ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EVALUATION OF ASPHALT ROAD PAVEMENT CONTAINING RECYCLED ASPAHLT PAVEMENT AS A PARTIAL MATERIAL IN ASPHALT BINDER COURSE MIX IN LABORATORY

(Case study: Ayertena – Alem Bank – Yeshi Debele Road Project)

BY: TAMRAT KEWETI GIDIRSA

A thesis submitted to the school of Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering.

(Road and Transportation Engineering)

Advisor: Alemayehu Ambo (PhD)

January, 2020

Addis Ababa, Ethiopia

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

EVALUATION OF ASPHALT ROAD PAVEMENT CONTAINING RECYCLED ASPAHLT PAVEMENT AS A PARTIAL MATERIAL IN ASPHALT BINDER COURSE MIX IN LABORATORY

(Case study: Ayertena - Alem Bank – Yeshi Debele Road Project)

BY: TAMRAT KEWETI GIDIRSA

Approved by the Board of Examiners

Name	Signature	Date
____________________	________________	______________
ADVISOR		
____________________	________________	______________
EXAMINER (Internal)		
____________________	________________	______________
EXAMINER (External)		
____________________	________________	______________
CHAIRMAN		

Table of Contents

DECLARATION

I declare that this thesis entitled "EVALUATION OF ASPHALT ROAD PAVEMENT CONTAINING RECYCLED ASPAHLT PAVEMENT AS A PARTIAL MATERIAL IN ASPHALT BINDER COURSE MIX IN LABORATORY (case study Ayertena - Alem Bank - Yeshi Debele Road Project)" is my original work. This thesis has not been presented elsewhere for assessment and award of any degree or diploma, and all sources of materials used for the thesis have been duly acknowledged.

Candidate:

Name: Tamrat Keweti Gidirsa

Signature: ---

Place: Addis Ababa University, Addis Ababa Institute of Technology.

School of Civil and Environmental Engineering

Date of submission: January, 2020 G.C

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AACRA:	Addis Ababa City Roads Authority
AASHTO:	American Association of State Highway and Transportation Officials
AC:	Asphalt Concrete
ASTM:	American Society for Testing and Material
ACV:	Aggregate Crushing Value
AIV:	Aggregate Impact Value
BS:	British standard
BC:	Bitumen Content
EN:	European Standards
ERA:	Ethiopian Roads Authority
FHWA:	Federal Highway Administration
HMA:	Hot Mix Asphalt
HMAR:	Hot Mix Asphalt Recycling
LAA:	Loss Angles Abrasion
MS-2:	Manual Series-2
NAPA;	National Asphalt Pavement Association
RAP:	Recycled Asphalt Pavement
RSDP:	Road Sector Development Program
TFV:	Ten Percent Fines Value
VFA:	Void Filled With Asphalt
VIM:	Void In Mix
VMA:	Voids In mineral Aggregates

ACKNOWLEDGEMENT

First of all I would like to thank the Almighty God, Who gave me the commitment and tolerance to pass various obstacles and come up to the accomplishment of this thesis. Next to God, I would like to express my gratitude to all those who gave me the possibility to complete this thesis. I am expressing my deepest appreciation to my advisor Dr. Alemayehu Ambo for his valuable advice, timely comments and thorough guidance throughout the work of this thesis.

I would like to also express my appreciation to all organizations and individuals who contributed directly or indirectly to this thesis and provided the necessary materials and support for its realization. Especially, I would like to thank the Addis Ababa City Roads Authority, Research Technology Transfer and laboratory Directorate staff who gave me the chance and assistance to do the necessary laboratory works. In addition, I would like to thank Eng. Zewdie Eskinder & Co.PLC for providing asphalt mix design data of the project under the case study.

Tamrat Keweti Gidirsa

Addis Ababa, January, 2020 G.C

ABSTRACT

Asphalt pavements deteriorate with traffic and time. Maintenance and overlaying may solve minor to medium pavement distress problems. When the condition of a pavement becomes badly deteriorated, rehabilitation of the pavement may become an economic and feasible solution. Rehabilitation of a pavement requires removal of pavement surfaces. Currently Addis Ababa city is undertaking various rehabilitation, upgrading, construction of new roads and regular maintenance works for existing road networks, this is basically dependent on the utilization of natural and industrial resources which enables to produce huge amount of recycled asphalt pavement. There is an insignificant effort made for the utilization of this used asphalt pavement produced due to lack of technology and specification.

This thesis presents a study into the possibilities of using Recycled Asphalt Pavements (RAP) as an alternative aggregate and bitumen in new asphalt binder course mixtures. Following the determination of the bitumen content, the aggregate gradation of RAP materials, Marshall Stability tests and moisture susceptibility tests were conducted to evaluate the mechanical properties of the asphalt binder mixture containing RAP. Besides, cost-benefit analysis was made to investigate the advantages and disadvantages of partial substitution of RAP as compared to the conventional HMA.

The experimental and theoretical results presented in this thesis prove that the asphalt binder course mixtures can be successfully produced using RAP material. Moreover, it was found that Asphalt binder course mixture containing RAP exhibits advantage in terms of cost compared to the conventional HMA.

Key Words: Asphalt Binder Course, Hot Mix Asphalt, Performance, Recycled Asphalt Pavement.

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

In the context of Ethiopia, road is the most important infrastructure that provides access to rural and urban areas in the country. It plays crucial role to reduce transportation costs and support economic growth in the country (ERA Road Sector Development Program: 19 Years Assessment, 2016).

Road transport is the dominant mode and accounts for 90 to 95 percent of motorized inter-urban freight and passenger movements. However, because of limited road network, provision of infrastructure has remained one of the formidable challenges for Ethiopia in its endeavor towards socio-economic development and poverty reduction (ERA, 2008a).

To address the problems in the road sector, the Ethiopian Government launched the Road Sector Development Program (RSDP) in 1997. Since then, four phases of RSDP were implemented over the period of 1997 - 2015 and the fifth phase RSDP V has been implemented since July 2015.Over nineteen years of RSDP, physical works consisting of rehabilitation and upgrading of trunk and link roads, construction of new link roads, rural roads and district roads and maintenance of federal and regional roads have been carried out by the Ethiopian Roads Authority (ERA); whereas, Regional Roads Authorities (RRAs), Woreda Road offices (WRO), communities and municipalities have been carrying out improvement and maintenance of roads under their jurisdictions (ERA Road Sector Development Program: 19 Years Assessment, 2016)

Construction and maintenance of asphalt roads is not an easy investment. It requires a huge amount of expenditure with foreign currency. For instance, over the nineteen years of the RSDP, physical works have been undertaken on a total of 128,470 km of roads, excluding routine maintenance works and community roads. The total budget for the planned works during this period amounted to ETB 232.5 billion (USD 15.9billion). The total amount disbursed in the same period, stood at ETB 266.2 billion (USD 17.4billion)(ERA Road Sector Development Program: 19 Years Assessment, 2016).

The rehabilitation, upgrading, new road construction and regular maintenances of all the federal, regional and administrational road projects are undertaking the conventional pavement construction method where virgin construction materials are almost the only option.

The concept of recycling old/existing pavement materials proved its potential to serve as an alternative road construction material in the developed world as a means of reducing huge financial outlays through proper utilization of scarce natural resources and environmental impacts since 1970s. Existing asphalt pavement materials are commonly removed during resurfacing, rehabilitation, or reconstruction operations. Once removed and processed, the pavement material becomes Recycled asphalt pavements (RAP), this contains valuable asphalt binder and aggregate (Federal Highway Administration, April 2011).

RAP are constructed using a combination of reclaimed asphalt pavement material and new paving material, where the aged surface layer is milled, grinded, sieved and recombined with new binder and aggregate in a predetermined percent. The use of RAP to new asphalt mixes reduces the requirement for new binder and aggregates used for pavement construction and also the amount of landfill required for disposing the reclaimed material. Generally speaking, the use of RAP in addition to economic, environmental and social benefit, it's important for sustainable resource utilization.

Currently, great emphasis is placed on sustainable construction and infrastructure. The Leadership in Energy and Environmental Design (LEED) program has seen a dramatic increase in prominence in the past few years and public agencies across the country are modifying building construction requirements to lessen the effect of such construction on the environment. One way to construct environmentally sound roads is through the use of recycled materials. More recently, increased awareness of the environment and in particular, the concern over guaranteeing sustainable development, and the pressing need to organize waste management have all contributed to enhancing the image of recycling as an important and even priority instrument for solving the problem of waste materials. Environmental awareness has also awakened recognition of the possible economic value of recyclable wastes through recycling into secondary raw materials.

Additionally, the interest in the use of RAP has increased dramatically due to the recent prices increases in crude oil and energy in general: by reusing aggregate and asphalt from deteriorated Pavement, the need for new materials is appreciably reduced and the overall cost of the improved pavement will be less.

Ultimately, recycling asphalt creates a cycle of reuse that optimizes the use of natural resources and sustains the asphalt pavement industry. Therefore, the aim of this thesis will be basically to contribute in opening the eyes of concerned stakeholders in the industry through laboratory investigation to be made on partial substitution of reclaimed asphalt layers, specifically by taking the case of Addis Ababa city.

1.2. Problem Statement

Asphalt pavements deteriorate with traffic (especially heavy trucks) and time. Maintenance and overlaying may solve minor to medium pavement distress problems. When the condition of a pavement becomes badly deteriorated, reconstruction of the pavement may become an economical and feasible solution. Reconstruction of a pavement requires removal of pavement surfaces. For the most part, the removed pavement surfaces are wasted.

Due to its growing economy, Ethiopia is spending huge investment in the road construction industry at national and regional levels. This industry is basically dependent on the utilization of natural and industrial materials either for new construction or maintenance works. The increasing demand of road network, rapid price increase of Asphalt Bitumen, Lack of quarry sites for production of natural aggregate around the city, environmental pollution during production of natural aggregate and Hot Mix Asphalt (HMA) and large waste of reclaimed asphalt Pavement due to major rehabilitation and maintenance work are all considered as challenges for the industry.

According to Addis Ababa City Road Authority, Road Maintenance Directorate, currently, there are many ongoing rehabilitation and upgrading projects around the city as main roads which were originally surfaced by asphalt concrete. However, according to the Directorate, there is an insignificant effort made for recycling due to lack of research and the fact that RAP materials are often thought to be inferior for the use in HMA.

1.3. Objectives of the study

1.3.1. General Objectives

The general objective of this research is to assess the viability of Reclaimed Asphalt Pavement for use in the Asphalt Binder course mix through Marshall Mix design method in the laboratory.

1.3.2. Specific Objectives

The specific objectives of this research are the following:

- To evaluate and compare milled RAP Aggregate and Virgin aggregate properties.
- To determine the optimum percentage of bitumen to be added in the Asphalt binder course mix containing recycled asphalt pavement for confronting the required specification by making trial at different percentages.
- To determine the effect of Recycled Asphalt pavement on basic properties (Moisture sensitivity, Stability, Flow, VIM, VMA and VFA) of the Asphalt binder course mix containing RAP Scope of the Study

1.4. Scope of the Study

This study has been aimed in assessing and evaluating laboratory properties of asphalt binder course mix containing varying amount of reclaimed asphalt as a partial material. The material used is taken from Ayertena - Alem Bank – Yeshi Debele road section (case study) that was milled for rehabilitation purpose by milling machine.

1.5. Limitation of the Study

The results of the study, which were successful at laboratory level, shall be tested for practical application to measure the properties of the HMA which contain RAP through a trial section in Addis Ababa city. Due to budget constraints, the time required for application, technological facilities, and machineries required for demonstration are beyond the capacity of an individual researcher; therefore, the study was limited at laboratory level. Besides, test on extracted bitumen from RAP material were not conducted due to limitations of Laboratory Apparatus.

1.6. Organization of the Report

This report is divided into five chapters. Chapter 1 presents the background, problem statement, research objectives, scope and limitation of the study. Chapter 2 describes literatures related to history, the present state of knowledge of RAP and laboratory and field studies of RAP containing asphalt paved road roads. The properties of the materials, equipment, and test procedures used in are presented in Chapter 3. Chapter 4 presents test results and data analysis. Conclusions and recommendations for future work are provided in Chapter 5.

CHAPTER TWO

LITERATURE REVIEW

2.1. General

Road pavements passed different stages in their developments since the start of the 20^{th}century. The introduction of standards for pavement construction along with the introduction of mechanical means of producing and laying materials helped develop the modern road network. The increased traffic, rise in construction costs and environmental impacts, have led to the introduction of performance specification and development of mixtures which reduce environmental impacts (Don-Caster 1999).

Asphalt pavement was first used in Paris in 1854; they were made from natural rock asphalt. The rock was limestone impregnated with binder (traditionally called bitumen).It was very expensive material and was consequently utilized at prestigious sites only (Nicholls1997).

Bituminous mixtures are used in construction of almost all the flexible layers of a road. Asphalt is favorable for use in the layers due to its high binder content, whereas macadam is selected for the upper layers for heavily trafficked roads, which demand improved resistance to permanent deformation (rutting). The characteristics of asphalt and macadam road layers are:

- Better load spreading properties than in other layers.
- They can be quickly and accurately spread by machinery.
- Strength is available for use as soon as the material is cooled down.
- Impervious to water and not affected by frost.
- Cost is greater than uncoated materials

According to Modern Road Pavements Design, a pavement is a load bearing, multi-layered structure constructed so that the imposed surface load is transmitted and spread onto a natural, or formed, and foundation in such a way that neither it, nor the structure itself is overstressed or permanently deformed during a reasonable life span. For many years, pavements were not designed to suit the requirements of traffic. The traffic was controlled to suit the road. Now roads are designed to carry the loads imposed by vehicles (David 2005).

The four main aims of pavement design are:

- Ensure that sub-grades do not fail due to repetitive traffic loading over the life of the pavement.
- Ensure pavement foundations provide an adequate construction platform on which to transport, lay and compact other pavement mixtures without any damage.
- Provide layer thickness and mixtures that can carry traffic loading over the life of the pavement without deterioration due to deformation or cracking.
- Achieve all the above economically.

2.2. Pavement Design and Construction

The design process begins by deciding what type of pavement is required and what methodology is going to be applied in determining layer thicknesses (Don-Caster 1999). There are two main types of pavement construction, rigid and flexible pavement construction.

2.2.1. Flexible Pavement Construction

Flexible pavement is a prominent pavement type commonly built with hot-mix asphalt (HMA) or asphalt surface treatments as a finishing layer. Flexible pavements having such surface finishes are very effective in providing load-carrying capacity, resisting distortion, providing a smooth riding surface, minimizing the intrusion of moisture from the surface, resisting traffic wear, and retaining anti-skid properties.

HMA is the highest quality asphalt surfacing mixture where both bitumen & aggregates are heated to an elevated temperature for a better quality and development of required flexible pavement characteristics.

The layers in a flexible pavement and their function can be summarized as follows:

Sub grade: The Sub grade is the natural or made up ground on which the pavement is constructed. On reconstructed ground it is usually well compacted by traffic; whereas, on new roads it is carefully shaped and compacted to the appropriate level and profile. The surface of the Sub grade is known as the formation.

Capping layer: A capping layer is sometimes laid over a weak sub grade to act as a sub grade improvement layer. This is usually a relatively low quality, cheap, locally available aggregate. With some soils, sub grade improvement can be achieved by treating the surface with lime or cement. In either case the aim is to ensure adequate support for plant used to lay the sub-base (BACMI 1992).

Sub-base: The sub-base is a layer of graded granular material which provides extra strength to the sub grade which consists of natural granular or processed granular material such as gravel, sand or stone fragments and shall be clean from dirt, organic matter and other deleterious substance. The materials used for the construction of sub-base layers shall be either:

- Natural Gravel;
- Scoria (Cinder Gravel);
- Weathered Rock;
- Crushed Gravel;
- Crushed Rock or crushed Boulders;
- Recycled Pavement Material.
- Any other granular material complying with the required specification and a
- Combination of any of the above (AACRA specification 2004).

Sub-base material shall be spread on the approved sub-grade by mechanical means without segregation. The material shall be loosely spread in layers to give a compacted thickness not exceeding 200 mm and not less than 100mm. The final compacted layer shall be free from concentrations of coarse or fine materials. The surface of each completed layer shall be moistened prior to the construction of the succeeding layer. The optimum moisture content shall be determined according to AASHTO T 180 method D. The aggregate shall be mixed and the moisture content adjusted to obtain a uniform mixture with moisture content within 2 per cent of the optimum moisture content. The mixture shall be spread and shaped on the prepared surface in a uniform layer (ERA 2013 Standard Technical specification).

Base course: The materials used for the construction of road base layers shall be one of the following materials: (AACRA specification 2004)

- Natural Gravel and/or crushed Gravel;
- Crushed rock or Crushed boulders;

- Naturally occurring granular materials and weathered rock, either unsterilized or chemically stabilized material.

The main functions of the Base course layer are:

- Provides a working platform for construction traffic and a compaction platform for the subsequent laying of the bituminous mixtures.
- Acts as an insulating layer in conjunction with the bituminous mixtures to protect the underneath layer from frost.
- May be used as a drainage layer to remove water from the pavement. The extent to which a sub-base material should be free draining depends on the amount of water likely to enter that layer. In thick layer of bituminous mixtures used for heavily trafficked pavements, water volumes are likely to be small. It is therefore crucial to have a layer which is dense and can withstand and transmit construction and traffic stresses. (Hunter 1994).

Asphalt binder course: This is the first of the bituminous layers and is the primary structural layer of the pavement. The material used reflects the traffic loading and the layer thickness is a function of material stiffness properties and the amount of traffic the road will carry during its service life. The function of the layer is to:

- Reduce the vertical stresses the on pavement layers
- Reduce flexural stresses in the surfacing by limiting the amount of deflection under load.
- Provide an accurate surface on which to lay the preceding layer. The asphalt binder course must achieve all the above without cracking prematurely.

Wearing course: is part of pavement upon which the traffic travels. It is slightly denser, and has a smaller nominal size of aggregate to allow more accuracy and to finer tolerances than the Asphalt binder course. It's is responsible for creating smooth riding quality in the pavement. It has several functions. These are: (David 2005)

- Seal the surface against the ingress of water.
- Provides skidding resistance.
- Shed water into surface water drainage systems.
- Provide a quite running surface.

- Give good aesthetic qualities to the road such as color.
- Carry road markings to aid safe usage by traffic.

2.3. Road Maintenance

Road sections having HMA surfacing are constructed for a longer service life through huge expenditures of public funds or other fund sources. However, after years of services, the quality of HMA surfacing declines gradually and needs preventive maintenance or reconstruction depending on the level of distress occurred on the pavement. In addition, after several years of services HMA mixtures have the greatest potential to be reused/ recycled in a newly constructed flexible pavement structure (Basic Asphalt Recycling Manual of FHWA, 2001).Pavement maintenance involves the assessment of the existing pavement condition by a variety of methods and the choice and implementation of the most appropriate and cost-effective solution. (BACMI 1992).

2.4. Overview of Recycled Asphalt Pavement Materials

Recycled Asphalt Pavement (RAP) is a removed or reprocessed material derived from existing aged asphalt pavements or plant hot mix asphalt (HMA) waste containing asphalt and aggregate. Generally, asphalt pavements are removed either by milling using a milling machine or full depth removal using a bulldozer or pneumatic pavement breaker. The removed asphalt material is processed using a series of operations including crushing, screening, conveying and stacking. The RAP is processed either at the central processing plant or on site. (Randy C.West, 2010)

Recycling is defined as "the reuse, usually after some processing, of a material that already has served its first-intended purpose". Relative to asphalt pavement recycling, there are several methods available. Therefore, each project being considered for recycling must be carefully evaluated to determine the method most appropriate. The factors should include:

- Existing pavement condition;
- Existing pavement material types and thickness;
- Recycled pavement structural requirements; and
- Availability of recycling additives (Basic Asphalt Emulsion Manual, Asphalt Pavement Recycling March 2004).

