natural resources
  - Increase employment: glass collector and equipment operator
  - Less pollution: as a result of decreased mining, reduced littering

- Costs (direct and secondary Costs)
  - Cost of glass cullet
  - Increased cost of construction
  - Increased in maintenance/ rehabilitation cost
  - Increased in transportation cost

### ***Quantitative analysis***

Quantitative economic analysis is undertaken by simple comparison of the unit rate for the production of asphalt concrete with only aggregate and the other one with 15% crushed glass.

#### *Basic Assumptions*

- Hauling distance of both glass and natural aggregate assumed to be equal.
- Unit rate for natural aggregate and bitumen obtained from Alemayehu Ketema General Contractor CMC – Karalo asphalt road project.
- Unit rate for glass obtained from AAGBF and Addis Ababa City Administration Sanitation Administration Agency.
- Labor and machine costs of asphalt concrete production for both conditions are assumed to be equal.

#### Conventional natural aggregate

Total cost of aggregate = Purchasing cost + Transport Cost + Waste Cost + Storage Cost

$$= 1264.32 \text{ Birr}$$

Total cost of 85/100 penetration grade bitumen for 5.27% OBC = 2593.25 Birr

Total labor cost = 93.37 Birr

Total equipment cost = 1,115.48 Birr

Total direct Cost = 5066.42 Birr/m<sup>3</sup>

Indirect Cost (15% of direct cost) = 759.96 Birr/m<sup>3</sup>

**Total unit rate = 5826.38 Birr/m<sup>3</sup> of HMA**

### Waste Glass

The cost of Recycling is dependent on the origin of the solid waste. Cullet from households collected by Addis Ababa City Administration Sanitation Agency in two ways either by private solid waste collecting companies or by small scale enterprises. The agency pays 74 Birr/ton and 54 Birr/ton respectively.

Also AAGBF collect cullet from beer and soft drink companies with only transportation cost.

Flint bottles transport cost = 65 Birr /ton

Amber bottles transport cost = 125 birr/ton

Unloading Cost = 21.33 birr/ton

Separation cost = 30 birr/ton

Direct total for Flint = 116.33 birr/ton

Direct total for Amber = 176.33 birr/ton

Indirect cost = crushing cost + washing cost = 43 birr / ton

Total cost for Flint = 159.33 birr/ton = 401.51 birr/m<sup>3</sup>

Total cost for Amber = 219.33 birr/ton = 552.71 birr/m<sup>3</sup>

Average glass cost = 477.11 Birr/m<sup>3</sup>

15% glass cost = 71.57 Birr/m<sup>3</sup>

Total cost of 85% aggregate = 1074.67 Birr/m<sup>3</sup>

Total cost of 85/100 penetration grade bitumen for 5.68% OBC = 2795.00 Birr

Total labor cost = 93.37 Birr

Total equipment cost = 1,115.48 Birr

Total direct Cost = 5150.09 Birr/m<sup>3</sup>

Indirect Cost (15% of direct cost) = 772.51 Birr/m<sup>3</sup>

**Total unit rate = 5922.60 Birr/m<sup>3</sup> of HMA**

As the analysis shows the cost of 1m<sup>3</sup> asphalt concrete with 15% cullet and 5.68 OBC is a little bit higher than that produced by only conventional natural aggregate with 5.27 OBC.

The quantitative economic analysis is done in a simplified way. For further study and decision making the analysis must be done taking in to account different factors. Additional costs are landfill space due to recycling, variation of construction cost, environmental cost, maintenance cost, user cost and saving in natural resources.

**CONCLUSIONS  
AND  
RECOMMENDATIONS**

## **CHAPTER 6**

### **CONCLUSIONS AND RECOMMENDATIONS**

#### **6.1 CONCLUSIONS**

The objective of this study is to investigate the effect of using crushed waste glass as asphalt mixture aggregate, where the results can be concluded as the follows:

- The use of glass tends to reduce the VMA and Va and increase VFA from Marshall-compacted specimens; thus, the optimum asphalt content must be determined with the target percent of glass to be used.
- The results of Marshall Stability decreases as the glass content increases with all values above local and international specification except for 20% glass content.
- Flow number and bulk density of glasphalt are consistent with the specifications range at the different percentages of glass contents and both reduce with increment of glass content.
- The Marshall Immersion result indicates retained compressive strength decreases with increasing glass content. But all values are above the minimum specification value.
- Crushed waste glass can be used in asphalt binder course with the maximal size of 4.75mm and the optimum replacement 15% glass.
- The cost of glass (including crushing to the proper gradation and the haul cost) will vary considerably. Probable cost will be at least equal to that of natural aggregate , thus, there is little monetary incentive to use recycled glass at the present time, particularly when it appears it is susceptible to stripping than many of our natural aggregates.

## 6.2 RECOMMENDATIONS

Based on results of this study and on practical engineering considerations, it is recommended that the following special provisions be developed.

