JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

HIGHWAY ENGINEERING STREAM

Experimental Study on the Possible Use of Waste Tire Powder as Mineral Filler in Hot Mix Asphalt

A Thesis Submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Highway Engineering).

By: Asebew Almaw

March, 2021

Jimma, Ethiopia

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Advisor: Engr. Elmer C. Agon (Assos.prof)

Co-advisor: Engr. Teyba Wedajo (Ph.D. Candidate.)

March, 2021

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Declaration

I, the undersigned, declare that this thesis entitled: “Experimental Study on the Possible Use of Waste Tire Powder as Mineral Filler in Hot Mix Asphalt." is my original work, and has not been presented by any other person for an award of a degree in this or any other University, and all sources of material used for this thesis have been duly acknowledged.

Candidate:

Asebew Almaw

Signature ____________________

As Master’s Research Advisors, we hereby certify that we have read and evaluated this MSc Thesis prepared under our guidance, by Asebew Almaw entitled: “Experimental Study on the Possible Use of Waste Tire Powder as Mineral Filler in Hot Mix Asphalt."

We recommend that it can be submitted as fulfilling the MSc Thesis requirements.

Engr. Elmer C. Agon (Assos.prof)	______________	______________
Main Advisor	Signature	Date
Engr. Teyba Wedajo (Ph.D. Candidate.)	______________	______________
Co-advisor	Signature	Date

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ABSTRACT

Construction and upgrading highway roads are increasing in Ethiopia and majority of the roads are flexible pavement type. Flexible pavement road consists of asphalt pavements whose maintenance and further expansion depends upon availability of natural resources like aggregates. One of the most commonly used materials as filler is crushed stone dust from the crushing aggregate but their incessant use in asphalt mixes has led to their scarcity. Therefore, it is important to see an alternative non-conventional filler material. This research focused on evaluating the possible use of waste tire powder as mineral filler in hot mix asphalt. To determine the Optimum Bitumen Content three identical hot mix asphalt specimens were prepared for (5.0%, 6.0%, and 7.0% crushed stone dust by weight of aggregates) and five different percentages bitumen content (4.0%, 4.5%, 5.0%, 5.5%, and 6.0% by weight of total mix). Following NAPA (National Asphalt Pavement Association) method the optimum bitumen content and optimum filler content were selected. Six varying percentage of waste tire powder by weight of optimum filler content with a rate of 0% (control), 3.0%, 6.0%, 9.0%, 12%, 15%, and 18% were prepared using optimum bitumen content to obtain the optimum replacement percentage. The study compares the performance of asphalt mixes using Stability, and flow with corresponding volumetric properties, and moisture susceptibility using Indirect Tensile Strength (ITS) test. Finally, the effect of waste tire powder on the bitumen content was evaluated using optimum waste tire powder at a bitumen content of two above and below the optimum at 0.5% increments, and compared with the control mix. A total of 105 HMA specimens were prepared. From those specimens, 45 were for the control mix, 18 were for replacement; 12 were to check the effect of waste tire powder on bitumen content and 30 for Indirect Tensile Strength test. From the test results, the optimum replacement percentage of waste tire powder found at 12% by weight of optimum filler content (6.0%) at a bitumen content of 5.0%. Asphalt mixes prepared with waste tire powder filler are not sensitive to the action of water and resulted better resistance to moisture-induced damage. Based on the obtained results waste tire powder can also be used with 4.5% and 5.5% bitumen content. 12% waste tire powder achieves the minimum requirements of local Specifications (Ethiopian Road Authority) and international Specifications (Asphalt Institute). It can be concluded that waste tire powder can be used as filler materials instead of most commonly used crushed stone dust filler.