With increased demand and limited aggregate and binder supply, HMA producers have began using reclaimed asphalt pavement (RAP) as a valuable component in HMA. As a result, there has been renewed interest in increasing the amount of RAP used in HMA. (FHWA, Reclaimed Asphalt Pavement in Asphalt Mixture, 2011)

While several factors influence the use of RAP in asphalt pavement, the two primary factors are economic savings and environmental benefits. RAP is a useful alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of HMA. The use of RAP also conserves energy, lowers transportation costs required to obtain quality virgin aggregate, and preserves resources. Additionally, using RAP decreases the amount of construction debris placed into landfills and does not deplete nonrenewable natural resources such as virgin aggregate and asphalt binder. Ultimately, recycling asphalt creates a cycle that optimizes the use of natural resources and sustains the asphalt pavement industry (FHWA, Reclaimed Asphalt Pavement in Asphalt Mixture, 2011).

Asphalt recycling is not a new concept. Cold recycling/rehabilitation of roadways with asphalt binders' dates to the early 1900's. The first documented case of asphalt recycling, in the form of Hot In-Place Recycling (HIR), was reported in the literature of the 1930's. However, only moderate advancements in asphalt recycling technology and equipment occurred until the mid-1970's.Two events of the 1970's rekindled the interest in asphalt recycling which has resulted in its worldwide use today. The petroleum crisis of the early 1970's and the development and introduction in 1975 of large scale cold planning equipment, complete with easily replaceable tungsten carbide milling tools, were the catalyst for renewed interest in asphalt recycling. Since that time, the equipment manufacturing and construction industries have been proactive in the development of asphalt recycling methods and technologies which have advanced exponentially in the last 25 years (FHWA, Basic Asphalt Recycling Manual)

Since 1970 for over three decades, two guiding principles of asphalt recycling have been used and these are:

- Mixtures containing RAP should meet the same requirements as mixes with all virgin materials; and

- Mixes containing RAP should perform equal to or better than virgin mixtures (Randy C. West, 2010).

Asphalt paving technologists reacted to this situation by developing recycling methods to reduce the demand on asphalt binder and, thereby, reduce the costs of asphalt paving mixtures. Motivations for recycling include economic savings and environmental benefits.

Environmental benefits include reduced emissions and fuel usage due to reduced extraction and transportation of virgin materials, reduced demands on non-renewable resources, and reduced landfill space for disposal of used pavements. Economic benefits include materials cost savings from replacing apportion of virgin aggregates and binders with RAP as well as reduced costs associated with transporting virgin materials to a site (Randy C.West, 2010).

A number of reasons can be raised for the less utilization of reclaimed asphalt pavement and some of these are: Quality concerns, RAP consistency, Binder grade and blending, Mix design procedures, volumetric requirements, Durability and cracking performance, Dust and moisture content (Copeland 2010).

2.5. Importance of Asphalt Pavement Recycling and Recycling Strategies

Recycling is a quite simple and easily applicable method. Recycling of reclaimed asphalt materials obtains new pavement materials and these results in saving virgin bitumen, virgin aggregate, energy and money. On the other side, the utilization of recycling helps to overcome the problem of disposal of old pavement waste. The advantages of recycling can be summarized as follows (Kandhal & Mallick, 1997):

- Saving of energy;
- Saving of bitumen and aggregates;
- Protection of environment;
- Preservation of the existing pavement geometrics;
- Cost reduction of construction;
- Less loss of time for users and
- Maintaining of existing roadway profile.

Recycling is one of the widespread pavement rehabilitation techniques. The recent increase in price of bitumen is a major factor in prompting the development of recycling. On the other hand, the asphalt industry is constantly encouraging the development of technologies that are cost effective, reduce energy consumption and environmentally friendly (Hodo, Kvasnak, & Brown, 2009). Over the years recycling has become one of the most desirable pavement rehabilitation alternatives. According to the continuous accumulation of performance data, field and laboratory Evaluations of recycled mixes, it is expected that recycling will continue to be the most attractive rehabilitation technique.

The choice of rehabilitation technique should be based on energy conservation, economic consideration, engineering consideration and environmental effects.

- Energy Conservation

The road industry has been seeking to minimize the amount of energy required to manufacture asphalt mixture and to lower asphalt plant emissions through combining energy savings and environmental benefits for many years (Romier, Audeon, David, Martineau & Olard 2007). Reusing of aggregates reduces necessities of quarrying, transportation and the subsequent processing in recycling methods. Consequently, cost and energy is saved in these processes. Recycled asphalt reduces the demand for new bitumen and saves energy at the refinery. Moreover, electric power consumption visibly decreases because of reduced demand for bitumen.

- Economic Consideration

Recycling techniques can be reviewed in terms of the cost of the pavements. Life-cycle costs of the rehabilitation alternatives must also be considered in economic analysis. Life-cycle costs include the initial construction costs as well as the costs of maintenance activities during the life-cycle. This analyzing period consists of costs components which are given as:

- Initial and future rehabilitation costs;
- Maintenance costs;
- Residual values;
- Engineering costs; and
- Costs for travel time, vehicle operation, accidents, delays and extra operating.
- Engineering Consideration

Before selecting a rehabilitation alternative, the engineer should take care about environment, drainage factors and practical limitations. Engineering consideration also depends on the type of original surface where the new pavement layer will be replaced. The most important consideration should be the amount and severity of distress condition on the existing pavement because different recycling techniques can remedy different types of distresses and the most appropriate method should be considered.

- Environmental Effects

Increasing environmental concerns have encouraged the development of using pollution-free, recyclable engineering materials that consume less energy to manufacture (Chiu, Hsu, & Yang, 2007). The most indispensable effect of recycling is the benefit to environment. Before strengthening of deteriorated urban or rural roads, bituminous materials are generally removed and deposited outside of way. This inevitability represents an economic loss and creates environmental problems. The utilization of recycling techniques can provide significant benefits to the nature.

2.6. Asphalt Recycling Methods.

Five broad categories of asphalt recycling techniques have been defined by Asphalt Recycling and Reclaiming Association (ARRA) to describe the various asphalt recycling methods. These categories are:

- Cold Planning (CP);
- Hot In-Place Recycling (HIR);
- Cold Recycling (CR);
- Full Depth Reclamation (FDR) and
- Hot In-Plant Recycling.
- Cold Planning (CP)

This method is automatically controlled removal of asphalt pavement to a desired depth and with restoration of the surface to a desired grade and slope and free of humps, ruts and other imperfections. Cold planning may be used for the roughening or texturing of a pavement to eliminate slipperiness and restore skid resistance. The pavement removal or milling is performed with a self-propelled drum cold planning machine with the reclaimed asphalt pavement (RAP) transferred to trucks for removal from the job site. The resulting pavement can be used immediately by regular traffic and overlaid at some future time or left as a textured surface. The textured pavement created from the milling operation provides a high skid resistant surface (see Figure 2.1 below) that can be driven on immediately or subsequently can be overlaid with a new or recycled asphalt mix.RAP generated from this process is normally hauled to a hot mix recycling Plant for processing and future incorporation into a recycled mix (Asphalt Recycling and Reclamation Association (ARRA), An overview of Recycling and Reclamation method for Asphalt Pavement Rehabilitation, 1992).

Figure 2.1: Typical front loading milling machine and milled pavement surface texture (FHWA, 2001 Basic Aspahlt Recycling Manual)

- Hot In-Place Recycling (HIR)

This method is performed on-site, in-place with the existing pavement typically processed to a depth of from 20 mm to 40mm (3/4 to 1 1/2 inches). The deteriorated asphalt pavement is heated and softened to allow it to be scarified or hot rotary mixed to a specified depth. As required, new hot mix material and/or recycling agent or other liquid additive is added to the reclaimed material. The three hot in place recycling methods are: heater-scarification, repaving and remixing (Asphalt Recycling and Reclamation Association (ARRA), An Overview of Recycling and Reclamation Method for Asphalt Pavement Rehabilitation and Basic Asphalt Emulsion Manual, Asphalt Pavement Recycling, March 2004).

- Cold In-Place Recycling

Cold in-place recycling is an asphalt pavement rehabilitation technique that reuses existing pavement materials. All work is completed while on the pavement being recycled and normally transportation of materials is not required except for the additive being used. The depth of treatment is typically from 3 to 4 inches. In some cases, virgin aggregate may be added to the recycled material to improve the RAP characteristics. Asphalt emulsions normally the additive for the process but asphalt rejuvenating agents also are used. This technique involves pulverizing the existing pavement, sizing of the RAP, incorporation of an additive and the placement and compaction of the recycled mix. (Asphalt Recycling and Reclamation Association (ARRA), An Overview of Recycling and Reclamation Method for Asphalt Pavement Rehabilitation, 1992)

- Full Depth Reclamation (FDR)

Full depth reclamation is a recycling method where all of the asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base course. Additives are used for an improved base which includes imported material, asphalt emulsion and chemical agent such as: calcium chloride, Portland cement, fly ash and lime (Asphalt Recycling and Reclamation Association (ARRA), An Overview of Recycling and Reclamation Method for Asphalt Pavement Rehabilitation, 1992).

Full depth reclamation consists of six basic steps:

- pulverization,
- additive and/or emulsion incorporation,
- spreading,
- compacting,
- shaping, and
- Placement of new asphalt surface (Basic Asphalt Emulsion Manual, Asphalt Pavement Recycling; March, 2004).
- Hot In Plant Recycling

With this method, RAP is combined with new aggregate and an asphalt cement or recycling agent to produce hot mix asphalt (HMA). The principal advantage of central plant hot recycling over insitu methods is that a greater degree of quality control can be achieved. The RAP generally is obtained by pavement milling with a rotary drum cold planning machine. The RAP also may be obtained from a ripping/crushing operation. The mix placement and compaction equipment and procedures are the same as for regular HMA. The ratio or blend of RAP to new aggregate will vary with this dependent on the recycled mix properties desired and the type of hot mix plant. RAP/aggregate blends typically have been from 10:90 to 30:70 with a maximum of 50:50 drum plant (Asphalt Recycling and Reclamation Association (ARRA), An Overview of Recycling and Reclamation Method for Asphalt Pavement Rehabilitation).

The advantages of central plant hot recycling are: environmental savings in both quarrying of raw materials and industrial pollution caused by binder processing, energy saving due to less mixing time, resulting mixture is indistinguishable for all practical purposes from material made of 100% virgin aggregates/binder and the process allows plants to process their own reclaimed material which is particularly necessary for the drum mix plant process.

The constraints of central plant hot recycling are: hot mix processing of bituminous material has the potential to cause emissions of noxious fumes; this may be avoided by ensuring that the heating of the bituminous material takes place away from the direct flame of the burner, transportation of the RAP off site to the plant.

The process of hot mix recycling basically entails the following:

- Reclaiming, hauling and stockpiling existing pavement material;
- Reprocessing of reclaimed material in a central plant; and
- Using the resultant mix in the construction of pavement layer (Hot mix recycling, Pretoria South Africa, 1996).

2.7. Quality Control

Recycled aggregates, however due to a lack of suitable specifications, there has been little basis for applying quality control. It is also due to the fact that these materials are often thought to be inferior to natural aggregates, they are mainly used in lower grade applications, though, suitable quality recycled aggregates may be used successfully in higher grade. The primary requirement for the provision of good quality products is input control for materials received at the recycling plant. Each load of unprocessed material received at the plant should be inspected for acceptance before placed on a stockpile assigned for the different quality aggregates been produced. It is important that stockpiles be kept free of contaminants from the beginning. It easy to understand how bad perceptions of RAP form when there is dirt, rubbish, or vegetation in RAP stockpiles, or when trash is found in the mix when it shows up on the job site or pops out of the pavement a few days after paving. Treat RAP stockpiles as the most valuable material on the plant yard because they are. Truck drivers bringing materials onto the plant yard must be clearly instructed where to dump their loads so that unwanted construction debris does not end up in the RAP stockpile. The plant QC personnel and the loader operator should also continuously monitor unprocessed and processed RAP stockpiles to make sure do not contain deleterious material. Figure 2.2 below shows multiple source RAP pile with dirt contamination.

Figure 2.2: Multiple source RAP pile with dirt contamination (photo at Kality Korki quarry site)

2.8. Managing the Reclaiming Process

RAP may be obtained from several sources. The most common method is through milling operations, also known as cold planning. Two other common sources of RAP are: full-depth pavement demolition and asphalt plant waste. This section discusses the different types of RAP sources.

A. Milling

Milling is a beneficial part of pavement rehabilitation. Advantages of milling include the following:

- removes distressed pavement layers,
- maintains clearances under bridges and avoids buildup of pavement weight on bridge decks,
- avoids filling up curbs and drop-offs at drainage inlets and pavement edges,
- restores pavement grades and profiles, which are important for smoothness,
- leaves a rough texture on the remaining surface that creates a very good bond with an overlay, and
- It is an efficient removal process that can be done within a short lane closure with the paving operations.

Selection of the milling depth is a critical agency decision in planning the rehabilitation of a pavement. Often, a milling depth is based on visual examination of cores to determine the depth of surface cracks and/or the location of weak layers or interfaces. Removal of these distressed or weak layers helps to achieve long-term performance of the overlay.

Milling processes should be closely examined to make sure the milled material is not contaminated with soil, base material, paving or other debris. This is particularly important for deep mills or milling on shoulders or widened roadways. Milled materials that become contaminated should be used only as shoulder material and should be stockpiled separately from RAP to be used in asphalt mix. A recommended maximum limit of 1% deleterious material should be used to evaluate RAP contamination. This limit is consistent with requirements for virgin aggregates. Finally, the milled surface should be inspected for uniform texture. A non-uniform texture resulting from worn or broken tips on the milling drum can cause problems with compaction of thin overlays. It may also cause an unsafe surface for motorcycles if the milled surface is opened to traffic. Figure 2.3 below shows milling machine removing asphalt pavement layer as part of pavement rehabilitation.

Figure 2.3: Milling machine removes asphalt pavement layer as part of pavement rehabilitation (photo at Yeshi Debele site).

B. Pavement Demolition

RAP may also be obtained from complete demolition of an existing pavement using a bulldozer or backhoe. This process is typically limited to small areas of pavement. It is slow and results in large chunks of pavement that may be more challenging to process into a useable recycled material. When pavement rubble is contaminated with underlying layers and soil, it is better for this material to be crushed and used as a shoulder or base material than used in an asphalt mixture. Figure 2.4 below shows pavement rubble from full depth demolition of roadway.

Figure 2.4: Pavement rubble from full depth demolition of roadway

C. Plant Waste

All asphalt plant operations generate some waste during plant start-up, transition between mixes and clean-out. Generally, start-up and shut-down plant wastes have very low asphalt contents. Another form of waste is mix rejected from a project due to incomplete coating or due to the mix temperature being too high or too low for the job. Other situations that may result in wasted mix include trucks loaded with too much mix to finish the job or mix that could not be placed due to inclement weather. These waste materials are often stockpiled for later processing into a recyclable material. Since these waste mixes have not been subjected to environmental aging from years of service, the asphalt binder is less aged than RAP recovered from a road. Waste materials also have fewer fines than other sources of RAP since it was not milled or broken up during demolition. However, waste materials must be thoroughly mixed and processed to make them into uniform, recyclable materials. Waste materials are often combined (Randy C.West, 2010).

2.9. Characteristics of RAP

The characteristics of RAP are largely dependent on the characteristics of the constituent materials and the type of the asphalt concrete [wearing course or binder course] used in old pavements. The aggregates used in the asphalt wearing course and binder course have different requirements, such as aggregate quality and size. This difference leads to the use of higher quality aggregate in the surface layer than in the asphalt base layer. The composition of RAP is influenced by several factors, such as the number of pavement resurfacings, the amount of patching and/or crack sealing, possible presence of prior seal coat applications, and percent of asphalt cement used in each maintenance activity. (David A. 2005)

Knowing characteristics of RAP is important to describe the suitability of RAP as a material for using in asphalt mix. Although different authors have various approaches to discuss the characteristics of RAP, they have similarities in raising common matters that characterizes RAP as a construction material. At the 2nd International Symposium on Environment & Asphalt Pavement which was held during October 2012 in France, Gabriele Lebakli et al. (2012) discuss the characteristics of RAP from the perspective of RAP production, cleanness, moisture content, grading, variability and bitumen content. Similarly, Joel R.M. Olivera et al. (2013) on an International Journal of Pavement Research and Technology raised related concepts for the characterization of RAP as a construction material.

A) RAP Cleanness and foreign material

Gabriele Lebalki et al. (2012) and Joel R.M. Olivera et al. (2013) relate cleanness with the mechanism of RAP production, storage and foreign matters like tar, asbestos & road markings. The production of recycling asphalt granulate is generally produced in two ways, either the pavement is milled with a milling machine or is removed in slabs with an excavator. The cold milling machine allows the separation of different layers with high precision and cleanness to obtain RAP of different type and quality. However, the chance of contamination with the underlying unbound materials is highly likely to occur while using excavators to produce RAP. Though it is difficult to have a well-defined protocol to evaluate the cleanness of the RAP; European Standard EN 12697-42 is commonly referred for the determining the amount and components of foreign matters in RAP which is a visual method. According to EN 12697-42 foreign matter is defined as ‘’matter in the reclaimed asphalt not derived from asphalt pavements or surplus production.

B) RAP Moisture Content

Asphalt pavements are subjected to recycling when they are affected by extended distresses and deep degradations which alter the surface integrity to permit the entry of water into the body of the structure. In this case, the pavement to be reclaimed is potentially wet and depending on the surface damage, it is crucial to choose the most suitable in-situ or in-plant recycling process. (Gabriele Lebakli et al., 2012).

When Recycled Asphalt Pavement aggregate is a component of bitumen emulsion stabilized material, its moisture plays an important role in reducing absorption of water into the aggregate. One of the criteria that need to be met in order to use a specific RAP material in the production of asphalt mixtures is its moisture content, which should not exceed approximately 5% (EN 13108-8). The moisture content specified, to the level of 5% is released by the RAP material while the drying process is undergoing before mixing with other components of pavement materials.

However, a similar or better reduction would be expected for a plant production situation, where the RAP would be dynamically exposed to temperature and air flow that can increase the drying capability. Thus, a production temperature of 150ºC should be selected to increase the productivity of the asphalt plant. This finally assures an adequate drying of the RAP material to reduce the negative influence of the moisture content in the final properties of the recycled mixture (Edward J. Hoppe, 2015)

C) RAP Gradation

The quality of aggregate may degrade to some extent after a milling or crushing process. In addition to the original gradation, the gradation of RAP depends on the milling or crushing process, the type of equipment used for removal, the type of aggregate used in pavement construction, and mixing with underlying base or sub-base aggregate during the removal. The gradation of a milled RAP is generally finer than its original gradation. A crushed RAP is generally not as fine as milled RAP, but is finer than the original gradation of the virgin aggregate crushed with the same type of equipment. In other words, crushing does not cause as much degradation as milling during RAP production (U.S. Department of transportation FHWA-RD-97-148). Typical range of particle size distribution for RAP is depicted in Table 2.1 below.

Table 2.1: Typical range of particle size distribution for RAP

(U.S. Department of transportation FHWA-RD-97-148)

Sieve Size (mm)	Percent finer after processing or milling
37.5	100
25	95-100
19	84-100
12.5	70-100
9.5	58-95
2.36	25-60
1.18	17-40
0.6	10-35
0.3	5-25
0.15	3-20
0.075	2-15

In addition, RAP particles often consist not of a single aggregate particle but are conglomerates of smaller aggregates glued together by the mastic.

D) Variability of RAP

One major factor that affects the mix design with high amounts of RAP materials is the variability of the stockpiles. Stockpiles that are not fractionated or split into more specific sizes can vary from being too coarse or too fine. Binder contents have also been shown to vary in stockpiles that have not been split. Varying stockpiles can cause varying mix designs which could be detrimental to future projects in the field (Russell Edgar Carlson IV, 2014). RAP derived from different sources can have significantly different gradation, oil content and density. This can be due to the milling process, rock source, type of oil, etc. Moreover, combined RAPs from several sources may change the quality of the product throughout the construction project because of this variation. One effective way to deal with this is to identify and segregate the various types of milled HMA. However, this can add expense and would require major changes to the current practices for storing RAP (Russell Edgar Carlson IV, 2014). Different researchers have undertaken multiples of investigations on the issue of variability considering binder content, particle size distribution, maximum dry density, etc. and it was found that RAP materials are prone to variability. Two solutions are recommended for achieving a more uniform RAP product, such as segregating RAP piles by source or adding virgin aggregate to the RAP, which would most likely, can reduce the variability it has (Eric J. MC Garrah, 2007).