- To allow crushed recycled glass to be used with natural aggregate in asphalt concrete.
- To allow a maximum of 15 percent crushed recycled glass to be used in asphalt mixes.
- Further studies are needed using various glass gradation, different percentages of glass content and lower increment rates.
- 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.
- Reuse of glass also saves on landfill space, which is also a valuable commodity and should be reserved for only those materials that cannot be recycled.
- 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.
- Glass is a recyclable product, and only that portion of glass that cannot be economically or efficiently utilized in the remanufacture of new glass should be used.
- The quantitative economic analysis better to be done taking in to consideration different factors and indirect costs like land fill cost increased cost of construction and increased in maintenance rehabilitation cost

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## **Appendix A**

### **Test Results from Marshal Mix Design**

**MARSHALL PROPERTIES OF BITUMINOUS MIXTURES  
AASHTO D1559 /AASHTO T245**

**Asphalt Surfacing**

**GENERAL DATA**

Description	Asphalt wearing course
Location	AAIT Marshal Lab
Date Sampled	
Date Tested	
Tested by	

**ASPHALT / BITUMEN**

Source	AACRA
Grade	85/100
Specific Gravity (G <sub>b</sub> )	1.011
Number of Blows:-	2*75 (heavy traffic)

SAMPLE No.	Asphalt by Wt. of Total mix(Pb)		Bulk S.G of agg	E <sub>1</sub> S.G of aggregate (G <sub>s</sub> )	Max. SG of mixing mix (G <sub>mm</sub> )	Mass (grams) in			Vol. of specimen (cc)	Bulk S.G of compd mix (gm/cc)	Air voids, % (D-J)*100/D	VMA, % L	VFA, % M	Vb (A*F)/G <sub>b</sub>	Vba J*(A/G <sub>b</sub> )+(B/C) -(100/D)	Vbe N-O	Pbc Q	Pba R	Stability(kN)		Flow, mm Dist Reading
	A	B				Water	Air dry	Air SSD											Factor	Adjusted	
A	4.0	2.594	2.650	2.489	2.489	705.1	1251.4	546.3	2.275	8.6	15.8	45.6	9.0	1.2	7.8	3.5	0.5	12.09	0.93	11.246	2.38
B	4.0	2.594	2.650	2.489	2.489	711.5	1254.5	543.0	2.290	8.0	15.3	47.5	9.1	1.2	7.8	3.5	0.5	12.08	0.93	11.231	2.38
C	4.0	2.594	2.650	2.489	2.489	722.8	1271.7	548.9	2.297	7.7	15.0	48.5	9.1	1.2	7.9	3.5	0.5	13.02	0.89	11.587	2.42
							Average =		<b>2.287</b>	<b>8.1</b>	<b>15.4</b>	<b>47.2</b>	<b>9.0</b>	<b>1.2</b>	<b>7.8</b>	<b>3.5</b>	<b>0.5</b>			<b>11.355</b>	<b>2.39</b>
A	4.5	2.594	2.638	2.460	2.460	723.3	1260.6	537.3	2.330	5.3	14.2	62.8	10.4	1.7	8.7	3.8	0.7	12.02	0.93	11.179	2.51
B	4.5	2.594	2.638	2.460	2.460	727.3	1262.9	535.6	2.346	4.6	13.6	66.0	10.4	1.7	8.7	3.8	0.7	11.88	0.96	11.465	2.53
C	4.5	2.594	2.638	2.460	2.460	721.7	1261.5	539.8	2.321	5.7	14.6	61.1	10.3	1.7	8.7	3.8	0.7	12.39	0.93	11.523	2.55
							Average =		<b>2.332</b>	<b>5.2</b>	<b>14.1</b>	<b>63.3</b>	<b>10.4</b>	<b>1.7</b>	<b>8.7</b>	<b>3.8</b>	<b>0.7</b>			<b>11.569</b>	<b>2.53</b>
A	5.0	2.594	2.651	2.482	2.482	727.9	1250.8	522.9	2.385	2.7	12.7	78.3	11.8	2.2	9.6	4.1	0.9	12.06	0.96	11.573	2.11
B	5.0	2.594	2.651	2.482	2.482	725.2	1252.6	527.4	2.371	3.3	13.2	74.8	11.7	2.2	9.6	4.1	0.9	12.17	0.96	11.683	2.21
C	5.0	2.594	2.651	2.482	2.482	725.0	1260.3	535.3	2.343	4.5	14.2	68.6	11.6	2.1	9.5	4.1	0.9	12.32	0.96	11.827	2.33
							Average =		<b>2.366</b>	<b>3.5</b>	<b>13.3</b>	<b>73.9</b>	<b>11.7</b>	<b>2.1</b>	<b>9.6</b>	<b>4.1</b>	<b>0.9</b>			<b>11.694</b>	<b>2.22</b>
A	5.5	2.594	2.662	2.443	2.443	734.2	1271.7	537.5	2.362	3.3	13.9	76.3	12.9	2.6	10.3	4.4	1.1	12.98	0.93	12.071	3.26
B	5.5	2.594	2.662	2.443	2.443	736.2	1258.9	532.7	2.404	1.6	12.4	87.1	13.1	2.6	10.5	4.4	1.1	12.08	1.00	12.080	3.29
C	5.5	2.594	2.662	2.443	2.443	729.9	1249.9	530.0	2.399	1.8	12.6	85.7	13.1	2.6	10.4	4.4	1.1	12.48	1.00	12.480	3.33
							Average =		<b>2.388</b>	<b>2.2</b>	<b>13.0</b>	<b>83.0</b>	<b>13.0</b>	<b>2.6</b>	<b>10.4</b>	<b>4.4</b>	<b>1.1</b>			<b>12.210</b>	<b>3.29</b>
A	6.0	2.594	2.681	2.439	2.439	744.2	1276.7	532.5	2.384	2.2	13.6	83.5	14.2	3.0	11.1	4.7	1.3	11.39	0.96	10.934	3.44
B	6.0	2.594	2.681	2.439	2.439	736.2	1261.9	525.7	2.390	2.0	13.4	85.0	14.2	3.0	11.1	4.7	1.3	11.25	0.96	10.800	3.41
C	6.0	2.594	2.681	2.439	2.439	729.9	1252.3	528.4	2.388	2.1	13.5	84.5	14.2	3.0	11.1	4.7	1.3	11.41	1.00	11.400	3.48
							Average =		<b>2.387</b>	<b>2.1</b>	<b>13.5</b>	<b>84.3</b>	<b>14.2</b>	<b>3.0</b>	<b>11.1</b>	<b>4.7</b>	<b>1.3</b>			<b>11.048</b>	<b>3.44</b>