Key Word: ***Crushed stone dust, Hot Mix Asphalt, Waste tire powder.***

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ACRONYMS

AASHTO	American Association of State Highways and Transport Officials
AC	Asphalt Concrete
ACV	Aggregate crushing value
AIV	Aggregate Impact value
ASTM	American Society for Testing of Materials
BS	British Standard
CR	Crumb Rubber
CSD	Crushed Stone Dust
DGA	Dense Graded Asphalt
ELT	End-of-Life Tire
Eq.	Equation
ERA	Ethiopian Road Authority
ERCC	Ethiopia Road Construction Corporation
gm/cm^3	Gram Per Centimeter cube
HMA	Hot Mix Asphalt
in.	Inch
ITS	Indirect Tensile Strength
JiT	Jimma Institute of Technology
KPa	Kilo Pascal
LAA	Los Angles Abrasion
NAPA	National Asphalt Pavement Association

NCHRP	National Cooperative Highway Research Program
OBC	Optimum Bitumen Content
OES	Optical Emission Spectroscopy
OFC	Optimum Filler Content
OWTP	Optimum Waste Tire Powder
PG	Performance grading
PMI	Positive Material Identification
SMA	Stone Matrix Asphalt
TSR	Tensile Strength Ratio
VFA	Voids Filled with Asphalt
VIM	Void in Total Mix
VMA	Voids in Mineral Aggregates
Wt.	Weight
WTP	Waste Tire Powder
XRF	X-ray Fluorescence Spectroscopy
^{o}c	Degree centigrade
%	Percent

CHAPTER ONE

INTRODUCTION

1.1 Background

Ethiopia, one of the developing countries of the world, where road and highway play an important role to connect one place to another, hence good road network is a key for the development of our country. Majority of the roads in Ethiopia are flexible pavement types. Flexible pavement road network consists of asphalt pavements whose maintenance and further expansion depends upon continual and frequent availability of natural resources like aggregates and carbon-based asphalt/asphalt binders [1].

Asphalt concrete is one of the vital structures in terms of civil engineering, and is used in very large-scale applications including roads and waterproofing due to its high resistance to durability, water-resistance, and good stability properties. It is a composite material containing asphalt binder, coarse and fine aggregates, and fillers [2]. Aggregates form a skeleton to resist traffic load imposed upon them and bitumen acts as a binder and lead to adhesion between these aggregates. The filler is the mineral fine part with physical size passing the number 200 standard mesh sieve (75 µm) which devoid of organic matter and displayed almost non-plastic behavior [1].

Fillers added in the asphalt mix to a maximum of 10% by mass following ERA 2013 design manuals. Mineral fillers serve a dual purpose when it is added to asphalt mixes, the portion of the mineral filler that is finer than the thickness of the asphalt film blends with asphalt cement binder to form a mortar or mastic that contributes to improved stiffening of the mix. Particles larger than the thickness of the asphalt film behave as mineral aggregate and hence contribute to the contact points between individual aggregate particles [3].

Research studies showed that the strength of hot mix asphalt (HMA) depends on different factors such as filler and aggregate type, and bitumen grade. Among these, filler material plays a major role in various properties of HMA, especially those related to mixture compatibility and aggregate bitumen adhesion [4]. Furthermore, it also affects several HMA properties such as workability, moisture sensitivity, stiffness, durability, fatigue behavior, and long term characteristics of HMA [5]. Fillers vary in physical and chemical properties, shape and texture, size, and gradation, its interaction with bitumen, and its volumetric concentration in the mix. Therefore, the selection of suitable filler is very vital for the ideal performance of HMA [6].

In civil engineering works, utilizing waste materials has turned into an important issue during recent years due to the decrease in natural resources, the increase in road construction activities, reducing energy consumption as well as considerations for environmental aspects. Hence, several researchers have tried to study the possibility of using waste material in pavement construction [7]. Such wastes include industrial, agricultural, and municipal solid waste. According to [8]; waste materials such as recycled lime waste, phosphate waste filler, municipal solid waste incineration ash, ceramic waste material, cement kiln dust, and rice husk ash materials were satisfactorily used as filler in different asphalt mixes.

In recent decades, the worldwide growth of the automobile industry and the increasing use of a car as the main means of transport have tremendously boosted tire production. This has generated massive stockpiles of used tires [9]. It is estimated that the annual generation of waste tires amounts to1.5 billion whole-tires worldwide contributing to the huge number of tires already found in landfills and stockpiles [10]. When tires are disposed of they have lost only a small percentage of their original mass, indicating that used tires are essentially the same in physical and chemical properties as new tires. Hence, waste tires present both an environmental challenge and a resource opportunity. Recycling and disposal are two current waste management options [11]. Since the amount of waste tire has been increasing, recycling instead of disposing is more important for sustainability.