On the other hand, Randy C. West (2010) proposed a third approach to minimize the degree of variability in RAP. Accordingly, materials from multiple sources that have different compositions must be processed to create a uniform material suitable for use in a new asphalt mixture. All around the world, contractors have found that they can make a very uniform and high quality RAP from a combination of pavement rubble, millings, and wasted mix. The key to achieving a consistent RAP from multiple sources is a careful blending as part of the processing operations. A bulldozer, excavator, or similar equipment should be used to blend materials from different locations in the multiple-source RAP stockpile as it is fed into the screening and crushing operation. This will tend to average-out variations in the RAP from different sources.

E) RAP Bitumen Properties

In general, asphalt binder demonstrates two stages of aging: short-term and long term. During construction (short-term), asphalt binder is exposed to hot air at temperatures ranging from 135°C to 163°C, resulting in a significant increase in viscosity and changes in the associated rheological and physiochemical properties such as complex shear modulus and adhesion. During service (long-term), asphalt binder also progressively ages and hardens through various mechanisms. Age hardening during construction and service has been associated with six major mechanisms (Roberts et al. 1996; Tyrion 2000; Karlsson and Isacsson 2006) that are stated below:

- ✓ Oxidation through diffusive reaction between the binder and oxygen in the air;
- ✓ Volatilization through evaporation of the lighter components especially during Construction;
- ✓ Polymerization through chemical reaction of molecular components;
- ✓ Thixotropy due to the formation of a structure within the asphalt binder over a long Period of time;
- ✓ Syneresis due to the exudation of thin oily components; and
- ✓ Separation through the removal of oily constituents, resins, and asphaltenes by absorptive aggregates.

The greater the damage to the pavement prior to recycling, the greater the changes are in the properties of the binder. This is illustrated by the reduced oxidation susceptibility in pavements that are better preserved. Stockpiling also accelerates binder aging as the material is more prone to air exposure and oxidation. As asphalt binder reacts and loses some of its components during the aging process, its rheological behavior will naturally differ from virgin materials. This suggests the importance of controlling the blending process between recycled and virgin binders. If the old binder is too stiff, the blend of old and virgin binders may not perform as expected. At small Percentages up to 25% of RAP substitution an aged binder does not significantly affect the properties of the blend of virgin and RAP binder and testing of the extracted asphalt is not required and the grade of the virgin asphalt binder is kept the same as that of the conventional mix (Kennedy et al. 1998). However, when used at intermediate to higher percentages, an aged binder can significantly influence the properties of the blend and may affect the resultant binder grade. Recent modifications have been introduced to conventional asphalt plants in order to reduce aging of the old binder during mix production. This includes counter flow drum mixer and microwave heaters (NAPA 1996).

2.10. Recycling Agents in Hot Mix Asphalt Pavement Recycling

Recycling agents have been defined as organic materials with chemical and physical characteristics selected to restore aged asphalt to desired specifications. In selecting the recycling agent, the viscosity characteristics of the combined aged asphalt binder and the recycling agent are the determining factors. These agents are also known as softening agents, reclaiming agents, modifiers, fluxing oils, extender oils, and aromatic oils (Pavement Recycling Guidelines of FHWA, 1997).

According to pavement recycling guideline (1997), there are four basic purposes for using recycling agents these are:

i. To restore the aged asphalt binder characteristics to a consistency level appropriate for construction purposes and end use of the mix;
ii. Restore the recycled HMA mix to its optimum characteristics for durability;
iii. Provide sufficient additional binder to coat any virgin aggregate added to the recycled mix; and
iv. Provide sufficient additional binder to satisfy mix design requirements.

2.11 Laboratory Test on HMA Containing RAP

Distresses, such as fatigue cracking, rutting and moisture damage develop on asphalt pavements due to environmental exposure and repeated traffic loading. Since RAP contains an aged binder, once blended with a virgin binder, it produces a stiffer mixture (Huang and Vukosavljevic, 2006). The durability or long-term fatigue resistance is a main concern when large quantity of RAP is used in pavement surface or load carrying layers. The incorporation of large quantity of RAP into a new HMA could cause a mixture to become too stiff which in turn, would greatly affect the fatigue performance of the asphalt mixture.

Huang and Vukosavljevic (2006) conducted a research to determine the maximum percentage of RAP that can be incorporated without affecting the performance of mixture. In their study, 0, 10, 20, and 30% RAP were included. They concluded that long-term aging of a binder increased the stiffness of the mixture and in return affected its resistance to fatigue cracking. At a higher percentage of RAP, the mixture became stiffer and the fatigue characteristics of RAP were compromised. They found that 20% RAP could be included without compromising fatigue characteristics.

Tedros M. (2019) conducted an experimental research to determine the maximum amount of RAP that should added to the wearing course mix after the optimum bitumen content of the control mix which conform the required specification is estimated. In his study 0, 10, 20, 30 and 40% RAP were included. Based on the laboratory result carried out the addition of RAP improves the properties of the bituminous mixes and mixes with 20 % RAP would perform better than the virgin and other mixes under similar condition.

2.12 Performance of Pavements Containing RAP

In 1995, the Louisiana Department of Transportation and Development evaluated the performance of ten recycled projects. These projects contained 20% to 50% RAP and had been serviced for six to nine years. The evaluation was done in terms of pavement condition ratings, serviceability, structural analysis, and mix and binder properties. This research showed that pavements containing RAP performed similarly to those with conventional mixtures for a service period of six to nine years. However, pavements containing RAP exhibited slightly more distresses with respect to longitudinal cracking. (Paul, 1996).

Ganuang and Larsen (1987) investigated the performance of hot mixed recycled pavements after 6-year service on Route 4, Burlington, Connecticut. A comparison was made between a conventional mixture and a mixture with 30% RAP. The findings from this study include: (1) no rutting was detected; (2) roughness of the pavement was low; and (3) the viscosity of the extracted asphalt was higher than that of the control mixture.

Kandhal et al. (1995) evaluated the performance of recycled hot mix asphalt in five projects in Georgia. In each project, a recycled section and a control section were investigated. The percentages of RAP used in these projects varied from 10 to 25%. In-situ mix properties, such as percent air void, resilient modulus, and indirect tensile strength, and binder properties were measured. A paired t-test statistical analysis showed no significant difference in these properties of virgin and recycled asphalt pavements that had been in service from 1.5 to 2.25 years. The results from additional ten virgin mix pavements and thirteen additional recycled pavements (evaluated as two independent groups) indicated no statistical difference in the penetration and viscosity of the recovered asphalt binder and virgin binder in service.

2.13. International utilization of RAP

2. 13.1. Current Status of RAP Utilization in the US-America

The use of RAP in the United States has continued to grow since it became more common place in asphalt mixtures in the 1980s. Originally, state highway agencies were concerned about mix design methodology and long-term performance, but researches have enhanced the state of the knowledge related to both of these topics. Best practices related to RAP sampling, testing, and material characterization have been developed to aid both contractors and departments of transportation in mix design and quality control (Application of RAP & RAS in HMA of Transportation Research Board, 2014).

In the early 1990s, FHWA and the U.S. Environmental Protection Agency estimated that more than 90 million tons of asphalt pavement were reclaimed (i.e., converted into material suited for use) every year, and over 80 percent of RAP was recycled, making asphalt the most frequently recycled material. RAP was most commonly used as an aggregate and virgin asphalt binder substitute in recycled asphalt paving, but it was also used as a granular base or sub base, stabilized base aggregate, and embankment or fill material (RAP in Asphalt Mixtures of FHWA, 2011).

However, in the late 1990s the consumption of RAP was limited in relation to the introduction of the super pave mix design method (RAP in Asphalt Mixtures of FHWA, 2011). There were two basic reasons for the occurrence of such minimized demand on RAP in HMA, such as the absence of guideline for the use of RAP in implementing the super pave mix design method and due to the high fine content in RAP in contrary to the Super pave method of design which encourages the use of coarse-graded mixtures.

As a result, many State transportation departments stopped allowing the use of high amounts of RAP in favor of implementing the super pave system with virgin materials to reduce the extent of variability with RAP (RAP in Asphalt Mixtures of FHWA, 2011). But after that, there has been an increasing effort to modify the Super paves design method to more effectively evaluate HMA containing RAP by developing guidelines for the use of RAP in HMA.

In 2006 and again in 2008, there were sharp increases in asphalt binder costs as well as diminishing supplies of quality aggregate. As a result, utilizing greater amounts of RAP became a priority in the HMA industry once again. The highway community was reassessing the economic and environmental benefits of allowing higher percentages of RAP in premium pavements and asphalt surfaces while also maintaining high-quality pavement infrastructures. High RAP is defined as using 25 percent or more RAP in an asphalt mixture by weight of the total mix (RAP in Asphalt Mixtures of FHWA, 2011).

2.13.2. Current Status of RAP Utilization in the Netherlands

The pushing factor in utilizing of RAP for the people of the Netherlands was similar with USA. The occurrence of oil embargo in the early 1970 was the driving force at that time to look for other ways to produce hot mix asphalt. Later on, environmental issues became another reason in implementing hot-mix recycling (Application of RAP & RAS in HMA of TRB, 2014)

Several developments have taken place since the first introduction of hot recycled asphalt. In 2012, around 4 million tons of reclaimed asphalt was available for recycling. Of this amount, 80% is used in the production of HMA and 15% is used in cold recycling (Application of RAP & RAS in HMA of TRB, 2014).

In the Netherlands, hot RAP mixtures have to comply with the same specifications and requirements as are set for mixtures made of virgin materials. The requirements include: stiffness, resistance to fatigue, resistance to permanent deformation, and moisture resistivity. There are a number of durability/performance related requirements that a RAP mixture should satisfy, some of it are: stiffness and fatigue, resistance to permanent deformation and moisture resistivity (Application of RAP & RAS in HMA of TRB, 2014).

Moreover, the Netherlands has limited the level of RAP consumption up to 20% due to the fact that increasing more than 20% has been challenged since with such level the mix it needs higher penetration grade bitumen. Therefore, achieving a high penetration mix might become a problem since the virgin aggregates have to be heated up to much higher temperatures and it is therefore likely that the virgin bitumen rapidly hardens because of being exposed to very hot virgin aggregates. However, to tackle such challenges, there are two new developments that are either using a completely new system for heating and mixing recycled mixtures or using a bio-additive to upgrade RAP and on smart handling of RAP (Application of RAP & RAS in HMA of TRB, 2014).

2.13.3. Current Status of RAP Utilization in France

Recycling of bituminous mixtures is less common in France relative to some other European countries (e.g., the Netherlands). France has consumed only $4x10^6$ tones of RAP in HMA & WMA which is by far lower than other European countries & United States. In addition, unlike the United States and Netherlands, in France almost 40% of RAP was used in unbound layers and for cold recycling with emulsion, foam or hydraulic cement (Application of RAP & RAS in HMA of TRB, 2014).

There were three main reasons which hindered the consumption of higher amount of RAP in France which include, doubts on adequate mixing of the RAP with new materials, the hypothesis that asphalt mixtures with high RAP content lack cohesion to fail in a short period of time due to the use of unprocessed RAP and hot-mix plants were not designed to handle high RAP content (Application of RAP & RAS in HMA of TRB, 2014).

However, this situation leads to seek another alternative and arrived at the development of mobile parallel drum plant which can allow high rate recycling up to100% (Application of RAP & RAS in HMA of TRB, 2014).In this system, the virgin aggregates are heated at about 200°C to 250°C in a first drum dryer, whereas the RAP aggregates are warmed at about 110°C to 150°C in a second parallel drum dryer, and afterwards both virgin and the recycled aggregates are introduced in a continuous pugmill to be mixed and coated with hot bitumen.

As a result, the status of RAP application in France has been in an ever-increasing use of available RAP (61.9% in 2012 versus 12.7% in 2003). Indeed, it has become increasingly common for the layers of mix that are constructed to contain RAP (average rate of 11.4%). More and more existing asphalt plants are retrofitted in order to make it possible to recycle both hot and warm mixes; some modern and innovative high-rate recycling asphalt plants do appear at the same time in France. Different Researches are under progress which includes the questions like can asphalt be recycled numerous times and how does it affect its performance (Application of RAP & RAS in HMA of TRB, 2014).

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Introduction

In this chapter, the methodologies used for addressing the objectives of the research, such as the possibility of RAP substitution and its impact have been discussed in depth. Hence; the methods, materials and procedures of the study, for each of these areas have been treated separately as necessary but also common issues were raised as well.

3.2. The Study area

The research mainly focused on laboratory evaluation of Asphalt binder course mixes containing reclaimed asphalt. The reclaimed asphalt pavement used for this research was collected from Addis Ababa City specifically along the Ayertena- Alem Bank – Yeshi Debele road section which has providing transportation serves for more than 11 years since 2007G.C. The asphalt pavement was milled through milling machine for rehabilitation purpose by the Addis Ababa City Roads Authority (AACRA), Own Force Road Maintenance Directorate.

3.3 Research design

The research was designed to have multiples of faces while addressing the issues raised for the study. It is majorly an experimental research studying the case of a specific project which is described in the study area.

In general, it is experimental because it has been tried to compare the results of laboratory tests for mixes which contains RAP with a specification which was developed for a conventional HMA production where only virgin aggregate & bitumen are considered. Therefore, the interference of the research was partial substitution of virgin materials by old/aged recyclable pavement materials to check whether it is possible to satisfy specification requirements that was adapted for conventional HMA.

3.4. Subject of the study

There are a number of subjects that has been studied in this research which include, but not limited to: quality tests of virgin and RAP materials, volumetric properties of loose and compacted hot mixed asphalt samples, Marshall properties of compacted mixes, specification of HMA for the case under consideration and mix design procedures.

3.5. Methods and procedures for partial substitution of RAP

The main aim of this research was studying partial substitution of RAP for virgin aggregate and bitumen considering the case of Addis Ababa City (a case study Ayertena - Alem Bank – Yeshi Debele) road rehabilitation project. Accordingly, this section will try to discuss the laboratory works and paths followed to evaluate laboratory mixed HMA samples by referring the stated specification.

3.5.1. History of Old Pavement

The sample used for this research was taken from one of the Addis Ababa City roads that is the Ayertena - Alem Bank – Yeshi Debele road which is currently a rehabilitation project and has given transportation service for more than 11years. Knowing the history of old pavement materials has multiples of invaluable benefits while planning HMA design which contain RAP. Table 3.1 below summarizes the history of old pavement made during design.

Table 3.1: History of old pavement

Item No	Description	Result
1	Optimum Bitumen Content (OBC) during design	6.000
2	Air Void (%)	3.800
3	VMA (%)	17.400
4	VFA (%)	77.500
5	Stability , KN	9.300
6	Flow, mm	2.750
7	Bitumen Penetration Grade	85/100
8	Specific Gravity of Bitumen	1.015

3.5.2. Sampling of RAP

Sampling is equally as important as the testing. Customarily, it is recommended to take a number of samples from RAP stockpiles at different locations and to minimize the effect of segregation. At least, 150 mm of the material from the surface of the stockpile should be removed before sampling. Figure 3.2 below illustrates sampling of RAP material at Ayertena Alem Bank area.

Figure 3.1: Sampling of RAP material at Ayertena Alembank

3.5.3. Moisture Content of RAP

Determining the moisture content of RAP has multiple of benefits while working with HMA pavements containing RAP. Among other benefits the following two are the top most:

D. To estimate the energy requirement of hot mixed asphalt at the batch plant; and
E. To make corrections on the weight of RAP during proportioning at the preliminary stage.

The laboratory determination of moisture (water) content of RAP material was done according to AASHTO T 265 laboratory determination of moisture content.

The moisture content of RAP sample was not significant that is 1.03% and table 4.6 summarizes the result.

3.5.4. Maximum Theoretical Specific Gravity (Gmm) of RAP

The maximum theoretical specific gravity (G_{mm}) test was conducted according to AASHTO T209 for four RAP samples which resulted 2.515 and table 4.7 summarizes the results for further consumption in the determination of bulk specific gravity of RAP aggregates and the results are presented next in Chapter Four. Figure 3.2 below shows determination of maximum theoretical specific gravity (Gmm) of RAP which was processed and produced at AACRA central laboratory.

Figure 3.2: Determination of maximum theoretical specific gravity (Gmm) of RAP (Photo at AACRA Central Laboratory)

3.5.5. Extraction of bitumen from RAP

In the process of working with recycled asphalt pavements, extraction test is the base of everything for preparing RAP for partial substitution of virgin aggregate & bitumen. This method covers the quantitative determination of bitumen in asphalt mixed paving mixtures and pavement samples. Thus, four samples of RAP were extracted in accordance to AASHTO T164/ASTM D2172 except the solvent is changed in to benzene since trichloroethylene was not available. Figure 3.3 below shows Extraction of RAP aggregate using centrifugal method.

Figure 3.3: Extraction of RAP aggregate using centrifugal method (photo at AACRA central laboratory.

3.5.6. Sieve Analysis RAP Aggregate

This method is used primarily to determine the grading of RAP materials proposed for use as aggregate or being used as aggregate. The result is used to determine compliance of the particle size distribution with applicable specification requirement and to provide necessary data for control of the production of various aggregate products and mixture containing aggregate. The Sieve analysis test was carried out according to AASHTO standard method T27 as show in the Figure 3.4 below.

Figure 3.4: Sieve analysis of RAP aggregate (photo at AACRA central laboratory)

3.5.8. Bulk Specific Gravity of RAP Aggregate

It is necessary to determine the bulk specific gravity of RAP aggregate due to its effect on a mixture's voids in mineral aggregate (VMA). Referring RAP Management-Best Practice of Randy C. West (2010), the effective specific gravity (Gse) of RAP aggregate can be calculated using the following equations with asphalt content [Pb (RAP)], measured as Gmm (RAP), and specific gravity of the binder in RAP, Gb.

$$G_{se(RAP)} = \frac{100 - P_{b(RAP)}}{\frac{100}{G_{mm(RAP)}} - \frac{P_{b(RAP)}}{G_b}}$$

Using Gb From the historical data as listed in the table 3.1, the bitumen content P_b (RAP) from extraction test 5.58%, and maximum theoretical specific gravity G_{mm} from table 4.7 ; 2.515. Therefore calculated Gse of RAP aggregate became 2.756.

$$G_{sb(RAP)} = \frac{G_{se(RAP)}}{\frac{P_{ba} \times G_{se(RAP)}}{100 \times G_b} + 1}$$

Using the calculated G_{se} 2.756 of the RAP aggregate, and percent binder absorbed (P_{ba}) which was 1.5%, calculated from the historical record the bulk specific gravity of the RAP (G_{sb} (RAP)) was calculated and became 2.648.

3.6. Mix Proportioning of RAP & Virgin Materials

In the process of HMA designing which contain RAP materials, there are a number of additional steps to be considered in comparison with conventional HMA designing. The following steps were adopted from MS-2 of Asphalt Institute (1995) to show the way forward with proportioning and mixing materials. The flow chart shown in Figure 3.5 below illustrates the steps to be followed in the design of hot mix asphalt containing recycled asphalt pavement. Since the property of recovered bitumen is not determined, the research was limited to make partial substitution up to 30%, in which the knowledge of old bitumen property may not be mandatory.