Remarks:- All samples prepared with 0% glass replaced of natural aggregate

**MARSHALL PROPERTIES OF BITUMINOUS MIXTURES /AASHTO T245**

**Asphalt Surfacing**

**GENERAL DATA**

Description	Asphalt wearing course
Location	AAIT Marshal Lab
Date Samples	
Date Tested	
Tested by	

**ASPHALT /BITUMEN**

Source	AAACRA
Grade	RS/100
Specific Gravity (G <sub>b</sub> )	1.011
Number of Blows:-	2*75 (heavy traffic)

SAMPLE No.	Asphalt by Wt. of Total mix (P <sub>b</sub> )	Bulk S.G. of agg (G <sub>s</sub> )	Etc S.G. of aggregate (G <sub>a</sub> )	Max S.G. of paving mix (G <sub>m</sub> )	Mass (grams) in			Bulk S.G. of emp'd mix (G <sub>m</sub> /c)	Air voids, %	VMA, %	VFA, %	Vb	V <sub>ha</sub>	V <sub>hc</sub>	Phe	Phi	Stability (kN)		Flow, mm	
					Air-dry	Water	Air-SSD										Read	Adjusted		Dist Reading
A	B	C	D	E	F	G	H	K	L	M	N	O	P	Q	R	-	-	-		
A	4.0	2.594	2.614	2.458	1232.4	627.7	1239.3	546.6	8.3	16.6	50.0	8.9	1.2	7.7	3.5	0.5	10.71	0.95	9.960	2.22
B	4.0	2.594	2.614	2.458	1226.0	635.4	1235.0	542.5	8.1	16.4	50.8	8.9	1.2	7.7	3.5	0.5	10.61	0.95	9.867	2.24
C	4.0	2.594	2.614	2.458	1234.4	702.5	1246.0	543.5	7.6	15.9	52.3	9.0	1.2	7.8	3.5	0.5	10.81	0.95	10.063	2.26
							Average =	2.262	8.0	16.3	51.0	8.9	1.2	7.7	3.5	0.5			9.960	2.24
A	4.5	2.594	2.603	2.431	1235.1	704.2	1243.0	538.8	5.7	15.6	65.4	10.2	1.7	8.5	3.8	0.7	11.04	0.95	10.267	2.58
B	4.5	2.594	2.603	2.431	1251.6	718.3	1259.3	541.0	4.8	14.8	67.5	10.3	1.7	8.6	3.8	0.7	10.82	0.95	10.063	2.55
C	4.5	2.594	2.603	2.431	1225.5	698.1	1234.8	536.7	6.2	16.1	61.3	10.1	1.7	8.5	3.8	0.7	10.87	0.96	10.435	2.61
							Average =	2.295	5.6	15.5	64.1	10.2	1.7	8.5	3.8	0.7			10.255	2.58
A	5.0	2.594	2.601	2.411	1232.8	723.9	1244.0	531.0	2.1	13.6	84.2	11.7	2.2	9.5	4.1	0.9	11.82	0.96	11.347	2.39
B	5.0	2.594	2.601	2.411	1248.0	722.8	1250.7	527.9	2.64	13.4	85.5	11.7	2.2	9.5	4.1	0.9	12.12	0.96	11.635	2.398
C	5.0	2.594	2.601	2.411	1241.3	714.3	1245.6	531.3	3.1	14.4	78.6	11.6	2.2	9.4	4.1	0.9	12.31	0.96	11.818	2.41
							Average =	2.333	2.4	13.8	82.8	11.6	2.2	9.5	4.1	0.9			11.690	2.40
A	5.5	2.594	2.616	2.406	1232.6	719.0	1238.1	539.1	3.4	15.4	77.7	12.6	2.6	10.1	4.4	1.1	10.75	0.95	9.998	3.08
B	5.5	2.594	2.616	2.406	1260.4	733.0	1263.3	530.3	1.2	13.4	90.9	12.9	2.6	10.3	4.4	1.1	11.43	0.96	10.973	3.16
C	5.5	2.594	2.616	2.406	1259.0	730.1	1262.3	532.4	1.7	13.9	87.6	12.9	2.6	10.2	4.4	1.1	11.22	0.96	10.771	3.11
							Average =	2.355	2.1	14.2	85.4	12.8	2.6	10.2	4.4	1.1			10.581	3.12
A	6.0	2.594	2.628	2.398	1254.5	734.5	1268.6	534.1	2.1	14.9	86.2	13.9	3.0	10.9	4.7	1.3	10.76	0.96	10.330	4.28
B	6.0	2.594	2.628	2.398	1246.6	732.1	1262.4	530.3	2.49	14.9	86.2	13.9	3.0	10.9	4.7	1.3	10.73	0.96	10.301	4.24
C	6.0	2.594	2.628	2.398	1232.3	730.4	1260.7	530.3	2.361	14.4	89.4	14.0	3.1	11.0	4.7	1.3	11.01	0.96	10.570	4.33
							Average =	2.353	1.9	14.7	87.3	14.0	3.0	10.9	4.7	1.3			10.400	4.28