This study was done to evaluate, waste tire powder as replacement of conventionally used crushed stone dust filler in hot mix asphalt. The possibility was evaluated by preparing laboratory test samples with different percentages of waste tire powder by weight of crushed stone dust using the optimum bitumen content, and properties like Stability, flow, and volumetric properties were evaluated by the method of Marshall Mix design.

1.2 Statement of the problem

The ever-increasing growth of various sectors has led to the continual usage of natural resources and the generation of huge quantities of solid wastes [12]. Among them; a waste tire is one of an important part which is becoming an environmental problem due to the development of the automobile industry and the continuously increased production of tires. It is estimated that the annual generation of waste tires amounts to1.5 billion whole-tires worldwide contributing to the huge number of tires already found in landfills and stockpiles [10].

In Ethiopia, the amount of waste tires generated is expected to grow with the increase in the vehicle fleet in the country. However, the situation of using waste tires either as a resource opportunity or an environmentally friendly is not studied well in Ethiopia. There is no specific law or regulation regarding waste tire management either [13]. Some of the current applications of scrap tires include: the making of rubber-based items, construction applications (e.g., retaining walls), burning as fuel, and cutting for the nylon cord, shoo sol, for animal feeding material, and other uses. It is easily observed that the current practices of utilizing used tires in Ethiopia are not effective, do not result in higher value-added products, and are not environment-friendly. Therefore, due to this environmentally safe and feasible new tire recycling techniques are needed.

Currently upgrading and construction of highway roads are increasing in Ethiopia. One of the materials that are mainly used as filler is crush stone dust [14]. This filler is directly obtained by mining the earth’s resources, and their incessant use in asphalt mixes has led to their scarcity and exhaustive mining for conventional fillers also leads to problems like vegetation loss, loss of water retaining strata, lowering of the groundwater table, and disturbance in the existing ecosystem [15].

Therefore, it is important to see an alternative non-conventional filler material. This research was focus to investigate the possible use of waste tire powder as mineral filler in HMA on the Marshall properties of asphalt paving.

1.3 Research Questions

1. What are the physical properties of Aggregates, Crushed Stone Dust, Bitumen, and Waste Tire Powder in Hot Mix Asphalt?
2. What are the potential effects of adding different percentages of waste tire powder on the Marshall properties of Hot Mix Asphalt?
3. What are effects of optimum waste tire powder on bitumen content?
4. What are the effects of using waste tire powder fillers on moisture susceptibility asphalt mixes?

1.4 Objectives of the study

1.4.1 General objective

The general goal of this study was to investigate the possible of waste tire powder as mineral filler in Hot Mix Asphalt using Marshall Test Method.

1.4.2 Specific objective

The specific objectives of this study were as follow:

- To identify the physical properties of Aggregates, Crushed Stone Dust, Bitumen, and Waste Tire Powder in Hot Mix Asphalt.
- To investigate the potential effects of adding different percentage of waste tire powder on Marshall Properties of Hot Mix Asphalt.
- To investigate the effects of waste tire powder on bitumen content.
- To evaluate the effect of waste tire powder filler on moisture susceptibility of asphalt mixes.

1.5 Scope of the study

The research was focused on evaluating the possible use of waste tire powder as a substitute for natural filler material in dense-graded, Hot Mix Asphalt concrete mix design. Also, evaluate the effect of waste tire powder on the Marshall properties such as Flow, Stability, Air voids (Va), Voids filled with asphalt (VFA), Voids in mineral aggregate (VMA), and bulk specific gravity, and determining optimum replacement rate. The materials that was used are 19mm maximum nominal size mineral aggregate gradation, crushed stone dust (CSD) filler passing 0.075 mm sieves, waste tire powder, and 80/100 penetration grade bitumen. The study determined the chemical compositions of waste tire powder, and evaluates the moisture susceptibility of the asphalt mixes, and the effect waste tire powder on bitumen content of the asphalt mixes. The type of a tire which was used in this study was taken from the Motorcars (station wagons) Properties of asphalt mixes were described according to Marshall Mix design procedure and criteria.

1.6 Significance of the study

The significance of the study is to evaluate the possibility of HMA concrete that is made with the partial replacement of crushed stone dust with waste tire powder. The finding of this research will help:

- To create an introduction for waste tire powder as alternative filler material in hot mix asphalt.
- It creates a new job in the chain of waste tire collection, transportation, and income for the seller.
- It creates a continuous way of waste management and environmental and health benefit will be gained.
- The research paper will give a clue for those who are interested in researching waste tire powder as filler material in HMA.
- It helps in the conservation of natural resources during the blasting of the quarry in the production of conventional road-making materials.