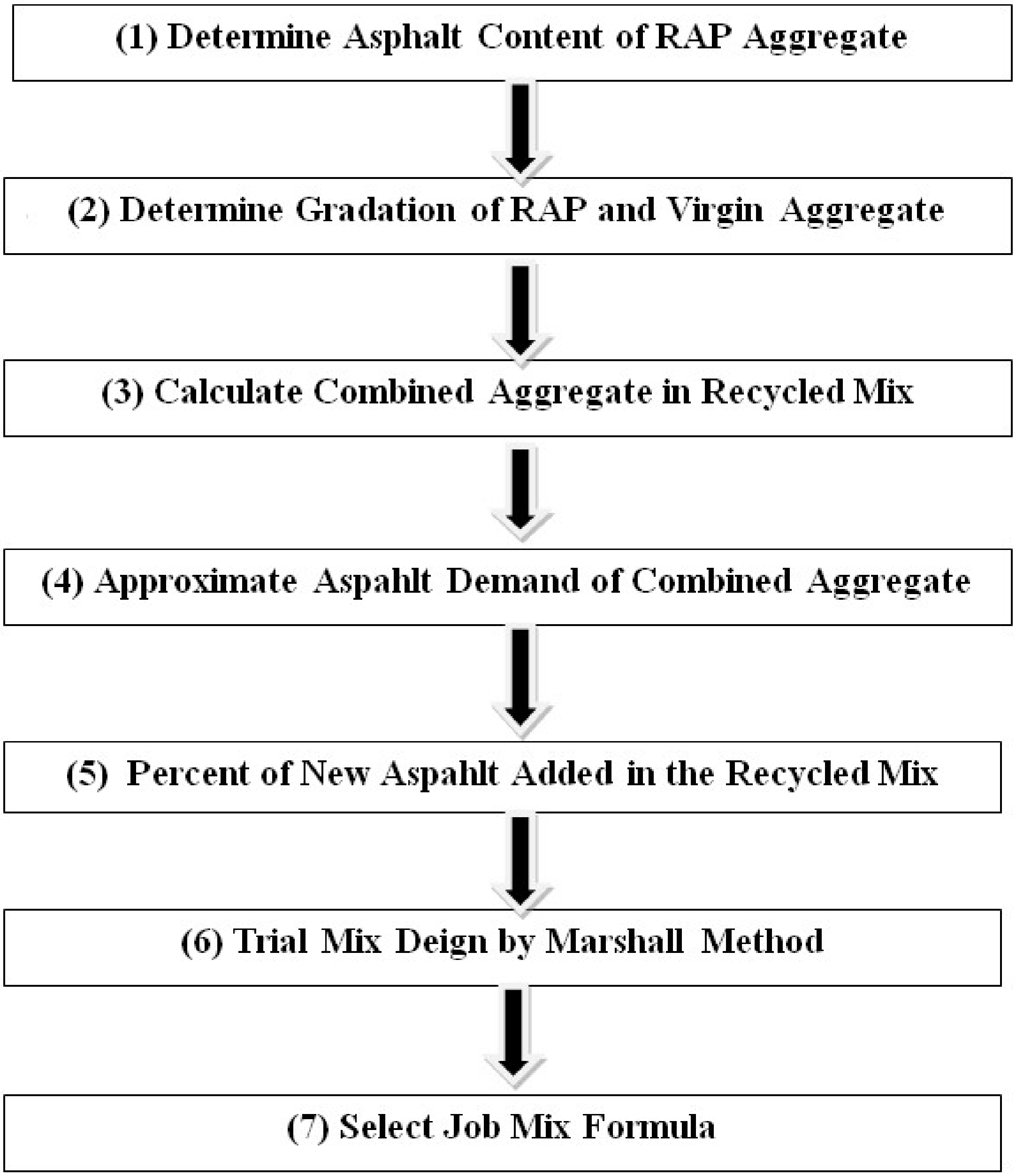


Figure 3.5 Flow chart for recycling hot mix design procedure (MS-2 1995)

3.6.1 Virgin aggregate and RAP proportioning

The aggregate extracted from recycled asphalt pavement and the virgin aggregate were proportioned and combined to meet the desired specification requirement and it's summarized in Table 3.2 below.

Table 3.2: Proportions of Virgin Aggregate and RAP

Item No.	Stock type	Percent Proportion of aggregates (%)		
1	RAP	10	20	30
2	(25-12.5mm)	18	15	14
3	(12.5-9.5mm)	13	11	10
4	(9.5-4.75mm)	12	12	11
5	(Pass 4.75mm)	45	40	34
6	External Filler	2	2	1
Total		100	100	100

Through the proportions listed in Table 3.2 above, the aggregates to be blended were evaluated to check whether the specification requirements are fulfilled. Table 3.3 summery of Sieve Analysis of Virgin aggregate and RAP. Subsequently, Figure 3.7 shows Virgin aggregate and Extracted RAP Combined Gradation.

Table 3.3: Summary for Sieve Analysis of Virgin aggregate and RAP

Combined Gradation for RAP and Virgin Aggregate (%pass)							
Sieve Size	10% RAP+90% Virgin Aggregate	20% RAP+80% Virgin Aggregate	30% RAP+70% Virgin Aggregate	Spec. Limit(MS-2)(19.0mmNominal Maximum Size) (%pass)			Remark
				Min %	Max %	Center	
25.0	100.0	100.0	100.0	100	100	100	COMPLY
19.0	93.2	94.1	94.2	90	100	95	COMPLY
9.5	76.3	77.2	75.9	56	80	68	COMPLY
4.75	55.9	57.2	56.3	35	65	50	COMPLY
2.36	39.1	39.9	39.0	23	49	36	COMPLY
0.300	13.3	13.9	13.2	5	19	12	COMPLY
0.075	5.0	5.4	4.9	2	8	5	COMPLY

As observed in Table 3.3, the final sieve analysis falls with the grading envelope of the desired specification. Detail data of individual and combined aggregate gradations are presented in Appendix A-6 to A9.

3.6.2. Estimation of Approximate Asphalt Bitumen Demand of Combined Aggregate

The approximate asphalt demand of the combined aggregate can be calculated using the following empirical Formula (MS-2 of Asphalt Institute, 1995)

$$P= 0.035a +0.045b +Kc +F$$

Where:

P = approximate total asphalt demand of recycled mix, percent by weight of mix.

a = Percent* of mineral aggregate retained on 2.36mm (No.8 sieve).

b=Percent* of mineral aggregate passing 2.36mm (No. 8) sieve minus percent pass on 75µm (No. 200 sieve).

c= Percent of mineral aggregate passing the 75µm (No. 200 sieve).

K= 0.15 for 11-15% passing 75µm sieve, 0.18 for 6-10% passing 75µm sieve and 0.2 for 5% or less passing 75µm

F = 0 to 2.0%, based on absorption of light or heavy aggregate.

In the absence of other data, a value 0.7 is suggested

* Expressed as a whole number.

Therefore, by substituting values of percentage pass from Table 3.3, approximate bitumen demand of the combined aggregates had been estimated and summarized in Table 3.4 below.

The approximate asphalt demand established will provide a basis for a series of trial mix design. Trial mix will vary in asphalt content in 0.5 increments in either side of calculated approximate asphalt demand. Accordingly trial mixes were prepared in asphalt contents at 4.5%, 5%, 5.5%, 6%, and 6.5%.

Table 3.4: Estimated bitumen content of trial mixes

Variables	Values of Variables for different % RAP blended aggregate		
	10% RAP	20% RAP	30% RAP
A	60.9	60.10	61.0
B	34.1	34.50	34.1
K	0.2	0.18	0.2
C	5.0	5.40	4.9
F	0.7	0.70	0.7
Estimated Bitumen content	5.4	5.30	5.3

3.6.3 Estimation of New Asphalt bitumen in the mix

The bitumen content in the RAP (i.e. 5.58%) had to be reduced from the asphalt demand of the combined aggregate; therefore, the quantity of new asphalt to be added to the trial mixes of the recycled mixture expressed by weight of total mix should be determined and is calculated using the following formula .(MS-2 of Asphalt Institute, 1995).

$$P_{nb} = \frac{(100^2 - r\,P_{sb})\,P_b}{100\,(100 - P_{sb})} - \frac{(100 - r)\,P_{sb}}{100 - P_{sb}}$$

Where

P_{nb}= Percent of new asphalt binder in recycled mix

r = new aggregate expressed as a percent of the total aggregate in the recycled mix

Pb= percent, an approximate asphalt demand of combined aggregates determined by the Empherical formula in section 3.6.2

P_{sb}= percent, asphalt content of reclaimed asphalt pavement (RAP)

Therefore, by substituting the values in the formula, the estimated amount of new asphalt required was calculated and summarized in Table 3.5 below.

Table 3.5: Estimated new bitumen content in the total recycled mix

Item No	Total Asphalt by weight of total mixes (%)	New asphalt by weight of total mix		
		10% RAP	20% RAP	30% RAP
1	4.5	3.9	3.4	2.8
2	5.0	4.4	3.9	3.4
3	5.5	4.9	4.4	3.9
4	6.0	5.4	4.9	4.4
5	6.5	5.9	5.4	4.9

Table 3.6 Estimated bitumen saving at different RAP and bitumen content

Item No	Total Asphalt by weight of total mixes (%)	Estimated bitumen saving at different RAP and Bitumen content (%)		
		10% RAP	20% RAP	30% RAP
1	4.5	13.3	24.4	37.8
2	5.0	12.0	22.0	32.0
3	5.5	10.9	20.0	29.1
4	6.0	10.0	18.3	26.7
5	6.5	9.2	16.9	24.6

3.6.4. Laboratory Batch Preparation

In the analysis of aggregates for a given mix, the final operation is computation of the laboratory batch. The goal of batching is to closely match the laboratory aggregate blend to the final asphalt plant aggregate blend.

Using separate pans, each specimen were weighed from each fraction for the study to produce a batch that can result in a compacted specimen having 63.5±1.27 mm in height. This height of specimen normally weighs around 1200gm of normal weight aggregate like the material used for this study. Detail data of aggregate properties and trial batch preparation can be referred to in Appendix A-10 to A15. Figure 3.8 below shows different fraction of Sieved aggregates and subsequently Figure 3.9 shows sample weighed fraction aggregate for one marshal specimen.

Figure 3.6: Different fraction of Sieved aggregate

3.7. Mixing and Compaction of Test Specimens

According to MS-2 of asphalt institute (1995), using aggregate fraction and asphalt contents calculated and attached in the appendix trial batches were heated till the temperature reached 150-160 ^{o}C then mixed together. Finally, 75 blows of compaction at both faces continued according to the step methods outlined for Marshall Method of mix design at MS-2 of Asphalt Institute (1995). Figure 3.10 below shows compacted marshal specimen at different bitumen and RAP content.

Figure 3.7: Compacted Marshall specimen at different bitumen and RAP content (photo at AACRA Central Laboratory)

3.8. Determination of Marshall Property

All specimens in the mold was allowed to cool in air for an overnight and removed from the mold by a means of extraction jack as shown in Figure 3.11 for Marshall Property tests as listed below.

A. Bulk Specific Gravity Determination (According to ASTM D2726).

B. Stability and Flow Test (ASSHTO T245/ASTM D1559).
C. Density and Voids Analysis.

Figure 3.8: Compacted Marshall specimen (Photo at AACRA central laboratory)

The detail Marshall Properties are summarized in the Appendix A-12 to A-14.

3.9. Moisture Sensitivity

Moisture damage in bituminous mixes refers to the loss of serviceability due to the presence of moisture. The extent of moisture damage is called the moisture susceptibility. Moisture-induced damage produces several forms of distress including localized bleeding, rutting, shoving, and ultimately complete failure due to permanent deformations and cracking.

This test is conducted as per the ASTM D-1075 and AASHTO T-165 specification (Effect of Water on Compressive Strength of Compacted Bituminous Mixtures) and Marshall Immersion test method is used where Marshall Stability is used as a strength parameter rather than compressive strength. Two groups of compacted specimens are prepared for each partial substitutions of RAP. One group is submerged in a 60°C water bath for 24 hours and shifted to the second water bath maintained at 25°C and it's stored for two hours for conditioning. The other group is maintained dry that is the unconditioned one. Then the Marshall stability for both conditioned and unconditioned specimens are determined. The potential for moisture damage is indicated by the ratio of the Marshall stability of the conditioned to that of the unconditioned one and the result obtained is summarized in chapter 4 table 4.12.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Introduction

In this chapter, the results of the analysis of material laboratory tests and mix designs are presented to evaluate the suitability of RAP containing mixes. Generally, two types of laboratory tests were applied. The first type was qualification tests which was conducted to identify the different properties of materials used in the study. Whereas, the second type was the main test used to measure the intended properties of the investigated mixtures.

4.2. Quality test and results

4.2.1. Virgin bitumen quality test

Asphalt bitumen with a penetration grade of 85/100 which comply the properties cited in AASHTO M20 was used for this particular research and the results are presented in Table 4.1 below.

Table 4.1 Quality test results for 85/100 penetration grade Asphalt bitumen

Type of Test Conducted	Test Method		Sample ID				Specification (AASHTO M-20)	Remark
	ASTM	AASHTO	A1	B1	C1	Average		
Penetration 100g,sec	D5	T49	92	91	94	92.3	85-100	Comply
Ductility(cm)	D113	T51	100+	100+	100+	100+	100+	Comply
Flash Point OC	D92	T48	278	278	276.0	277.3	232+	Comply
Specific Gravity		T228	1.013	1.013	1.013	1.013	-	Comply
Solubility in Trichloroethylene (%)	D2042	T44	99.62	99.64	99.62	99.63	99+	Comply
Loss on heating (%)	D 1754		0.020	0.020	0.020	0.02	<1	Comply
Penetration on Residue 100g,sec	D5	T49	83	84	82.0	83.0	50+	Comply
Ductility on Residue(cm)	D113	T51	100+	100+	100+	100+	10+	Comply

4.2.2. Virgin Aggregate Test

The test method used and the results for the virgin aggregate are summarized in Table 4.2 below.

Table 4.2: Quality test results of Virgin aggregate

Type of Test Conducted	Standard Test Method	Acceptance Criteria(ERA 6402/5)	Test Result	Remark
Soundness By Sodium Sulphate	AASHTO T104	Maximum 10%	2.00	Comply
Los Angeles Abrasion(LAA)	AASHTO T-96	Maximum 35%	15,Grade B	Comply
Aggregate Crushing Value	BS-812 Part 110	Maximum 35%	13	Comply
TFV (Dry) KN	BS-812 Part 111	Minimum 160%	300	Comply
TFV(Wet/Dry)	BS-812 Part 111	Minimum 75%	93	Comply
Flakiness Index	BS-812 Part 105	Minimum 35%	28.0	Comply
Stripping and Coating	AASHTO T-182	Minimum 95%	>95%	Comply

4.2.3. RAP material test

A. Extraction of Bitumen from RAP

Four samples of RAP had been extracted in accordance to AASHTO T164/ASTM D2172. As it can be seen from Table 4.3 below, the average bitumen content (BC) was found to be 5.58% of the total weight of RAP. The 5.58% BC as compared to the 6% BC of the historical data as discussed in the methodology Section 3.4.3 is expectable.

Table 4.3: Extraction tests result on RAP materials

Extraction	Extraction #A	Extraction #B	Extraction #C	Extraction #D
Mass of sample(gm)=A	1,392	1,359	1,277	1,361
Mass of aggregate after extraction(gm) =B	1,303	1,271	1,187	1,270
Mass of filler + filter(gm)=C	11.5	10.8	11.2	10.6
Mass of Filter (gm) = D	10	10	10	10
Mass of extracted Filler (g) E=C-D	1.5	0.8	1.2	0.6
Weight of Ash (gm) = F	11	13	14	15.5
Mass of Total Aggregate (g) G= B+E+F	1,315.5	1,284.8	1,202.2	1,286.1
Mass of Bitumen (gm) H=A-G	76.5	74.20	74.8	74.9
Bitumen Content (%) by Mass of Aggregate I=H/G*100	5.82	5.78	6.22	5.82
Bitumen Content (%) by Mass of Total mix J= H/A*100	5.50	5.46	5.86	5.50
Average Bitumen Content of RAP (in the total mix)	5.58			

B. Sieve Analysis RAP Aggregate

To determine the particle distribution of extracted RAP aggregates, sieve analysis was conducted on four samples using wet sieve method of analysis as described in the methodology and outlined in the AASHTO T27 and the results are summarized in Table 4.4 below.

Table 4.4: Particle size distribution of extracted RAP aggregate

Particle size distribution of extracted RAP aggregate					
Sieve Size (mm)	Extraction #A	Extraction #B	Extraction #C	Extraction #D	Average(Passing)
	%Passing	%Passing	%Passing	%Passing	
25	100	100.0	100.0	100.0	100.0
19	98.00	97.8	98.4	96.0	97.6
9.5	77.00	73.0	76.0	72.0	74.5
4.75	64.00	62.0	63.6	60.5	62.5
2.36	46.00	43.0	44.0	41.0	43.5
0.300	16.00	15.2	17.0	15.0	15.8
0.075	7.00	6.4	7.8	6.2	6.9

It has been tried to compare the particle size distribution of milled extracted RAP aggregate with other stocks of aggregates that is with the original parent aggregate with whom the old pavement is constructed and virgin aggregate gradation. As a result, RAP aggregates were found finer than the virgin aggregates which are currently used and the parent original aggregate which the old pavement is constructed. This condition is common to occur in RAP aggregate since the effect of milling can reduce the size of coarser aggregates in the old pavement which result to shift the balance to the finer side. Table 4.5 below shows the particle size distribution of extracted RAP, original parent aggregate and virgin aggregate.

Table 4.5: Particle Size distribution of extracted RAP, original parent aggregate and virgin aggregate

Sieve size (mm)	Milled Extracted RAP	Original Gradation	Virgin Aggregate	Specification Limit	
	%Passing	%Passing	%Passing	Lower Limit	Upper Limit
25	100.0	100.0	100.0	100.0	100.0
19	97.6	95.0	93.8	90.0	100.0
9.5	74.5	68.0	78.8	56.0	80.0
4.75	62.5	50.0	57.3	35.0	65.0
2.36	43.5	36.0	39.9	23.0	49.0
0.300	15.8	12.0	13.3	5.0	19.0
0.075	6.9	5.0	4.8	2.0	8.0

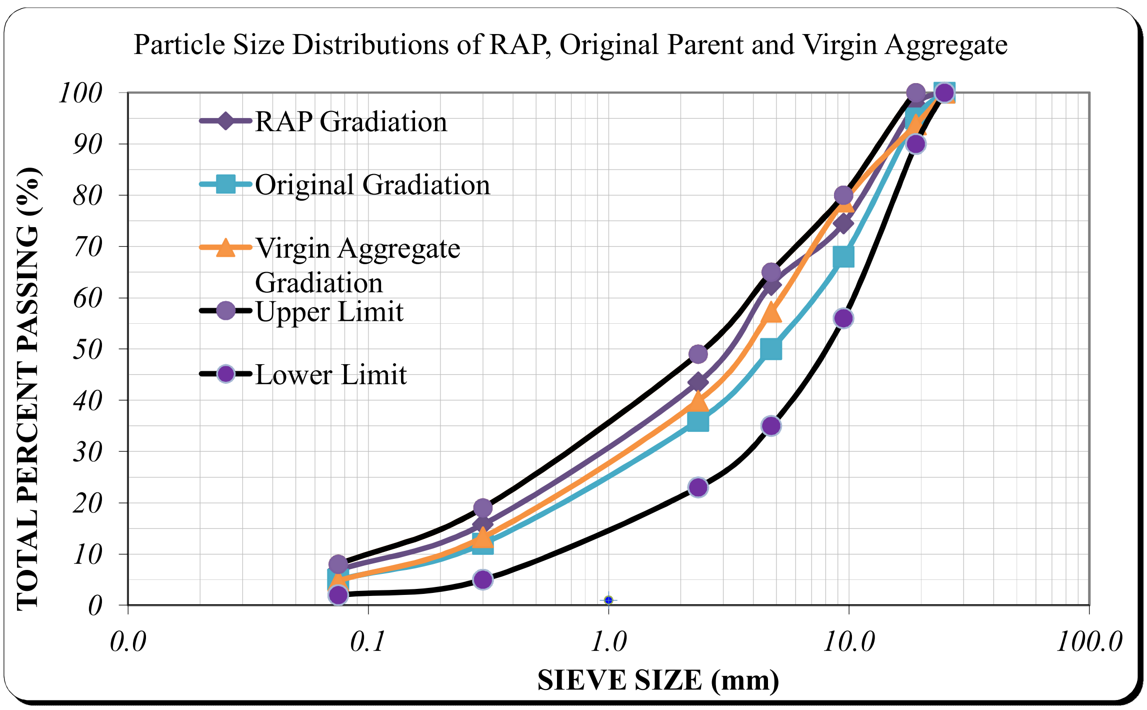


Figure 4.1 Particle Size Distributions of RAP, Original Parent and Virgin Aggregate.