Remarks- All samples prepared with 5% glass replaced of natural aggregate.

**MARSHALL PROPERTIES OF BITUMINOUS MIXTURES  
AASHTO D1559 /AASHTO T245**

**Asphalt Surfacing**

**GENERAL DATA**

Description	Asphalt wearing course
Location	AAIT Marshal Lab
Date Sampled	
Date Tested	
Tested by	

**ASPHALT / BITUMEN**

Source	AACRA
Grade	85/100
Specific Gravity (G <sub>b</sub> )	1.011
Number of Blows:-	2*75 (heavy traffic)

SAMPLE No.	Asphalt by Wt of Total mix (Pb)		Bulk S.G. of agg	E <sub>s</sub> S.G. of aggregate (G <sub>s</sub> )	Max SG. of paving mix (G <sub>mm</sub> )	Mass (grams) in			Vol of specimen (cc)	Bulk S.G. of empty mix (gm/cc)	Air voids, % (D-J)*100/D	VMA, % (L-K)-(0.00-A)*J/B	VFA, % (L-K)*100/L	V <sub>b</sub> (A*)/G <sub>b</sub>	V <sub>ha</sub> O	V <sub>hc</sub> P	P <sub>he</sub> Q	P <sub>ha</sub> R	Stability (kN)		Flow, mm
	A	B				C	D	E											F	G	
A	4.0	2.594	2.601	2.447	1214.3	673.2	1216.4	543.2	2.235	8.6	17.3	40.9	8.8	1.2	7.6	3.5	0.5	10.14	0.93	9.430	2.25
B	4.0	2.594	2.601	2.447	1243.4	680.3	1246.0	557.6	2.238	8.529	17.2	50.3	8.9	1.2	7.6	3.5	0.5	9.98	0.89	8.882	2.23
C	4.0	2.594	2.601	2.447	1239.8	688.4	1239.8	551.4	2.237	8.567	17.2	50.2	8.9	1.2	7.6	3.5	0.5	9.70	0.89	8.633	2.21
A	4.5	2.594	2.598	2.427	1253.2	694.4	1255.4	561.0	2.234	7.958	17.8	53.2	9.9	1.6	8.3	3.8	0.7	10.90	0.86	9.574	2.07
B	4.5	2.594	2.598	2.427	1236.5	684.9	1239.6	554.7	2.229	8.153	17.9	54.5	9.9	1.6	8.3	3.8	0.7	10.41	0.89	9.265	2.08
C	4.5	2.594	2.598	2.427	1250.1	691.4	1253.4	562.0	2.224	8.490	18.1	53.9	9.9	1.6	8.3	3.8	0.7	10.97	0.86	9.454	2.09
A	5.0	2.594	2.577	2.392	1243.5	691.1	1245.4	554.3	2.229	8.153	17.9	54.5	9.9	1.6	8.3	3.8	0.7	11.45	0.89	10.191	2.99
B	5.0	2.594	2.577	2.392	1247.8	699.3	1249.1	549.8	2.270	5.119	16.9	69.2	11.1	2.1	9.1	4.1	0.9	11.59	0.89	10.315	3.01
C	5.0	2.594	2.577	2.392	1256.6	704.8	1259.7	557.9	2.252	5.837	17.5	66.7	11.1	2.1	9.0	4.1	0.9	11.67	0.89	10.386	3.03
A	5.5	2.594	2.574	2.372	1262.0	708.0	1263.1	555.1	2.273	4.154	17.2	75.8	12.4	2.6	9.8	4.4	1.1	12.26	0.89	10.911	3.66
B	5.5	2.594	2.574	2.372	1262.8	711.8	1263.4	551.6	2.289	3.485	16.6	79.0	12.5	2.6	9.9	4.4	1.1	12.10	0.89	10.769	3.67
C	5.5	2.594	2.574	2.372	1265.6	709.2	1266.3	557.1	2.272	4.226	17.2	75.5	12.4	2.6	9.8	4.4	1.1	12.32	0.89	10.965	3.69
A	6.0	2.594	2.571	2.353	1263.6	714.8	1264.2	552.4	2.278	3.955	17.0	76.8	12.4	2.6	9.8	4.4	1.1	11.78	0.89	10.882	3.67
B	6.0	2.594	2.571	2.353	1261.1	706.2	1261.9	556.3	2.265	3.272	17.0	79.2	13.4	3.0	10.4	4.7	1.3	11.65	0.89	10.569	4.03
C	6.0	2.594	2.571	2.353	1263.4	714.0	1264.5	550.5	2.275	2.469	16.8	85.4	13.6	3.0	10.6	4.7	1.3	11.86	0.89	10.555	3.99
								Average =	2.283	2.992	17.3	82.8	13.5	3.0	10.5	4.7	1.3			10.469	4.03