C. Moisture content of RAP

The moisture content test for RAP material is determined in accordance with AASHTO T265 and average test result obtained is 1.03.

Table 4.6: Moisture content of RAP sample

Description	Test 1	Test 2	Test 3	Average
Container No	1	2	3	1.03
A. Weight of Wet RAP Sample & Cont. (g)	2170.0	2140	2158	
B. Weight of Dry RAP Sample & Cont. (g)	2151.0	2125	2140	
C. Weight of Cont, (g)	453.0	454	450	
D. Weight of Moisture (g) (A-B)	19.00	15.00	18.00	
E. Weight of Dry RAP sample (g) (B-C)	1698	1671	1690	
Moisture Content (%) (D/E)*100	1.12	0.90	1.07	

D. Maximum Theoretical Specific Gravity of RAP Aggregate

The maximum theoretical specific gravity (Gmm) test was conducted according to AASHTO T209 for four RAP samples and Table 4.7 below shows the summary of the results for further consumption in the determination of bulk specific gravity of RAP aggregates as discussed in the methodology section of this research.

Table 4.7: Theoretical Maximum Specific Gravity (Gmm) of RAP

Theoretical Maximum Specific Gravity (Gmm) of RAP (AASHTO :T209-05/ASTM :D2041-00) (Rice Specific Gravity) Flask [Pycnometer] Method					
Description		Test No.			
		Test 1	Test 2	Test 3	Test 4
Mass of Dry Sample in Air (A): (gm)	A	613.6	570.0	535.0	585
Mass of Calibrated Pycnometer/Flask filled with Water up to mark at 25C (D): (gm)	D	4263.6	4263.6	4263.6	4263.6
Mass of Pycnometer filled with Sample and Water in Air at (E): gm	E	4633.1	4606.2	4586.5	4616.1
Theoretical Maximum Specific Gravity (Gmm):	((A/(A+D-E))	2.514	2.507	2.522	2.516
Theoretical Maximum Specific Gravity (Gmm):(Average)		2.515			

4.3. Marshall Mix design results and analysis

Laboratory mix design results will be evaluated according to the specification of the AACRA road project for Asphalt binder course mix under consideration which is summarized in Table 4.8 below.

Table 4.8: Specification requirements for Asphalt binder course HMA

Marshall Property	Acceptance Criteria
Void in the mix (VIM) (%)	3-5
Void in mineral Aggregate (VMA) (%)	14-17
Void filled with asphalt (VFA) (%)	65-75
Stability, KN	>=8
Flow, mm	2-4
Water Sensitivity (loss of stability on immersion in water) Retained strength	>75

The detail calculation of each Marshall Mix design is attached through Appendix A-12 to A-14.

4.3.1 Summery of Volumetric and Marshall Mix Design Results

Tables 4.9, 4.10, and 4.11 below present Volumetric and Marshall Properties of 10%, 20% and 30% RAP substituted HMA respectively.

Table 4.9: Volumetric and Marshall Properties 10% RAP Substituted HMA

Bitumen content (%)	Gmb	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability KN	Flow mm
4.50	2.357	2.523	6.5	15.64	57.91	9.49	2.80
5.00	2.372	2.499	5.1	15.55	67.29	10.65	3.10
5.50	2.384	2.475	3.7	15.57	76.38	11.58	3.32
6.00	2.390	2.469	3.2	15.80	79.75	10.03	3.48
6.50	2.377	2.449	3.0	16.72	82.34	9.53	3.60

Table 4.10: Volumetric and Marshall Properties of 20% RAP Substituted HMA

Bitumen content (%)	Gmb	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability KN	Flow mm
4.50	2.365	2.531	6.6	15.30	57.04	10.20	2.60
5.00	2.389	2.502	4.5	14.87	69.68	11.53	2.90
5.50	2.410	2.493	3.3	14.59	77.14	12.30	3.11
6.00	2.418	2.486	2.7	14.75	81.49	10.91	3.29
6.50	2.411	2.462	2.1	15.46	86.52	9.88	3.44

Table 4.11: Volumetric and Marshall Properties of 30% RAP Substituted HMA

Bitumen content (%)	(Gmb)	Gmm	VIM (%)	VMA (%)	VFA (%)	Stability KN	Flow mm
4.50	2.369	2.541	6.8	15.09	55.13	9.23	2.48
5.00	2.387	2.520	5.3	14.90	64.54	10.40	2.61
5.50	2.408	2.509	4.0	14.59	72.47	10.97	2.91
6.00	2.424	2.497	2.9	14.48	79.83	9.78	3.13
6.50	2.416	2.473	2.3	15.23	84.76	9.40	3.29

4.4. Analysis of Test Results

As an objective of the study, the first thing to analyze is evaluating test results of each partially substituted mixes relative to the parameters outlined in the specification. However, as an additional way of analyzing test results and to see the effect of RAP in HMA, the trend of specification parameters were compared and discussed across the mixes designed for this research. Therefore, Stability Vs Bitumen content, Flow Vs Bitumen Content, Percent Voids filled with Asphalt (VFA) Vs Bitumen Content, Void in mix (VIM) Vs Bitumen content and Voids in Mineral Aggregate (VMA) Vs Bitumen content are presented with graphical analysis.

4.4.1 Air Void Content in the Mix (VIM)

Air void content in the mixes 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 void in a mix plays a big role in its performance, Excessive air voids in the mixture would result in cracking due to insufficient bitumen binders to coat on the aggregates and also indicative of poorly compacted material, while too low air void may induce more plastic flow (rutting) and bitumen bleeding.

When the trends of air void content were compared to each other, specifically between the upper & lower limits of the specification, it was been observed that air void content was decreasing as the partial substitution of RAP increases. Reason for the reduction in air voids at higher % RAP may be due to the higher ACV of the RAP aggregate compared to the Virgin aggregate thus causing the increased crushing of specimens containing RAP prepared in the Marshall hammer. However, this was not always true, especially at 30% RAP substitution, the mix has exhibited a contrary character which shifts the air void content back to the higher level, due to the large volume of substitution. Therefore, it could be concluded that the air void content is influenced by higher amount of RAP material. Generally, the air void requirement for all mixes can be satisfied between 5.0 to 6.0 percent of bitumen content. Figure 4.1 below illustrates Bitumen Content versus Void in the mix.

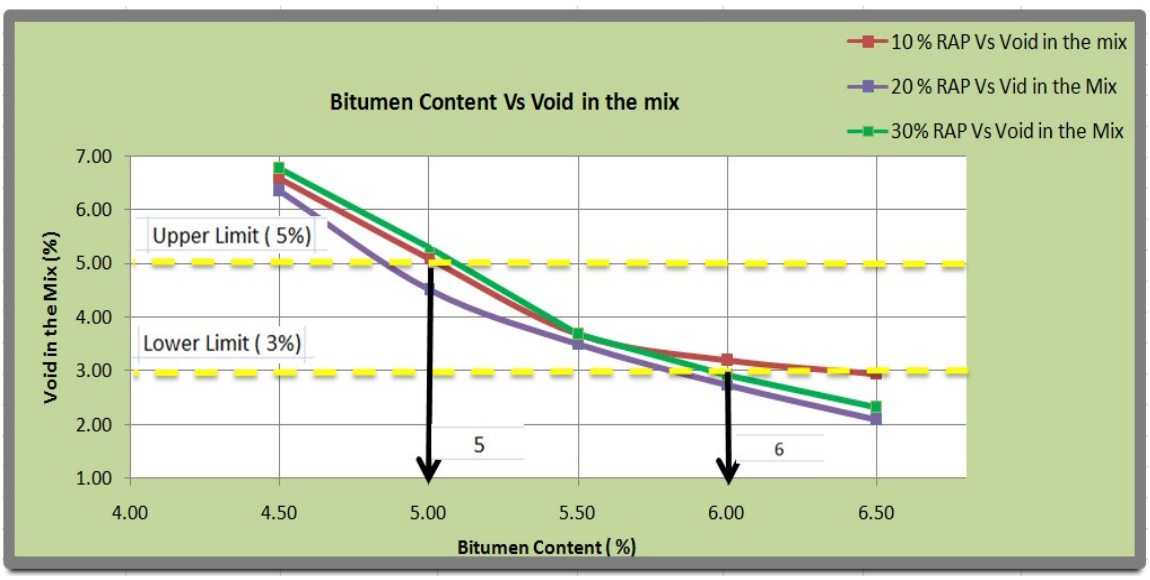


Figure 4.2: Bitumen content Vs Void in the mix

4.4.2 Voids in the Mineral Aggregate (VMA)

Figure 4.2 below shows that the VMA decreased as the % RAP increased. The crushing of the RAP aggregate could have caused these phenomena. Commonly, the rate of change of VMA is slower i.e. as the bitumen content increases VMA slowly reduces to a point or flattened for some intervals of BC and gradually started to increase as the asphalt content increased.

The trend of VMA showed that as the percentage share of RAP increased, the lowest value of VMA decreased for all mixes. Since VMA is mainly influenced by mixed aggregate properties, the invariably reduction character of VMA of all mixes could be due to the bulk specific gravity of RAP aggregate which decreased the bulk specific gravity of combined aggregates as its volume of substitution increased. As it can be seen from Figure 4.2 below, the VMA of mixes designed in this research has satisfied the requirements of the specification for all substitutes of RAP.

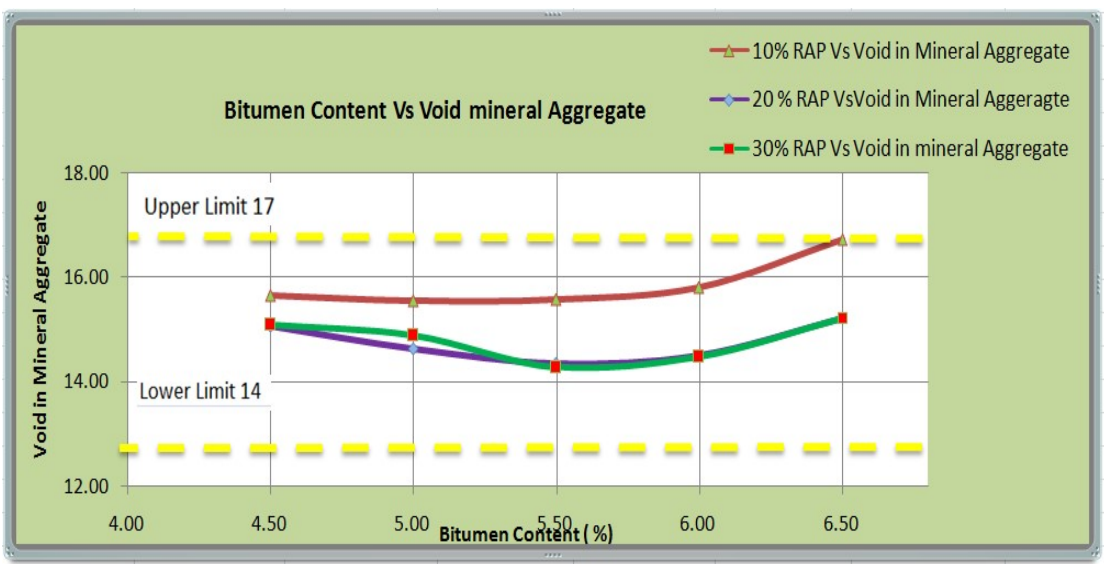


Figure 4.3: Bitumen content Vs Void in mineral aggregate

4.4.3 Void filled with Asphalt (VFA)

Void filled with asphalt (VFA) is the voids in the mineral aggregate framework filled with bitumen binder. This represents the volume of effective bitumen content. It can also be described as the percent of the volume of the VMA that is filled with bitumen. VFA is inversely related to air voids and hence as air voids decrease, the VFA increases. The decrease of VFA indicates a decrease of effective bitumen film thickness between aggregates, which will result in higher low-temperature cracking and lower durability of bitumen mixture.

It is easy to understand from Figure 4.3 below that all mixes have shown the known behavior of VFA i.e. as bitumen content increases the value of VFA increases too. In general, the minimum bitumen content to satisfy the minimum requirement was near to 5.0% for 30 % RAP substituted mix. On the other hand, the maximum specified limit in this group of mixes can be satisfied near to 5.5% bitumen content for 20% RAP containing mix. Therefore, the VFA specification requirement can be satisfied between 5 & 5.5% bitumen content for all mixes. Figure 4.3 below illustrates the bitumen content versus void filled with asphalt.

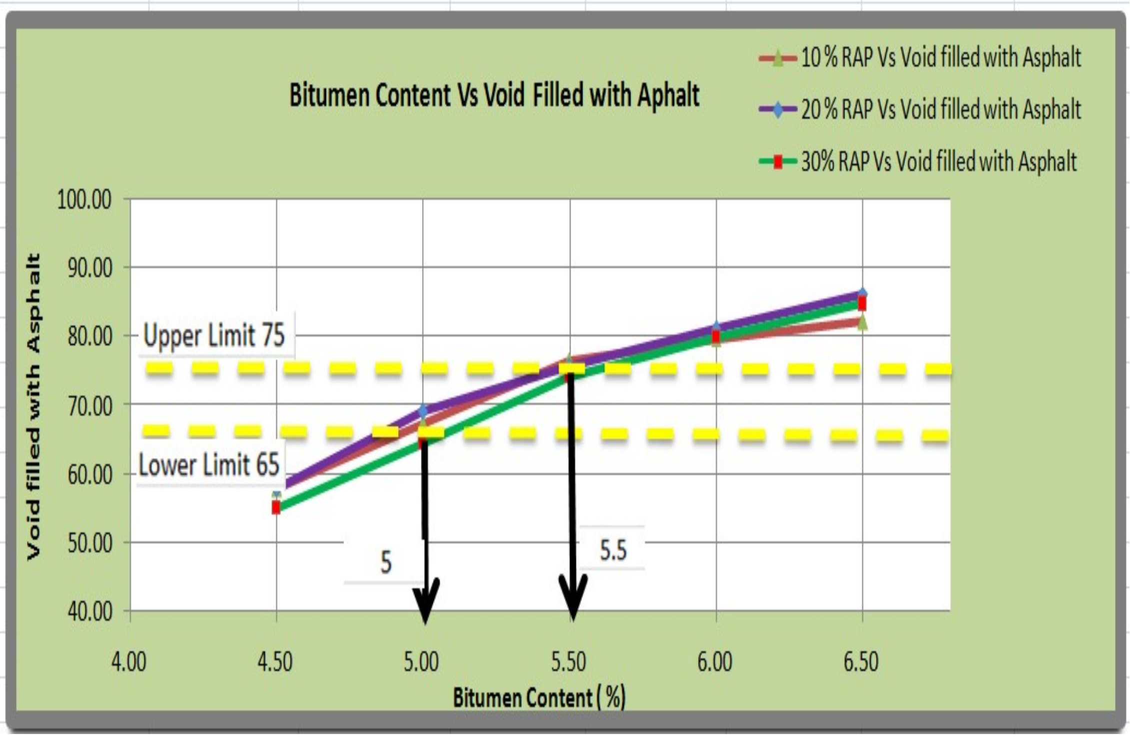


Figure 4.4: Bitumen content Vs Void filled with Asphalt

4.4.4. Stability of Mixes

Stability is generally a measure of resistance to deformation of bituminous mixtures under sustained or repeated loads which is affected significantly by the angle of internal friction of the aggregate and the viscosity of the asphalt cement. The mechanics behind the load resistance character of a mix is due to bituminous materials holds the aggregates in position, and the load is taken by the aggregate mass through the contact points.

As it can be seen in Figure 4.4 below, the stability of mixes designed in this research has satisfied the minimum requirement 8KN of the specification for all substitution of RAP. Initially, as the bitumen increased, the stability of all mixes increased and reached its maximum load carrying capacity, then started to decline once it reached its maximum. This is true because as bitumen content increased the voids were filled with bitumen and the contact of the aggregate particles started to lose. Finally, the load transmitted by hydrostatic pressure through bitumen and hence the strength of the mix reduced. That is why stability of the mix starts reducing when bitumen content is increased further beyond a certain value. Figure 4.4 below illustrates bitumen content versus stability of mixes.

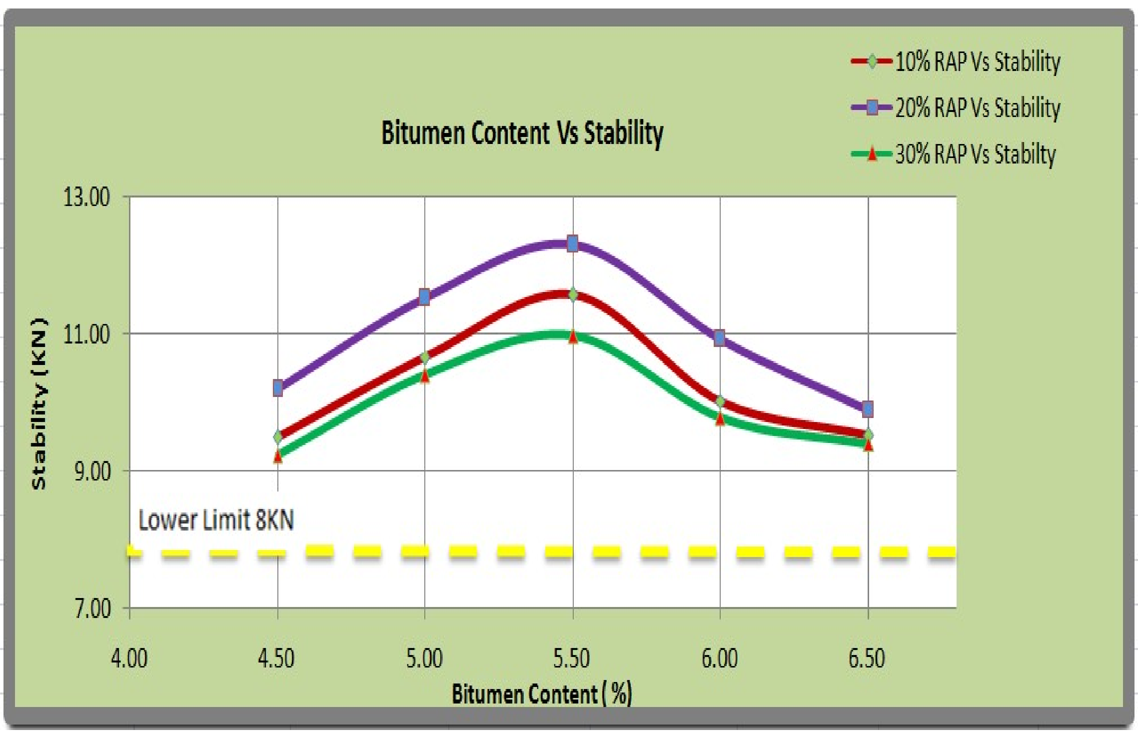


Figure 4.5: Bitumen content Vs stability of mixes

It is seen in Figure 4.4 above that the stability graphs were shifting to the top as the RAP content increased from 10% to 20%. However, the graph of the mix which contain 30% RAP had shifted back to the bottom of other mixes, this may be due fatigue of such material because of aging.

4.4.5. Flow of the Mixes

Flow refers that the vertical deformation of the sample which is measured from start of loading to the point at which stability begins to decrease. 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 mixes designed for the case under consideration had flow values which fall within the specification envelops with a trend difficult to catch as the preceding mix properties. In general there had been a sign of flow value decrement as the RAP proportion increases. The issue of hardening of bitumen due to aging in the RAP could be the reason for the reduced flow value of mixes. Figure 4.5 below shows bitumen content and flow of mixes.