Remarks:- All samples prepared with 10% glass replaced of natural aggregate

**MARSHALL PROPERTIES OF BITUMINOUS MIXTURES  
AASHTO D1559 /AASHTO T245**

**Asphalt Surfacing**

**GENERAL DATA**

Description	Asphalt wearing course
Location	AAIT Marshal Lab
Date Sampled	
Date Tested	
Tested by	

**ASPHALT / BITUMEN**

Source	AACRA
Grade	85/100
Specific Gravity (G <sub>b</sub> )	1.011
Number of Blows:-	2*75 (heavy traffic)

SAMPLE No.	Asphalt by Wt of Total mix (P <sub>B</sub> )		Bulk S.G of agg		Effect S.G of aggregate (G <sub>a</sub> )		Max. S.G of paving mix (G <sub>m</sub> )		Mare (grams) in			Vol of specimen (cc)			Bulk S.G of compo mix (g/cc)	Air voids, %	VMA, %	VFA, %	V <sub>b</sub>	V <sub>ba</sub>	V <sub>be</sub>		V <sub>bc</sub>	Pha	Read	Stability (kN)	Adjusted	Fines, mm	
	A	B	B	C	C	D	E	F	G	H	I	J	K	L							M	N							O
A	4.0	2.594	2.623	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
B	4.0	2.594	2.623	2.466	1241.1	678.7	1242.7	564.0	2.201	10.8	18.6	42.0	8.7	1.2	7.5	8.7	1.2	7.5	8.7	1.2	7.5	8.7	1.2	7.5	8.7	1.2	7.5	8.7	2.18
C	4.0	2.594	2.623	2.466	1223.1	669.7	1224.5	584.8	2.205	11.0	18.8	41.4	8.7	1.2	7.5	8.7	1.2	7.5	8.7	1.2	7.5	8.7	1.2	7.5	8.7	1.2	7.5	8.7	2.20
A	4.5	2.594	2.623	2.447	1248.0	686.6	1250.3	563.7	2.214	10.8	18.5	48.5	9.9	1.6	8.2	9.9	1.6	8.2	9.9	1.6	8.2	9.9	1.6	8.2	9.9	1.6	8.2	9.9	2.86
B	4.5	2.594	2.623	2.447	1249.0	687.9	1252.6	564.7	2.212	9.6	18.6	48.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	2.83
C	4.5	2.594	2.623	2.447	1242.0	681.6	1244.5	562.9	2.206	9.8	18.8	47.6	9.8	1.6	8.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	1.6	8.2	9.8	2.82
A	5.0	2.594	2.610	2.409	1256.9	695.3	1259.7	564.2	2.211	7.9	18.4	57.1	11.0	2.1	9.0	11.1	2.1	9.0	11.1	2.1	9.0	11.1	2.1	9.0	11.1	2.1	9.0	11.1	3.06
B	5.0	2.594	2.610	2.409	1251.6	693.9	1253.0	593.1	2.230	7.5	18.0	58.6	11.1	2.1	9.0	11.1	2.1	9.0	11.1	2.1	9.0	11.1	2.1	9.0	11.1	2.1	9.0	11.1	3.03
C	5.0	2.594	2.610	2.409	1254.5	694.4	1256.8	562.4	2.231	7.8	18.3	57.5	11.0	2.1	9.0	11.0	2.1	9.0	11.0	2.1	9.0	11.0	2.1	9.0	11.0	2.1	9.0	11.0	3.10
A	5.5	2.594	2.595	2.389	1259.6	704.4	1260.8	586.4	2.224	5.2	17.5	70.1	12.3	2.5	9.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	4.21
B	5.5	2.594	2.595	2.389	1238.2	706.3	1239.4	584.9	2.207	5.1	17.4	70.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	2.5	9.8	12.3	4.21
C	5.5	2.594	2.595	2.389	1231.7	697.0	1232.6	583.0	2.235	5.0	17.8	68.0	12.3	2.5	9.9	12.3	2.5	9.9	12.3	2.5	9.9	12.3	2.5	9.9	12.3	2.5	9.9	12.3	4.23
A	6.0	2.594	2.600	2.376	1270.3	715.8	1270.8	585.0	2.289	3.7	17.1	76.3	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	4.53
B	6.0	2.594	2.600	2.376	1248.5	701.7	1249.3	587.6	2.280	4.0	17.4	57.6	13.5	3.0	10.5	13.5	3.0	10.5	13.5	3.0	10.5	13.5	3.0	10.5	13.5	3.0	10.5	13.5	4.46
C	6.0	2.594	2.600	2.376	1256.0	708.3	1257.2	588.9	2.288	3.7	17.1	78.4	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	4.56
									Average =	3.8	17.2	77.9	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	3.0	10.6	13.6	4.52