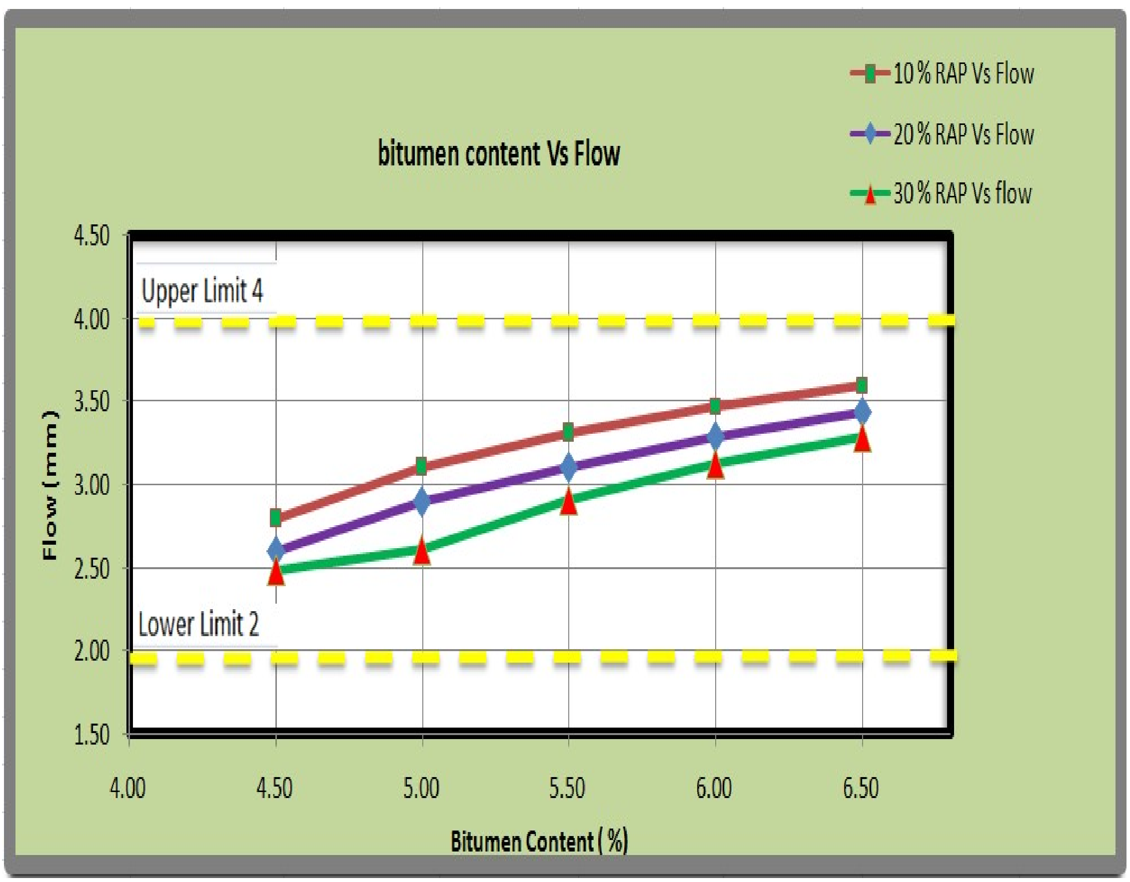


Figure 4.6: Bitumen content Vs Flow of mixes

4.5 Moisture Sensitivity

The moisture sensitivity result expressed in terms of Marshall Stability ratio through Marshall Immersion test for the different partial substitutions of RAP is summarized in Tables 4.12 below.

Table 4.12 Moisture sensitivity expressed in terms Marshall Stability ratio

Mixed Design	Sample ID	Conditioned	Unconditioned	Marshall Stability (KN)	Average Marshall stability	Marshall stability ratio (%)	Remark
10 % RAP	A			10.23	10.05	82.35	COMPLY
	B			10.06			
	C			9.85			
	D			8.45	8.27		
	E			8.75			
	F			7.62			
20% RAP	A			11.98	11.67	79.1	COMPLY
	B			11.02			
	C			12.02			
	D			8.75	9.23		
	E			9.2			
	F			9.75			
30% RAP	A			9.85	9.7	76.12	COMPLY
	B			10.21			
	C			9.04			
	D			6.08	7.38		
	E			7.95			
	F			8.12			

Higher Marshall Stability ratio value typically indicates that the mixture will perform well with a good resistance to moisture damage. The higher the ratio value, the lesser will be the strength reduction by the water saving condition. Table 4.12 shows that as the percentage of RAP increased in the mix, the moisture susceptibility of the mix also increased but all the mixes meet the least requirement as per the specification. It can be concluded that Mix subjected to the long-term aging showed increase in the moisture susceptibility.

4.6. Optimum Bitumen Content Selection of Mixes

The design asphalt content of asphalt paving mix is selected by considering the data discussed above. As an initial starting point, asphalt institute (MS-2) recommends choosing the asphalt content at median of the percent air void limit, which is four (4). All of the calculated and measured mix properties at this asphalt content were evaluated by comparing with the specification criteria.

In general from Table 4.13, it has been observed that the OBC requirement is decreasing as the percentage of RAP substitution increases unless for 30% substitution. This may be due to the fact that the excess amount of aged bitumen in the RAP.

Table 4.13: Optimum bitumen content of HMA consisting of different percentage of RAP

Optimum Bitumen Content (OBC) of Hot Mix Aspahlt containing RAP									
Item No.	Mix Property	Specification Limit		Mix Type					
				10 % RAP		20 % RAP		30 % RAP	
				OBC (%)	5.3	OBC (%)	5.1	OBC (%)	5.5
		Lower Limit	Upper Limit	Result	Remark	Result	Remark	Result	Remark
1	VIM (%)	3	5	4	Comply	4	Comply	4	Comply
2	VMA (%)	14	16	15.55	Comply	14.8	Comply	14.65	Comply
3	VFA (%)	65	75	73	Comply	70	Comply	72	Comply
4	Stability (KN)	8		10.8	Comply	12.0	Comply	10.9	Comply
5	Flow (mm)	2	4	3.25	Comply	3.05	Comply	2.85	Comply

4.7 Cost-Benefit Analysis of Partially Substituted HMA

To determine the cost implication of partial substitution, the amount of RAP proportioned with virgin aggregate & bitumen (OBC) which satisfies the requirements as confirmed during the laboratory tests of the study are evaluated. Finally the cost saving from such partial substitutions is compared with the conventional HMA. Therefore, as it can be seen from table

4.14 partial substitutions of RAP for virgin aggregate & bitumen has shown increment in cost savings as the amount of substitution increases for each mix proportions with varying degree of savings. As the RAP percentage increases from 10% to 20% there is 11% of cost saving, however at the same increment from 20% to 30% the rate of cost reduction was reduced to 4% reduction, due to the higher amount of optimum bitumen content during laboratory mix design.

Table 4.14: Cost analysis of partially substituted HMA using different amount of RAP

Item No.	Mix Type	Unit	Cost (ETB/M^3)	% of Cost Saving
1	0% RAP	M^3	2223.53	-
2	10 % RAP	M^3	2065.23	7.1
3	20% RAP	M^3	1822.00	18.1
4	30 % RAP	M^3	1732.57	22.1

The detailed cost break down for the conventional HMA and the different partial substitution of RAP is presented in Appendix A-19 through A-22.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Introduction

This thesis presents a comprehensive study into the possibilities of using milled Recycled Asphalt Pavements (RAP) as an alternative aggregate in new bituminous mixtures. The experimental and theoretical results presented in this thesis prove that bituminous mixtures can be successfully produced using RAP aggregates, from road rehabilitation.

5.2. Conclusions

From the work carried out in this thesis, the following conclusions are made:

- The particle distribution of RAP aggregate was found to be finer than the virgin aggregate and its parent material, this is due to the effect of milling action.
- The effect of RAP substitution has been seen to improve various properties of HMA, and optimum bitumen content demand was decreasing when the RAP content was increasing unless for 30% of substitution.
- Mix stability increase up to 20 % of RAP substitution, and then decrease for 30% substitution. This may be due to fatigue of such material by aging, but the minimum requirement 8KN of the specification is fulfilled for all partial substitution of RAP.
- As the percentage of RAP increased in the mix, the moisture susceptibility of the mix also increased but all the mixes containing 10%, 20% and 30% of RAP meet the least requirement as per the specification.
- It is quite possible to design acceptable quality and economical mixes with 5.1% of optimum bitumen content and 20 % RAP substitution that meets the required volumetric and mechanical properties criteria.
- As compared to the conventional hot mix asphalt, RAP containing HMA is cheaper and there are financial savings. At 20% RAP substitution, there could be 18.06% of cost savings as compared to conventional HMA. (100% new asphalt consumption mix).

5.3. Recommendations

- In general due to the Cost saving and the potential to conform specification requirements, it is possible to recommend that partial substitution of RAP for HMA binder course.
- The RAP material should better handle and store properly to reduce the effect of contamination and seasonal whether condition.
- It is better to use a milling machine for removing the deteriorated pavement rather than using a bulldozer or backhoe. This would help to avoid contamination and large chunk of pavement that may be more challenging to process into a useable recycled material.
- Hence, in practice RAP materials from multiple sources that have different compositions are used, to avoid the effect of variability and to create a uniform material suitable for use in a new asphalt mixture careful blending should be done.
- Higher learning institutions and research center are recommended to do more in and to be equipped with different laboratory facilities for the investigation of partial substitution of RAP material for use in asphalt binder course mix.

5.4. Proposed Future Research Areas

Finally more research shall be conducted to evaluate the fatigue and rutting behavior of the HMA containing RAP as partial material. Since higher laboratory facilities unlike HMA are not required partial substitution of RAP for unbounded base course & sub base layers shall be investigated.

REFERENCES

1. Aaron Lodge, 2013 'Variability and characteristics of recycled asphalt shingles Sampled from different sources'. Louisiana State University.
2. AACRA, 2004 'Technical Specification Manual'.
3. AASHTO, 2001 'Standard Specifications for Transportation Materials and Method of Sampling and Testing, Washington DC', USA.
4. Asphalt pavement recycling Manual, 2004, '*Basic Asphalt Emulsion Manual*'.
5. ASTM , 2011 'American Society for Testing and Materials Manual'
6. Brajesh Mishra, '*A study on use of RAP materials in flexible pavement*', International journal of innovative research in science, Engineering & Technology, vol – 4 issue12, India 2015.
7. BRE, (2000), 'Quality control in the production of recycled aggregates'.
8. British Standards Institution, (1989). '*Methods for determination of particle shape'*, BS812: Part 105:
9. British Standards Institution, (1990).'*Methods for determination of aggregate crushing Value*', BS 812: Part 110:
10. British Standards Institution, (1990). 'Methods for determination of ten percent fines *Value*', BS 812: Part 111:
11. Chiu, C., Hsu, T. & Yang, W. (2007),'Life cycle assessment on using recycle material for rehabilitating asphalt pavements, Resources, Conservation and Recycling',
12. David A. Byrne BEng (Hons)(2005) '*Recycling of asphalt pavement in new bituminous mixes*' A thesis submitted in partial fulfillment of the requirements of Napier University for the Degree of Doctor of Philosophy.
13. Don caster College (A), October 1999. '*Asphalt Technology Pavement concept*'.
14. European Asphalt Pavement Association (EAPA), (1995). 'Recycling of asphalt mixes and use of waste in asphalt pavements', EAPA.
15. Edward J. Hoppe, Ph.D., D. Stephen Lane, G. Michael Fitch, Ph.D., Sameer Shetty, 2015, '*Feasibility of Reclaimed Asphalt Pavement -Use As Road Base and Sub base Material*', Virginia Center for Transportation Innovation and Research, Virginia.

16. FHWA, Federal Highway Administration, April 2011, '*Reclaimed Asphalt Pavement in Asphalt Mixtures-State of the Practice*', Virginia, USA.
17. FHWA, Federal Highway Administration, 1997, '*Pavement Recycling Guidelines for State & Local Governments-Participant's Reference Book*', National center for Asphalt Technology, Washington DC, USA.
18. FHWA, Federal Highway Administration, 2001, '*Basic Asphalt Recycling Manual*', Asphalt Recycling & Reclaiming Association, Washington DC, USA.
19. Gabriele Iebakli, Eshan Dave, Paul Marsac, Patrick Muraya, Martin Hugener, IarcoPa.setto, Andrea Graziani, Andrea Grilli, Alessanciro Marracli, Louisette Venclling, 2013, '*Classification of recycled asphalt (RA) material*', France.
20. Ganung, G. & Larsen D. A. (1987). 'Performance evaluation of hot mixed recycled pavement', Burlington,
21. Hodo, W., Kvasnak, A., & Brown, E. R. (2009). 'Investigation of foamed asphalt (warm mix asphalt) with high reclaimed asphalt pavement (RAP) content for sustainment and rehabilitation of asphalt pavement' Washington, D.C: Transportation Research Board 88th Annual Meeting.
22. Hunter, R. N, (1994), 'Bituminous mixtures in road construction.'
23. Huang, B. & Vukosavljevic, D. (2006), 'Laboratory study of fatigue characteristics of HMA mixtures containing recycled asphalt pavement (RAP).' The University of Tennessee, Knoxville.
24. Ibrahim Worku, September 2013 'Road Sector Development and Economic Growth in Ethiopia.'
25. Kandhal, P. S., & Mallick, R. B. (1997). '*Pavement recycling guidelines for state and local governments' participant's reference book*,' Auburn: National Center for Asphalt Technology, Auburn University.
26. Kandhal, P. S., Rao, S. S., Watson, D .E., & Young, B. (1995). '*Performance of recycled hot-mix asphalt mixtures in the state of Georgia*', National Center for Asphalt Technology, NCAT Report 95–01.
27. Larry Santucci, PE, January 2007 '*Recycling Asphalt Pavements- A strategy revisited*', California, USA.

28. Mustaque Hossain, Haritha Y. Musty, Nasim Sabahfer. 2012 'Use of High-Volume Reclaimed Asphalt Pavement (RAP) for Asphalt Pavement Rehabilitation Due to *Increased Highway Truck Traffic from Freight Transportation.*' University of Nebraska.
29. Randy C. West August 2010 '*Reclaimed Asphalt Pavement management Best Practices*'.
30. Randy C. West, Ph.D., P.E National Center for Asphalt Technology and Audrey Copeland, Ph.D., P.E. National Asphalt Pavement Association, December 2015, '*High RAP Asphalt Pavements Japan Practice*.'
31. Romier, A., Audeon, M., David, J., Martineau, Y. & Olard, F. (2007). '*Low-energy asphalt with performance of hot-mix asphalt*'. Journal of the Transportation Research Board, 1962, 101-112.
32. Scott Koch, Khaled Ksaibati October 2010 '*Performance of Recycled Asphalt Pavement in Gravel Roads*' Department of Civil and Architectural Engineering, University of Wyoming
33. The Asphalt Institute, 1986, '*Asphalt Hot-Mix Recycling, Manual Series No. 20 (MS-20)*', Second Edition, Lexington, KY, USA
34. The Asphalt Institute Asphalt Institute, 1995, 'Mix design methods for Asphalt Concrete and Others Hot-mix type, Manual Series No. 2 (MS-2)', sixth edition, Lexington, KY, USA.
35. Theodros Meles, 2019, '*The Utilization of HMA containing Reclaimed Aspahlt Pavement'* Addis Ababa University, Addis Ababa Institute of Technology.
36. Transportation Research Board, January 2014, *'Application of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Hot-Mix Asphalt*', National and International Perspective on Current Practice, USA.

APPENDIX

A-1 Specific Gravity of Filler

Description		Test 1	Test2	Average
Pycnometer No		1	2	
Temperature of water (°C)		25	25	
A. Mass of Dry Sample in Air (g)		48.99	48.90	
C. Mass of Flask + Water (g)		175.35	174.73	
D. Mass of Flask + Water + Sample (g)		205.8	205.0	
Specific Gravity	$\frac{A}{A-(D-C)}$	2.642	2.625	2.634

A-2 Specific Gravity of Fine Aggregate (Pass 4.75mm)

Description		Test 1	Test2	Average
Pycnometer No		1	2	
Temperature of water (°C)		25	25	
A. Mass of Oven Dry Sample in Air (g)		493.2	494.2	
B. Mass of Saturated Surface Dry (SSD)Sample in Air (g)		500.0	500.0	
C. Mass of Flask + Water (g)		1687.7	1689.3	
D. Mass of Flask + Water + Sample (g)		2003.5	2002.5	
Apparent Specific Gravity	$\frac{K*A}{A - (D - C)}$	2.78	2.73	2.753
Bulk Specific Gravity(Oven Dry)	$\frac{K*A}{B - (D - C)}$	2.68	2.64	2.659
Bulk Specific Gravity (S.S.D basis)	$\frac{K*B}{B - (D - C)}$	2.71	2.67	2.693
Correction Factor K @ 24°c = 0.9991				

A-3 Specific Gravity and water absorption of Aggregate (Pass 9.5mm _ 4.75mm Retain)

Description		Test 1	Test2	Average
Container No		1	2	
Temperature of water (°C)				
Mass o f Container (g)				
Mass o f Container +Oven Dry Sample in Air (g)				
A. Mass o f Oven Dry Sample in Air (g)		1955.0	1956.0	
Mass o f Container + Saturated Surface Dry (SSD) Sample in Air (g)				
B. Mass o f Saturated Surface Dry (SSD) Sample in Air (g)		2000.0	2000.0	
C. Mass Saturated Sample in Water (g)		1279.0	1281.0	
Absorption	((B - A)/A)*100	2.3	2.2	2.28
Apparent Specific Gravity	(A/A-C)*K	2.892	2.898	2.895
Bulk Specific Gravity(Oven Dry)	(A/B-C)*K	2.712	2.720	2.716
Bulk Specific Gravity (SSD basis)	(B/B-C)*K	2.774	2.782	2.778
Correction Factor K @ 24°c =				
Specific Gravity Reported to 0.001 Water Absorption Reported to 0.01				

A-4 Specific Gravity and water absorption of Aggregate (Pass 12.mm pass _ 9.5mm Retain)

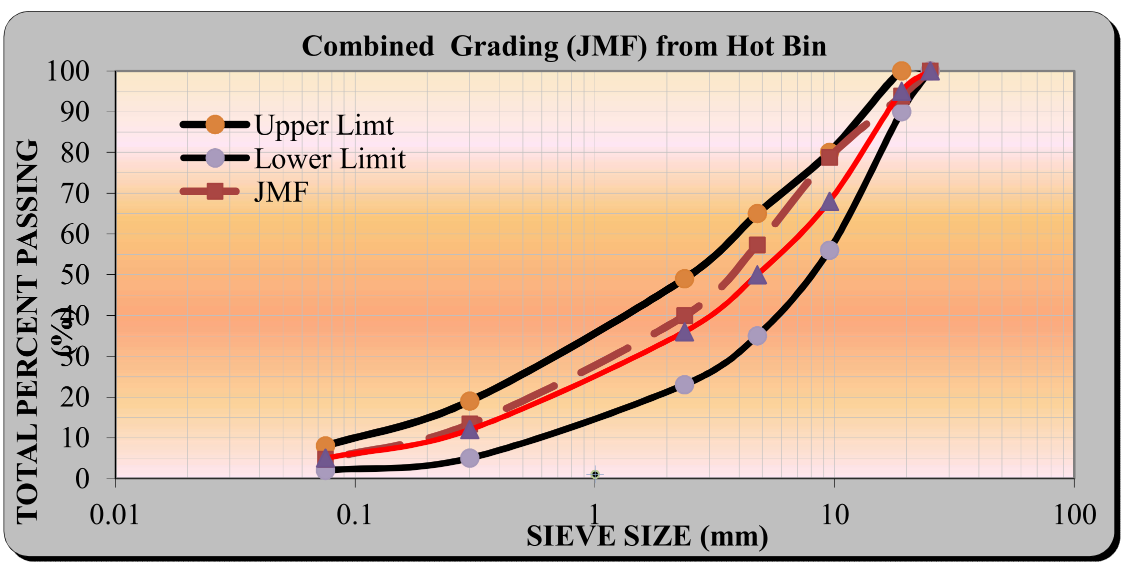
Description		Test 1	Test2	Average
Container No		1	2	
Temperature of water (°C)				
Mass o f Container (g)				
Mass o f Container +Oven Dry Sample in Air (g)				
A. Mass o f Oven Dry Sample in Air (g)		1962.0	1964.0	
Mass o f Container + Saturated Surface Dry (SSD) Sample in Air (g)				
B. Mass o f Saturated Surface Dry (SSD) Sample in Air (g)		2000.0	2000.0	
C. Mass Saturated Sample in Water (g)		1268.0	1266.4	
Absorption	((B - A)/A)*100	1.94	1.83	1.88
Apparent Specific Gravity	(A/A-C)*K	2.827	2.815	2.821
Bulk Specific Gravity(Oven Dry)	(A/B-C)*K	2.680	2.677	2.679
Bulk Specific Gravity (SSD basis)	(B/B-C)*K	2.732	2.726	2.729
Correction Factor K @ 24°c =				
Specific Gravity Reported to 0.001 Water Absorption Reported to 0.01				