Remarks- All samples prepared with 15% glass replaced of natural aggregate



## **Appendix B**

### **Test Results from Marshal Immersion Test**

# EFFECT OF WATER ON COMPRESSIVE STRENGTH OF COMPACTED BITUMINOUS MIXTURE

## ASTM D 1074/1075 AASHTO 167

### ASPHALT / BITUMEN

Source	AACRA
Grade	85/100
Specific Gravity (G <sub>se</sub> )	1.02
Glass Content	0%

SAMPLE No.	Asphalt, by Wt of Total mix (Pb)	Bulk S.G of agg	Efct S.G of aggregate (G <sub>sc</sub> )	Mass ( grams) in			Vol of specimen (cc)	Bulk S.G of cmptd mix (gm/cc)	Compressive Strength	
				Air dry	Water	Air SSD			Load (KN)	Compressive strength (Mpa)
	A	B	C	E	F	G	H	J	K	L
	-	-	-	-	-	-	G - F	E / H	Load (KN)	Compressive strength (Mpa)
A	5.27			1248.6	703.8	1250.5	546.7	2.284	26.7	3.4
B	5.27	Air bath for 4 hours	25.000	1241.3	701.4	1244.6	543.2	2.285	25.7	3.3
C	5.27			1242.6	700.1	1243.5	543.4	2.287	26.3	3.3
				Average				2.285	26.2	3.3
1	5.27	Water bath for 24 hrs. & 25 for 2 hr		1256.2	690.0	1257.7	567.7	2.213	24.1	3.1
2	5.27			1254.0	697.5	1258.2	560.7	2.236	24.3	3.1
3	5.27			1258.9	694.9	1261.6	566.7	2.221	24.5	3.1
				Average =				2.224	24.3	3.1

Where S1 = Compressive strength of dry specimens (A,B,C)

S2 = Compressive Strength of immersed specimens (1,2,3)

Index of retained strength % = (S2/S1) \*100= **93.0**

**EFFECT OF WATER ON COMPRESSIVE STRENGTH OF COMPACTED BITUMINOUS MIXTURE**

**ASTM D 1074/1075 AASHTO 167**

**ASPHALT / BITUMEN**

Source	AAARA
Grade	85/100
Specific Gravity	1.02
Glass Content	5%

SAMPLE No.	Asphalt, by Wt of Total mix (Pb)	Bulk S.G of agg	Bulk S.G of aggregate (G <sub>w</sub> )	Mass ( grams) in			Vol of specimen (cc)	Bulk S.G of compacted mix (gm/cc)	Compressive Strength	
				Air dry	Water	Air SSD			K	L
		B	C	E	F	G	H	J	K	L
		-	-	-	-	-	G - F	E / H	Load (KN)	Compressive strength
A	4.97			1237.5	696.6	1240.0	543.4	2.277	24.4	3.1
B	4.97	Air bath for 4 hours	25.000	1244.6	701.9	1249.0	547.1	2.275	24.2	3.1
C	4.97			1265.4	718.8	1274.0	555.2	2.279	24.0	3.0
				Average =				2.277	24.2	3.1
1	4.97	Water bath for 24 hours	60 for 24 hrs. & 25 for 2 hr	1242.5	700.4	1246.3	545.9	2.276	22.2	2.8
2	4.97			1244.9	701.8	1248.5	546.7	2.277	22.1	2.8
3	4.97			1246.1	702.9	1249.9	547.0	2.278	22.3	2.8
				Average =				2.277	22.2	2.8
<p align="center">Index of retained strength % = (S2/S1) *100 = <b>91.3</b></p> <p align="center">Where S1 = Compressive strength of dry specimens (A,B,C)</p> <p align="center">S2 = Compressive Strength of immersed specimens (1,2,3)</p>										

**EFFECT OF WATER ON COMPRESSIVE STRENGTH OF COMPACTED BITUMINOUS MIXTURE**

**ASTM D 1074/1075 AASHTO 167**

**ASPHALT / BITUMEN**

Source	AACRA
Grade	85/100
Specific Gravity	1.02
Glass Content	10%

SAMPLE No.	Asphalt, by Wt of Total mix (Pb)	Bulk S.G of agg	Efct S.G of aggregate (G <sub>se</sub> )	Mass (grams) in			Vol of specimen (cc)	Bulk S.G of cmptd mix (gm/cc)	Compressive Strength	
				Air dry	Water	Air SSD			K	L
	A	B	C	E	F	G	H	J	K	L
	-	-	-	-	-	-	G - F	E / H	Load (KN)	Compressive strength (Mpa)
A	5.27			1237.9	696.3	1242.4	546.1	2.267	22.0	2.8
B	5.27	Air bath for 4 hours	25,000	1248.6	699.3	1249.5	550.2	2.269	22.2	2.8
C	5.27			1261.0	707.3	1262.8	555.5	2.270	22.5	2.8
				Average =				<b>2.269</b>	<b>22.2</b>	<b>2.8</b>
1	5.27	Water bath for 24 hrs. & 25 for 2 hr		1245.5	697.9	1247.1	549.2	2.268	20.0	2.5
2	5.27			1247.7	699.4	1249.3	549.9	2.269	20.5	2.4
3	5.27			1248.1	700.5	1250.3	549.8	2.270	20.1	2.5
				Average =				<b>2.269</b>	<b>20.2</b>	<b>2.5</b>
Index of retained strength % = (S2/S1) *100=				88.1		Where S1 = Compressive strength of dry specimens (A,B,C) S2 = Compressive Strength of immersed specimens (1,2,3)				

**EFFECT OF WATER ON COMPRESSIVE STRENGTH OF COMPACTED BITUMINOUS MIXTURE**

**ASTM D 1074/1075 AASHTO 167**

**ASPHALT / BITUMEN**

Source	AACRA
Grade	85/100
Specific Gravity	1.02
Glass Content	15%

SAMPLE No.	Asphalt, by Wt. of Total mix (Pb)	Bulk S.G of agg	Bulk S.G of aggregate (G <sub>100</sub> )	Mass (grams) in			Vol of specimen (cc)	Bulk S.G of emptd mix (gm/cc)	Compressive Strength	
				Air dry	Water	Air SSD			K	L
	A	B	C	E	F	G	H	J	K	L
	-	-	-	-	-	-	G - F	E / H	Load (KN)	Compressive strength (Mpa)
A	5.27			1246.2	697.9	1249.1	551.2	2.261	20.0	2.5
B	5.27	Air bath for 4 hours	25.000	1246.2	695.9	1247.3	551.4	2.260	20.4	2.6
C	5.27			1244.7	695.9	1246.2	550.3	2.262	20.2	2.6
				Average				2.261	20.2	2.6
1	5.27	Water bath for 24 hrs. & 25 for 2 hr	60 for 24 hrs. & 25 for 2 hr	1244.5	696.1	1246.8	550.7	2.260	18.8	2.4
2	5.27			1246.8	696.5	1247.7	551.2	2.262	18.3	2.3
3	5.27			1245.9	698.0	1249.0	551.0	2.261	18.0	2.3
				Average =				2.261	18.4	2.3
Index of retained strength % = (S2/S1) *100=				90.9		Where S1 = Compressive strength of dry specimens (A,B,C) S2 = Compressive Strength of immersed specimens (1,2,3)				

# EFFECT OF WATER ON COMPRESSIVE STRENGTH OF COMPACTED BITUMINOUS MIXTURE

## ASTM D 1074/1075 AASHTO 167

### ASPHALT / BITUMEN

Source	AACRA
Grade	85/100
Specific Gravity (G <sub>b</sub> )	1.02
Glass Content	20%