A-5 Specific Gravity and water absorption of Aggregate (Pass 25mm pass _ 12.5mm Retain)

Description		Test 1	Test2	Average
Container No		1	2	
Temperature of water (^oC)				
Mass o f Container (g)				
Mass o f Container +Oven Dry Sample in Air (g)				
A. Mass o f Oven Dry Sample in Air (g)		2945.0	2944.6	
Mass o f Container + Saturated Surface Dry (SSD) Sample in Air (g)				
B. Mass o f Saturated Surface Dry (SSD) Sample in Air (g)		3000.0	3000.0	
C. Mass Saturated Sample in Water (g)		1895.0	1898.0	
Absorption	((B - A)/A)*100	1.87	1.88	1.87
Apparent Specific Gravity	(A/A-C)*K	2.805	2.813	2.809
Bulk Specific Gravity(Oven Dry)	(A/B-C)*K	2.665	2.672	2.669
Bulk Specific Gravity (SSD basis)	(B/B-C)*K	2.715	2.722	2.719
Correction Factor K @ 24°c =				
Specific Gravity Reported to 0.001 Water Absorption Reported to 0.01				

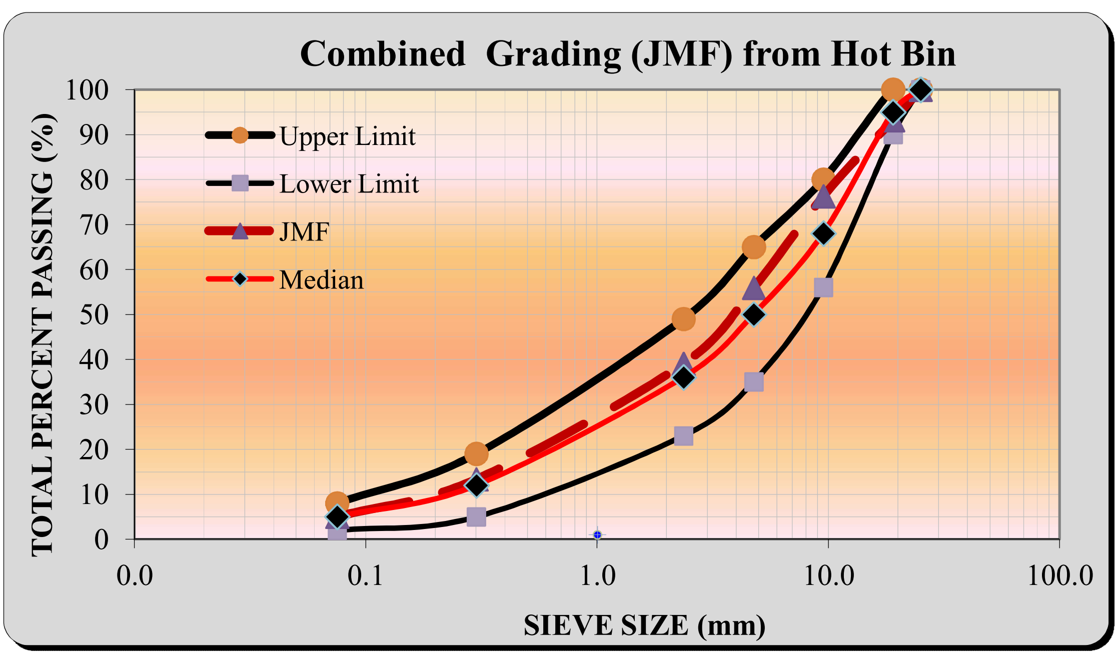
A-6 Combined Gradation for Binder Course (Virgin Aggregate)

Combined Gradation for Binder Course (0% RAP)									
Sieve Size	Average of Fractional Gradation					JMF	Spec.Limit (MS-2)		
	(25-12.5mm)	(12.5-9.5mm)	(9.5~4.75mm)	Pass 4.75mm	Artefecial Filler		Min %	Max %	Median
25.0	100.0	100.0	100.0	100.0	100.0	**100.0**	**100**	**100**	**100**
19.0	64.1	100.0	99.7	100.0	100.0	**93.8**	**90**	**100**	**95**
9.5	6.4	65.0	97.3	100.0	100.0	**78.8**	**56**	**80**	**68**
4.75	0.5	3.9	23.6	98.4	100.0	**57.3**	**35**	**65**	**50**
2.36	0.3	1.6	11.8	69.0	100.0	**39.9**	**23**	**49**	**36**
0.300	0.1	0.4	5.7	20.0	100.0	**13.3**	**5**	**19**	**12**
0.075	0.0	0.1	1.5	5.6	80.0	**4.8**	**2**	**8**	**5**
% Composition	**17.0%**	**14.0%**	**15.0%**	**52.0%**	**2.0%**	**1.00**			



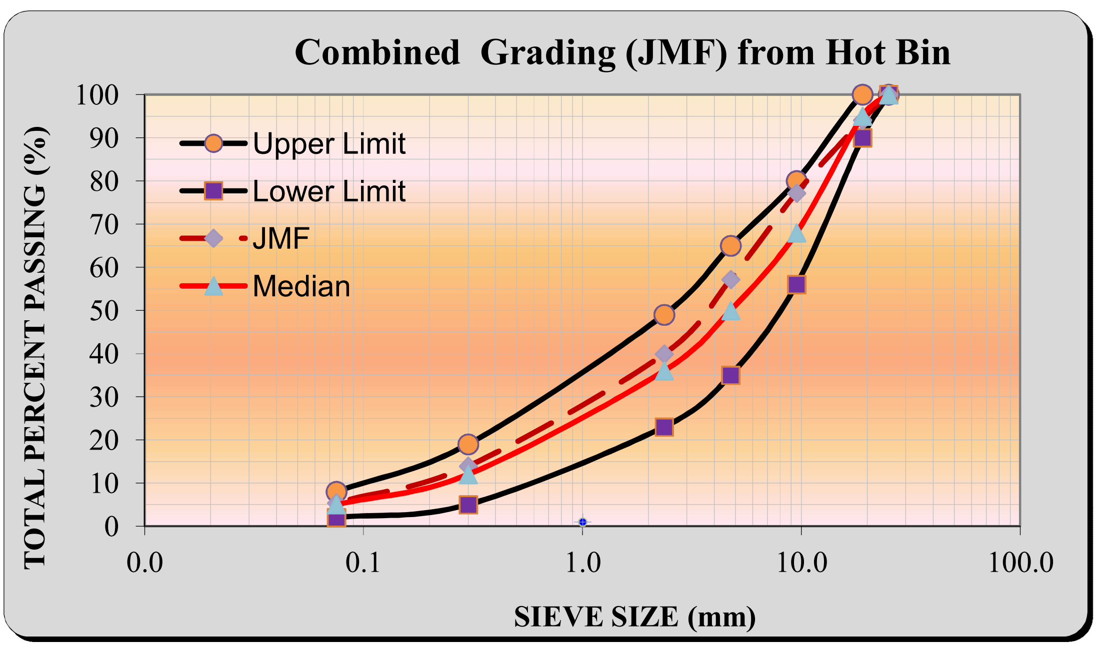
A-7 Combined Gradation for Binder Course (Virgin Aggregate+10%RAP)

Combined Gradation for Binder Course (Virgin Aggregate+10%RAP)										
Sieve Size	**Average of Fractional Gradation**						**JMF**	**Spec.Limit(MS-2)**		
	(25-12.5mm)	**(12.5-9.5mm)**	**(9.5~4.75 mm)**	**RAP**	**Pass 4.75mm**	**Artificial Filler**		**Min %**	**Max %**	**Median**
25.0	100.0	100.0	100.0	100.0	100.0	100.0	**100.0**	**100**	**100**	**100**
19.0	64.1	100.0	99.7	97.6	100.0	100.0	**93.2**	**90**	**100**	**95**
9.5	6.4	69.5	97.3	74.5	100.0	100.0	**76.3**	**56**	**80**	**68**
4.75	0.5	3.9	23.6	62.5	98.4	100.0	**55.9**	**35**	**65**	**50**
2.36	0.3	1.6	11.8	43.5	69.0	100.0	**39.1**	**23**	**49**	**36**
0.300	0.1	0.4	5.7	15.8	20.0	100.0	**13.3**	**5**	**19**	**12**
0.075	0.0	0.1	1.5	6.9	5.6	80.0	**5.0**	**2**	**8**	**5**
% Composition	**18.0%**	**13.0%**	**12.0%**	**10.0%**	**45.0%**	**2.0%**				



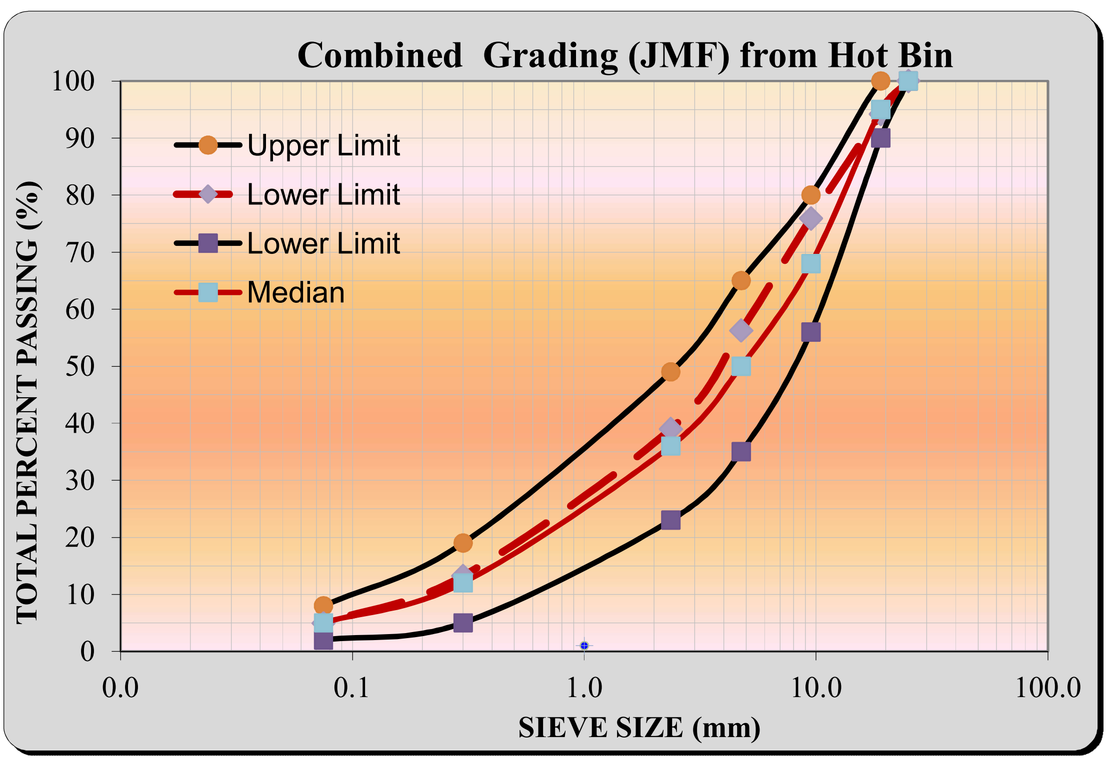
A-8 Combined Gradation for Binder Course (Virgin Aggregate+20 %RAP)

Combined Gradation for Binder Course (Virgin Aggregate+20 %RAP)										
Sieve Size	**Average of Fractional Gradation**						**JMF**	**Spec. Limit(MS-2)**		
	(25-12.5mm)	**(12.5-9.5mm)**	**(9.5~4.75mm)**	**RAP**	**Pass 4.75mm**	**Artificial Filler**		**Min %**	**Max %**	**Median**
25.0	100.0	100.0	100.0	100.0	100.0	100.0	**100.0**	**100**	**100**	**100**
19.0	64.1	100.0	99.7	97.6	100.0	100.0	**94.1**	**90**	**100**	**95**
9.5	6.4	69.5	97.3	74.5	100.0	100.0	**77.2**	**56**	**80**	**68**
4.75	0.5	3.9	23.6	62.5	98.4	100.0	**57.2**	**35**	**65**	**50**
2.36	0.3	1.6	11.8	43.5	69.0	100.0	**39.9**	**23**	**49**	**36**
0.300	0.1	0.4	5.7	15.8	20.0	100.0	**13.9**	**5**	**19**	**12**
0.075	0.0	0.1	1.5	6.9	5.6	80.0	**5.4**	**2**	**8**	**5**
% Composition	**15.0%**	**11.0%**	**12.0%**	**20.0%**	**40.0%**	**2.0%**				



A-9 Combined Gradation for Binder Course (Virgin Aggregate+30 %RAP)

A-8 Combined Gradation for Binder Course (Virgin Aggregate+30 %RAP)										
Sieve Size	**Average of Fractional Gradation**						**JMF**	**Spec.Limit(MS-2)**		
	(25-12.5mm)	**(12.5-9.5mm)**	**(9.5~4.75mm)**	**RAP**	**Pass 4.75mm**	**Arteficial Filler**		**Min %**	**Max %**	**Median**
25.0	100.0	100.0	100.0	100.0	100.0	100.0	**100.0**	**100**	**100**	**100**
19.0	64.1	100.0	99.7	97.6	100.0	100.0	**94.2**	**90**	**100**	**95**
9.5	6.4	69.5	97.3	74.5	100.0	100.0	**75.9**	**56**	**80**	**68**
4.75	0.5	3.9	23.6	62.5	98.4	100.0	**56.3**	**35**	**65**	**50**
2.36	0.3	1.6	11.8	43.5	69.0	100.0	**39.0**	**23**	**49**	**36**
0.300	0.1	0.4	5.7	15.8	20.0	100.0	**13.2**	**5**	**19**	**12**
0.075	0.0	0.1	1.5	6.9	5.6	80.0	**4.9**	**2**	**8**	**5**
% Composition	**14.0%**	**10.0 %**	**11.0%**	**30.0 %**	**34.0 %**	**1.0%**				



A-10 Aggregate Properties @ 10% RAP

Aggregate size	Percent by Wt of total aggregate (%)	Bulk Specific Gravity	Apparent Specific Gravity	Water Absorption (%)
(25-12.5mm)	18.00%	2.669	2.809	1.87
(12.5-9.5mm)	13.00%	2.679	2.821	1.88
(9.5-4.75mm)	12.00%	2.716	2.895	2.28
Pass 4.75mm	45.00%	2.659	2.753	
RAP	10.00%	2.648		
Filler	2.00%	2.634		
Total	1.00			

Calculation of Volumetric Composition

Specific Gravity of the bitumen (G_b) =1.013

Bulk Specific Gravity of total aggregate (G_{sb})

G_{sb} = 2.668

Apparent Specific Gravity of total aggregate (G_{sapp})

G_{sapp} = 2.774

Effective Specific Gravity of total aggregate (G_{se})

Bitumen Content (%)	Max SG of mix (G_{mm})	Effective SG (G_{se})
4.5%	2.523	2.714
5.0%	2.499	2.708
5.5%	2.475	2.702
6.0%	2.469	2.718
6.5%	2.449	2.717
Mean G_{se} =		2.712

Bulk Sp. Gravity<	Effective Sp.Gravity<	Apparent Sp. Gravity	
2.668	2.712 <	2.774	Ok

A-11 Aggregate Properties @ 20% RAP

Aggregate size	Percent by Wt of total aggregate (%)	Bulk Specific Gravity	Apparent Specific Gravity	Water Absorption (%)
(25-12.5mm)	15.00%	2.669	2.809	1.87
(12.5-9.5mm)	11.00%	2.679	2.821	1.88
(9.5-4.75mm)	12.00%	2.716	2.895	2.28
Pass 4.75mm	40.00%	2.659	2.753	
RAP	20.00%	2.648		
Filler	2.00%	2.634		
Total	1.00			

Calculation of Volumetric Composition

Specific Gravity of the bitumen (G_b) =1.013

Bulk Specific Gravity of total aggregate (G_{sb})

G_{sb} = 2.666

Apparent Specific Gravity of total aggregate (G_{sapp})

G_{sapp} = 2.760

Effective Specific Gravity of total aggregate (G_{se})

Bitumen Content (%)	Max SG of mix (G_{mm})	Effective SG (G_{se})
4.5%	2.531	2.723
5.0%	2.502	2.712
5.5%	2.497	2.730
6.0%	2.486	2.740
6.5%	2.462	2.734
Mean G_{se} =		2.728

Bulk Sp. Gravity <	Effective Sp. Gravity <	Apparent Sp. Gravity	
2.666 <	2.728<	2.760	Ok

A-12 Aggregate Properties @ 30% RAP

Aggregate size	Percent by Wt of total aggregate (%)	Bulk Specific Gravity	Apparent Specific Gravity	Water Absorption (%)
(25-12.5mm)	14.00%	2.669	2.809	1.87
(12.5-9.5mm)	10.00%	2.679	2.821	1.88
(9.5-4.75mm)	11.00%	2.716	2.895	2.28
Pass 4.75mm	34.00%	2.659	2.753	
RAP	30.00%	2.648		
Filler	1.00%	2.634		
Total	1.00			

Calculation of Volumetric Composition

Specific Gravity of the bitumen (G_b) =1.013

Bulk Specific Gravity of total aggregate (G_{sb})

G_{sb} = 2.664

Apparent Specific Gravity of total aggregate (G_{sapp})

G_{sapp} = 2.748

Effective Specific Gravity of total aggregate (G_{se})

Bitumen Content (%)	Max SG of mix (G_{mm})	Effective SG (G_{se})
4.5%	2.541	2.735
5.0%	2.520	2.734
5.5%	2.509	2.745
6.0%	2.497	2.755
6.5%	2.473	2.748
Mean G_{se} =		2.743

Bulk Sp. Gravity < Effective Sp. Gravity < Apparent Sp. Gravity

2.664 2.743 < 2.748 Ok

A-13: Trial Batches of 10% RAP containing hot mix asphalt

Asphalt Content	Mass of oven dry aggregate(gm) (A)	Mass of Oven Dry RAP(gm) (B)	Mass of Filler (gm) (C)	A+B+C	Mass of Asphalt by Weight of mix(gm)	New Asphalt by Weight of mix(gm)	Total Batch Weight(gm)
4.5%	1025.4	120	54.0	1199.4	56.52	48.6	1255.9
	1026.0	120	54.0	1200.0	56.56	48.6	1256.6
	1025.0	120	54.0	1199.0	56.50	48.7	1255.5
	1025.6	120	54.0	1199.6	56.53	48.7	1256.1
5.0%	1025.6	120	54.0	1199.6	63.14	56.5	1262.7
	1025.1	120	54.0	1199.1	63.11	56.5	1262.2
	1026.1	120	54.0	1200.1	63.16	56.5	1263.3
	1024.9	120	54.0	1198.9	63.10	56.5	1262.0
5.5%	1026.2	120	54.0	1200.2	69.85	63.15	1270.1
	1025.7	120	54.0	1199.7	69.82	63.12	1269.5
	1026.0	120	54.0	1200.0	69.84	63.13	1269.9
	1025.2	120	54.0	1199.2	69.80	63.11	1269.0
6.0%	1026.1	120	54.0	1200.1	76.60	69.84	1276.7
	1025.7	120	54.0	1199.7	76.58	69.82	1276.3
	1026.3	120	54.0	1200.3	76.62	69.85	1276.9
	1025.4	120	54.0	1199.4	76.56	69.81	1276.0
6.5%	1025.9	120	54.0	1199.9	83.42	69.84	1283.3
	1025.7	120	54.0	1199.7	83.40	69.82	1283.1
	1026.3	120	54.0	1200.3	83.44	69.85	1283.8
	1025.4	120	54.0	1199.4	83.38	69.81	1282.8

A-14: Trial Batches of 20% RAP containing hot mix asphalt

Asphalt Content	Mass of oven dry aggregate(gm) (A)	Mass of Oven Dry RAP (gm) (B)	Mass of Filler (gm) (C)	A+B+C	Mass of Asphalt by Weight of mix(gm)	New Asphalt by Weight of mix (gm)	Total Batch Weight (gm)
4.5%	908.0	240	51.9	1199.9	56.54	42.24	1256.4
	907.6	240	51.9	1199.5	56.52	42.22	1256.0
	907.3	240	51.9	1199.2	56.21	41.91	1255.4
	906.8	240	51.9	1198.7	55.68	41.39	1254.4
5.0%	907.2	240	51.9	1199.1	63.11	48.66	1262.2
	906.8	240	51.9	1198.7	63.09	48.65	1261.8
	908.1	240	51.9	1200.0	63.16	48.69	1263.1
	907.5	240	51.9	1199.4	63.12	48.67	1262.5
5.5%	907.4	240	51.9	1199.3	69.80	55.19	1269.1
	906.9	240	51.9	1198.8	69.77	55.17	1268.5
	908.1	240	51.9	1200.0	69.84	55.23	1269.8
	907.2	240	51.9	1199.1	69.79	55.19	1268.9
6.0%	907.0	240	51.9	1198.9	76.52	61.77	1275.4
	906.5	240	51.9	1198.4	76.49	61.74	1274.9
	908.0	240	51.9	1199.9	76.59	61.82	1276.5
	907.6	240	51.9	1199.5	76.56	61.80	1276.0
6.5%	907.8	240	51.9	1199.7	83.40	68.48	1283.1
	906.3	240	51.9	1198.2	83.30	68.39	1281.5
	907.1	240	51.9	1199.0	83.35	68.44	1282.3
	908.0	240	51.9	1199.9	83.41	68.49	1283.3

A-15: Trial Batches of 30% RAP containing hot mix asphalt

Asphalt Content	Mass of oven dry aggregate(gm) (A)	Mass of Oven Dry RAP (gm) (B)	Mass of Filler (gm) (C)	A+B+C	Mass of Asphalt by Weight of mix(gm)	New Asphalt by Weight of mix (gm)	Total Batch Weight (gm)
4.5%	797.3	360	41.5	1198.8	56.49	34.53	1255.3
	798.3	360	41.5	1199.8	56.53	34.55	1256.3
	797.6	360	41.5	1199.1	56.50	34.54	1255.6
	796.8	360	41.5	1198.3	56.46	34.53	1254.7
5.0%	798.3	360	41.5	1199.8	63.15	42.21	1262.9
	796.8	360	41.5	1198.3	63.07	42.17	1261.3
	798.3	360	41.5	1199.8	63.15	42.22	1262.9
	797.5	360	41.5	1199.0	63.10	42.20	1262.1
5.5%	796.9	360	41.5	1198.4	69.75	48.63	1268.1
	797.4	360	41.5	1198.9	69.78	48.67	1268.6
	797.8	360	41.5	1199.3	69.80	48.67	1269.1
	798.0	360	41.5	1199.5	69.81	48.68	1269.3
6.0%	797.2	360	41.5	1198.7	76.51	55.17	1275.2
	796.5	360	41.5	1198.0	76.47	55.14	1274.4
	796.9	360	41.5	1198.4	76.49	55.15	1274.9
	798.2	360	41.5	1199.7	76.57	55.21	1276.2
6.5%	798.4	360	41.5	1199.9	83.41	61.82	1283.3
	798.0	360	41.5	1199.5	83.39	61.80	1282.9
	797.9	360	41.5	1199.4	83.38	61.79	1282.7
	797.5	360	41.5	1199.0	83.35	61.78	1282.3

A-16 Marshall properties of bituminous mix at 10% RAP

MARSHALL PROPERTIES OF BITUMINOUS MIXTURES												
Sample No	% Bitumen by total mix	Mass in grams			Bulk Vol cm^3	Bulk S.G Specimen	Max. S.G (G_{mm})	% Air Void	% VMA	% VFA	Corrected Stability	Flow (mm)
		In Air	In Water	SSD in Air								
4.5A	4.5	1255.9	725.0	1257.0	532.0	2.361					8.50	2.75
4.5B	4.5	1256.6	726.3	1259.3	533.0	2.358					10.20	2.98
4.5C	4.5	1255.5	724.6	1258.4	533.8	2.352					9.45	2.85
4.5D	4.5	1256.1	726.1	1259.0	532.9	2.357					9.80	2.60
Average						2.357	2.523	6.5	15.64	57.91	9.49	2.80
5.0A	5.0	1262.7	731.0	1263.5	532.5	2.371					9.00	3.10
5.0B	5.0	1262.2	730.8	1263.0	532.2	2.372					10.80	3.20
5.0C	5.0	1263.3	732.0	1263.9	531.9	2.375					11.60	2.90
5.0D	5.0	1262.0	730.4	1263.0	532.6	2.370					11.20	3.20
Average						2.372	2.499	5.1	15.55	67.29	10.65	3.10
5.5A	5.5	1270.1	738.0	1271.3	533.3	2.382					10.00	3.25
5.5B	5.5	1269.5	737.3	1271.0	533.7	2.379					12.50	3.40
5.5C	5.5	1269.9	737.8	1271.5	533.7	2.379					11.80	3.15
5.5D	5.5	1269.0	737.6	1270.5	532.9	2.381					12.00	3.46
Average						2.384	2.475	3.7	15.57	76.38	11.58	3.32
6.0A	6.0	1276.7	744.2	1277.5	533.3	2.394					8.90	3.60
6.0B	6.0	1276.3	743.8	1277.2	533.4	2.393					10.40	3.52
6.0C	6.0	1276.9	744.5	1278.2	533.7	2.393					11.30	3.47
6.0D	6.0	1276.0	743.2	1277.4	534.2	2.389					9.50	3.32
Average						2.390	2.469	3.2	15.80	79.75	10.03	3.48
6.5A	6.5	1283.3	744.5	1284.2	539.7	2.378					8.20	3.60
6.5B	6.5	1283.1	744.1	1284.0	539.9	2.377					10.50	3.69
6.5C	6.5	1283.8	745.0	1284.5	539.5	2.380					10.80	3.47
6.5D	6.5	1282.8	743.0	1283.6	540.6	2.373					8.60	3.65
Average						2.377	2.449	3.0	16.72	82.34	9.53	3.60

A-17 Marshall properties of bituminous mix at 20% RAP

MARSHALL PROPERTIES OF BITUMINOUS MIXTURES												
Sample No	% Bitumen by total mix	Mass in grams			Bulk Vol cm^3	Bulk S.G Specimen	Max. S.G (G_{mm})	% Air Void	% VMA	% VFA	Corrected Stability	Flow (mm)
		In Air	In Water	SSD in Air								
4.5A	4.5	1256.4	726.9	1257.9	531.0	2.366					10.41	2.45
4.5B	4.5	1256.0	726.2	1257.4	531.2	2.364					9.30	2.63
4.5C	4.5	1255.4	725.3	1256.3	531.0	2.364					11.30	2.70
4.5D	4.5	1254.4	724.7	1255.4	530.7	2.364					9.80	2.60
Average						2.365	2.531	6.6	15.30	57.04	10.20	2.60
5.0A	5.0	1262.2	734.6	1263.1	528.5	2.388					12.10	2.85
5.0B	5.0	1261.8	733.6	1262.3	528.7	2.387					10.90	2.78
5.0C	5.0	1263.1	736.0	1264.2	528.2	2.391					11.30	2.90
5.0D	5.0	1262.5	735.3	1263.4	528.1	2.391					11.80	3.05
Average						2.389	2.502	4.5	14.87	69.68	11.53	2.90
5.5A	5.5	1269.1	744.5	1270.3	525.8	2.414					13.90	3.10
5.5B	5.5	1268.5	743.5	1269.6	526.1	2.411					12.10	2.98
5.5C	5.5	1269.8	744.0	1271.1	527.1	2.409					11.80	3.15
5.5D	5.5	1268.9	742.8	1270.4	527.6	2.405					11.40	3.20
Average						2.410	2.493	3.3	14.59	77.14	12.30	3.11
6.0A	6.0	1275.4	749.0	1276.3	527.3	2.419					10.60	3.32
6.0B	6.0	1274.9	748.5	1275.6	527.1	2.417					11.20	3.28
6.0C	6.0	1276.5	749.6	1277.2	527.6	2.418					9.84	3.16
6.0D	6.0	1276.0	749.2	1277.4	528.2	2.416					12.00	3.41
Average						2.418	2.486	2.7	14.75	81.49	10.91	3.29
6.5A	6.5	1283.1	752.0	1284.1	532.1	2.411					10.80	3.41
6.5B	6.5	1281.5	750.2	1282.3	532.1	2.408					9.60	3.52
6.5C	6.5	1282.3	751.0	1283.2	532.2	2.409					9.10	3.20
6.5D	6.5	1283.3	752.3	1284.0	531.7	2.414					10.00	3.62
Average						2.411	2.462	2.1	15.46	86.52	9.88	3.44

A-18 Marshall properties of bituminous mix at 30% RAP

MARSHALL PROPERTIES OF BITUMINOUS MIXTURES												
Sample No	% Bitumen by total mix	Mass in grams			Bulk Vol cm^3	Bulk S.G Specimen	Max. S.G (G_{mm})	% Air Void	% VMA	% VFA	Corrected Stability	Flow (mm)
		In Air	In Water	SSD in Air								
4.5A	4.5	1255.3	726.9	1256.7	529.8	2.369					10.00	2.30
4.5B	4.5	1256.3	727.5	1257.4	529.9	2.371					9.60	2.63
4.5C	4.5	1255.6	727.0	1256.8	529.8	2.370					8.70	2.40
4.5D	4.5	1254.7	725.0	1255.4	530.4	2.366					8.60	2.60
Average						2.369	2.541	6.8	15.09	55.11	9.23	2.48
5.0A	5.0	1262.9	735.0	1263.9	528.9	2.388					10.80	2.75
5.0B	5.0	1261.3	734.5	1262.5	528.0	2.389					9.60	2.63
5.0C	5.0	1262.9	735.3	1264.4	529.1	2.387					11.30	2.45
5.0D	5.0	1262.1	734.0	1263.4	529.4	2.384					9.89	2.62
Average						2.387	2.520	5.3	14.89	64.53	10.40	2.61
5.5A	5.5	1268.1	745.0	1270.0	525.0	2.406					11.54	2.95
5.5B	5.5	1268.6	745.3	1270.6	525.3	2.409					10.75	2.85
5.5C	5.5	1269.1	746.2	1271.1	524.9	2.413					10.60	2.73
5.5D	5.5	1269.3	746.7	1271.4	524.7	2.404					11.00	3.10
Average						2.408	2.509	4.0	14.59	72.47	10.97	2.91
6.0A	6.0	1275.2	750.5	1277.0	526.5	2.422					10.30	3.20
6.0B	6.0	1274.4	750.2	1275.6	525.4	2.426					9.20	2.98
6.0C	6.0	1274.9	750.5	1276.0	525.5	2.426					11.00	3.16
6.0D	6.0	1276.2	751.0	1277.8	526.8	2.423					8.60	3.17
Average						2.424	2.497	2.9	14.48	79.82	9.78	3.13
6.5A	6.5	1283.3	753.0	1284.1	531.1	2.416					9.20	3.25
6.5B	6.5	1282.9	752.5	1282.3	529.8	2.421					9.60	3.45
6.5C	6.5	1282.7	752.1	1283.2	531.1	2.415					8.60	3.30
6.5D	6.5	1282.3	751.8	1284.0	532.2	2.409					10.20	3.15
Average						2.416	2.473	2.3	15.23	84.76	9.40	3.29

A-19 Cost breakdown for conventional mix (0% RAP)

DESCRIPTION	**Asphalt Binder Mix Production**										DAILY PRODUCTION OUTPUT		336.00	m3
											HOURLY RESULTANT		42.00	m3/hr
QUANTITY	**1 m3**													
MATERIAL COST					**LABOR COST**					**EQUIPMENT COST**				
type of material	unit	qty	rate	cost/un	**labor by trade**	No	UF	index hourly cost	hourly cost	**type of equipment**	No.	UF	hourly rate	hourly cost
00 Aggregate (Pass 4.75mm)	m3	0.54	420.50	227.07	Asphalt Foreman	1.00	1.00	75.51	75.51	Asphalt Plant	1.00	1.00	7,088.00	7,088.00
01 Aggregate(12.5-9.5 & 9.5-4.75mm)	m3	0.29	297.90	86.39	Material Inspector	1.00	1.00	75.51	75.51	Loader	1.00	1.00	1,319.00	1,319.00
02 Agg (25mm pass-12.5 Retain)	m3	0.17	483.50	82.20	Plant Operator I	1.00	1.00	75.51	75.51	Welding Machine	1.00	0.75	90.00	67.50
Bitumen 85/100	m3	0.052	23,500.00	1,222.00	Range Melter	10.00	1.00	60.38	603.80					
				-	Generator Operator	1.00	0.50	60.20	30.10					
					Loader Operator	1.00	1.00	113.83	113.83					
					Laborer	10.00	0.80	29.44	235.52					
					Mechanic	1.00	1.00	61.44	61.44					
TOTAL				1,617.66	TOTAL				1,407.47	TOTAL				8,474.50
		material unit cost		1,617.66			manpower unit cost		33.51			equipment unit cost		201.77
PRODUCTION COST OF WORK ITEM (Assuming 20% Overhead) = (Material Unit Cost + Manpower Unit Cost + Equipment Unit Cost)*1.2 =													2,223.53	ETB / M^3

A-20 Cost breakdown for 10% RAP substitutions

DESCRIPTION	Asphalt Binder Mix Production									DAILY PRODUCTION OUTPUT			336.00	m3
										HOURLY RESULTANT			42.00	m3/hr
QUANTITY	1 m3													
MATERIAL COST					**LABOR COST**					**EQUIPMENT COST**				
type of material	unit	qty	rate	cost/un	**labor by trade**	No	UF	index hourly cost	hourly cost	**type of equipment**	No.	UF	hourly rate	hourly cost
00 Aggregate (Pass 4.75mm)	m3	0.47	420.50	197.64	Asphalt Foreman	1.00	1.00	75.51	75.51	Asphalt Plant	1.00	1.00	7,088.00	7,088.00
01 Aggregate(12.5-9.5 & 9.5-4.75mm)	m3	0.25	297.90	74.48	Material Inspector	1.00	1.00	75.51	75.51	Loader	1.00	1.00	1,319.00	1,319.00
02 Agg (25mm pass-12.5 Retain)	m3	0.18	483.50	87.03	Plant Operator I	1.00	1.00	75.51	75.51	Welding Machine	1.00	0.75	90.00	67.50
Bitumen 85/100	m3	0.047	23,500.00	1,113.90	Range Melter	10.00	1.00	60.38	603.80					
RAP	m3	0.10	127.00	12.70	Generator Operator	1.00	0.50	60.20	30.10					
					Loader Operator	1.00	1.00	113.83	113.83					
					Laborer	10.00	0.80	29.44	235.52					
					Mechanic	1.00	1.00	61.44	61.44					
TOTAL				1,485.74	TOTAL				1,407.47	TOTAL				8,474.50
			material unit cost	1,485.74				manpower unit cost	33.51				equipment unit cost	201.77
PRODUCTION COST OF WORK ITEM (Assuming 20% Overhead) = (Material Unit Cost + Manpower Unit Cost + Equipment Unit Cost)*1.2 =													2,065.23	ETB / M^3

A-21 Cost breakdown for 20% RAP substitutions

DESCRIPTION	**Asphalt Binder Mix Production**									DAILY PRODUCTION OUTPUT			336.00	m3
										HOURLY RESULTANT			42.00	m3/hr
QUANTITY	**1 m3**													
MATERIAL COST					**LABOR COST**					**EQUIPMENT COST**				
type of material	unit	qty	rate	cost/un	**labor by trade**	No	UF	index hourly cost	hourly cost	**type of equipment**	No.	UF	hourly rate	hourly cost
00 Aggregate (Pass 4.75mm)	m3	0.42	420.50	176.61	Asphalt Foreman	1.00	1.00	75.51	75.51	Asphalt Plant	1.00	1.00	7,088.00	7,088.00
01 Aggregate(12.5-9.5 & 9.5-4.75mm)	m3	0.23	297.90	68.52	Material Inspector	1.00	1.00	75.51	75.51	Loader	1.00	1.00	1,319.00	1,319.00
02 Agg (25mm pass-12.5 Retain)	m3	0.15	483.50	72.53	Plant Operator I	1.00	1.00	75.51	75.51	Welding Machine	1.00	0.75	90.00	67.50
Bitumen 85/100	m3	0.040	23,500.00	940.00	Range Melter	10.00	1.00	60.38	603.80					
RAP	m3	0.20	127.00	25.40	Generator Operator	1.00	0.50	60.20	30.10					
					Loader Operator	1.00	1.00	113.83	113.83					
					Laborer	10.00	0.80	29.44	235.52					
					Mechanic	1.00	1.00	61.44	61.44					
TOTAL				1,283.05	TOTAL				1,407.47	TOTAL				8,474.50
			material unit cost	1,283.05				manpower unit cost	33.51				equipment unit cost	201.77
PRODUCTION COST OF WORK ITEM (Assuming 20% Overhead) = (Material Unit Cost + Manpower Unit Cost + Equipment Unit Cost)*1.2 =													1,822.00	ETB / M^3

A-22 Cost breakdown for 30% RAP substitutions.

DESCRIPTION	**Asphalt Binder Mix Production**									DAILY PRODUCTION OUTPUT			336.00	m3
										HOURLY RESULTANT			42.00	m3/hr
QUANTITY	**1 m3**													
MATERIAL COST					**LABOR COST**					**EQUIPMENT COST**				
type of material	unit	qty	rate	cost/un	**labor by trade**	No	UF	index hourly cost	hourly cost	**type of equipment**	No.	UF	hourly rate	hourly cost
00 Aggregate (Pass 4.75mm)	m3	0.35	420.50	147.18	Asphalt Foreman	1.00	1.00	75.51	75.51	Asphalt Plant	1.00	1.00	7,088.00	7,088.00
01 Aggregate(12.5-9.5 & 9.5-4.75mm)	m3	0.21	297.90	62.56	Material Inspecter	1.00	1.00	75.51	75.51	Loader	1.00	1.00	1,319.00	1,319.00
02 Agg (25mm pass-12.5 Retain)	m3	0.14	483.50	67.69	Plant Operator I	1.00	1.00	75.51	75.51	Welding Machine	1.00	0.75	90.00	67.50
Bitumen 85/100	m3	0.038	23,500.00	893.00	Range Melter	10.00	1.00	60.38	603.80					
RAP	m3	0.30	127.00	38.10	Generator Operator	1.00	0.50	60.20	30.10					
					Loader Operator	1.00	1.00	113.83	113.83					
					Laborer	10.00	0.80	29.44	235.52					
					Mechanic	1.00	1.00	61.44	61.44					
TOTAL				1,208.52	TOTAL				1,407.47	TOTAL				8,474.50
		material unit cost	1,208.52				manpower unit cost	33.51				equipment unit cost	201.77	
PRODUCTION COST OF WORK ITEM (Assuming 20% Overhead) = (Material Unit Cost + Manpower Unit Cost + Equipment Unit Cost)*1.2 =													1,732.57	ETB / M^3