SAMPLE No.	Asphalt, by Wt of Total mix (Pb)	Bulk S.G of agg	Bulk S.G of aggregate (G <sub>sc</sub> )	Mass (grams) in			Vol of specimen (cc)	Bulk S.G of cmptd mix (gm/cc)	Compressive Strength	
				Air dry	Water	Air SSD			K	L
	A	B	C	E	F	G	H	J	K	L
	-	-	-	-	-	-	G - F	E / H	Load (KN)	Compressive strength (Mpa)
A	5.27			1245.9	696.5	1248.5	552.0	2.257	18.5	2.3
B	5.27	Air bath for 4 hours	25	1238.9	691.9	1241.8	549.9	2.253	18.3	2.3
C	5.27			1235.3	689.2	1238.2	549.0	2.250	18.1	2.3
				Average				2.253	18.3	2.3
1	5.27			1240.3	691.6	1242.1	550.5	2.253	16.0	2.0
2	5.27	Water bath for 24 hours	60 for 24 hrs. & 25 for 2 hr	1241.7	692.5	1243.9	551.4	2.252	16.0	2.0
3	5.27			1244.5	694.5	1246.6	552.1	2.254	16.7	2.1
				Average =				2.253	16.2	2.0

Index of retained strength % = (S2/S1) \*100=

88.4

Where S1 = Compressive strength of dry specimens (A,B,C)

S2 = Compressive Strength of immersed specimens (1,2,3)

# Appendix C

## Equations

$$G_{mb} = A / (B - C) \dots\dots\dots Eq 1$$

**Where**

$G_{mb}$  = bulk specific gravity of compacted specimen  
 A = mass of the dry specimen in air, g  
 B = mass of the saturated surface-dry specimen in air, g, and  
 C = mass of the specimen in water, g

$$V_a = 100 \left[ 1 - \frac{G_{mb}}{G_{mm}} \right] \dots\dots\dots Eq 2$$

**Where**

$V_a$  = Air void content, volume %  
 $G_{mb}$  = Bulk specific gravity of compacted mixture  
 $G_{mm}$  = Theoretical maximum specific gravity of loose mixture

$$VMA = V_a - V_{be} \quad \text{or} \quad \dots\dots\dots Eq 3$$

$$VMA = 100 \left[ 1 - \frac{G_{mb}(1 - P_b)}{G_{sb}} \right] \dots\dots\dots Eq 4$$

**Where**

**VMA** = Voids in the mineral aggregate, % by total mixture volume  
 $V_a$  = Air void content, % by total mixture volume  
 $V_{be}$  = Effective binder content, % by total mixture volume

$$P_b = 100 \left[ \frac{M_b}{(M_s + M_b)} \right] \dots\dots\dots Eq 5$$

**Where**

$P_b$  = Total asphalt binder content, % by mix mass  
 $M_b$  = Mass of binder in specimen  
 $M_s$  = Mass of aggregate in specimen

$$V_b = \frac{P_b \cdot G_{mb}}{G_b} \dots\dots\dots Eq 6$$

**Where**

$V_b$  = Total asphalt binder content, % by total mix volume  
 $P_b$  = Total asphalt binder content, % by mix mass  
 $G_{mb}$  = Bulk specific gravity of the mixture  
 $G_b$  = Specific gravity of the asphalt binder

$$V_{ba} = G_{mb} \left[ \frac{P_b}{G_b} + \frac{P_s}{G_{sb}} - \frac{100}{G_{mm}} \right] \dots\dots\dots Eq 7$$

**Where**

- V<sub>ba</sub> = Absorbed asphalt content, % by total mixture volume
- G<sub>mb</sub> = Bulk specific gravity of the mixture
- P<sub>b</sub> = Total asphalt binder content, % by mix mass
- G<sub>b</sub> = Specific gravity of the asphalt binder
- P<sub>s</sub> = Total aggregate content, % by mix mass  
= 100 - P<sub>b</sub>
- G<sub>sb</sub> = Average bulk specific gravity for the aggregate blend
- G<sub>mm</sub> = Maximum specific gravity of the mixture

$$V_{be} = V_b - V_{ba} \dots\dots\dots Eq 8$$

**Where**

- V<sub>be</sub> = Effective asphalt content, % by total mixture volume
- V<sub>b</sub> = Total asphalt binder content, % by mixture volume
- V<sub>ba</sub> = Absorbed asphalt content, % by total mixture volume

$$P_{be} = P_b \left( \frac{V_{be}}{V_b} \right) \dots\dots\dots Eq 9$$

$$P_{ba} = P_b - P_{be} \dots\dots\dots Eq 10$$

**Where**

- P<sub>be</sub> = Effective asphalt binder content, % by total mass
- P<sub>b</sub> = Asphalt binder content, % by total mass
- V<sub>be</sub> = Effective asphalt binder content, % by total mixture volume
- V<sub>b</sub> = Asphalt binder content, % by total mixture volume
- P<sub>ba</sub> = Absorbed asphalt binder, % by total mixture mass

$$VFA = 100 \left( \frac{V_{be}}{V_{MA}} \right) \dots\dots\dots Eq 11$$

$$VFA = 100 \left( \frac{V_{MA} - V_a}{V_{MA}} \right) \dots\dots\dots Eq 12$$

**Where**

VFA = The voids filled with asphalt, as a volume percentage.

# **Appendix D**

## **Photos**



**Sample Preparation**



**Crushed glass with different sieve size**



Samples in water and air bath for Marshall Immersion Test



Compressive strength measurement



Marshall mix samples