1.7 Limitation of the study

The study was limited only one type of waste tire that was the most available types of waste tire and from the three distinct parts of tire i.e. rubber only, rubber and textile insert, and rubber, metallic and textile insert. From these parts rubber only were taken for laboratory experiment to use as filler in hot mix asphalt because it is difficult to separate the rubber covered with steel wire and textile manually. In this study, due to limitation of defined cost for waste tire powder it is difficult to conduct the economic evaluation of asphalt mixes.

CHAPTER TWO

REVIEW OF RELATED LITERATURE

2.1 Introduction

The pavement is the most common part of the transportation infrastructure and the basic idea in building a pavement for all-weather use by vehicles is to prepare a suitable subgrade, provide necessary drainage and construct a pavement that will have sufficient total thickness and internal strength to carry the expected traffic loads; have adequate properties to prevent or minimize the penetration of internal accumulation of moisture, and have a surface that is reasonably smooth and skid resistant at the same time, as well as reasonably resistant to wear, distortion and deterioration [14].

There are three major types of pavements: flexible pavements, rigid pavements, and composite pavements. Flexible pavements are constructed of bituminous and granular materials. The pavement is a layering system with better materials on top where the intensity of stress is high and inferior materials at the bottom where the intensity is low. Starting from the top the pavement consists of seal coat, surface course, tack coat, binder course, prime coat, base course, sub-base course, compacted subgrade, and natural subgrade .the use of the various courses is based on either necessity or economy and some of the courses may be omitted [16]. The types of HMA most frequently used in tropical countries are manufactured in an asphalt plant by hot-mixing appropriate proportions of coarse aggregate, fine aggregate, filler, and a paving grade bitumen with viscosity characteristics appropriate for the type of HMA, the climate and loading conditions where it will be used [17]. Among them, the filler is one of the most important components of asphalt concrete. It plays a significant role in the properties of asphalt concrete [18].

2.2 Flexible Pavement Layers

Asphalt concrete pavements are not a thin covering of asphalt concrete over soil, they are engineered structures composed of several different layers. Consisting of sub-grade, sub-base layer, base course layer, asphalt binder course, and asphalt wearing course. These layers together constitute the pavement. Each layer receives the loads from the above layer and spreads them out to the next layer [17].

A. Subgrade

The subgrade is the foundation of a pavement on which the vehicle load and the weight of the pavement layers finally rest.it is an in situ or a layer of selected material compacted to the desired density near the optimum moisture content. It is graded into a proper shape, properly drained, and compacted to receive the pavement layer [19].

B. Sub-base

The sub-base course is the layer of material beneath the base course. The reason that two different granular materials are used is for the economy. Instead of using the more expensive base course material for the entire layer, local and cheaper materials can be used as a sub-base course on top of the subgrade. If the base course is open-graded, the sub-base course with more fines can serve as a filter between the subgrade and the base course [16]. Sometimes the sub-base course is omitted from a pavement and a relatively thick base course is placed directly on the subgrade soil.

C. Base-course

The base course is the layer of material immediately beneath the surface or binder course. It can be composed of crushed stone, crushed slag, or other untreated or stabilized materials [16]. All base course materials must have a particle size distribution and particle shape which provide high mechanical stability and should contain sufficient fines (amount of material passing the 0.425 mm sieve) to produce a dense material when compacted [14].

D. Binder course

Binder course, sometimes termed as intermediate layer, consisting of one or more lifts of structural HMA placed between the wearing course and either granular base course or stabilized base course of an existing pavement or another HMA binder course [20]. Its purpose is to distribute traffic loads so that stresses transmitted to the pavement foundation will not result in permanent deformation of that layer. Additionally, it facilitates the construction of the surface layer [21].

E. Surface layer

The surface layer normally contains the highest quality materials and it is the top course of asphalt pavement, sometimes called the wearing course. It provides characteristics such as friction, smoothness, noise control, rut and shoving resistance, and drainage.

Also, it serves to prevent the entrance of excessive quantities of surface water into the underlying HMA layers, bases, and subgrade [20].

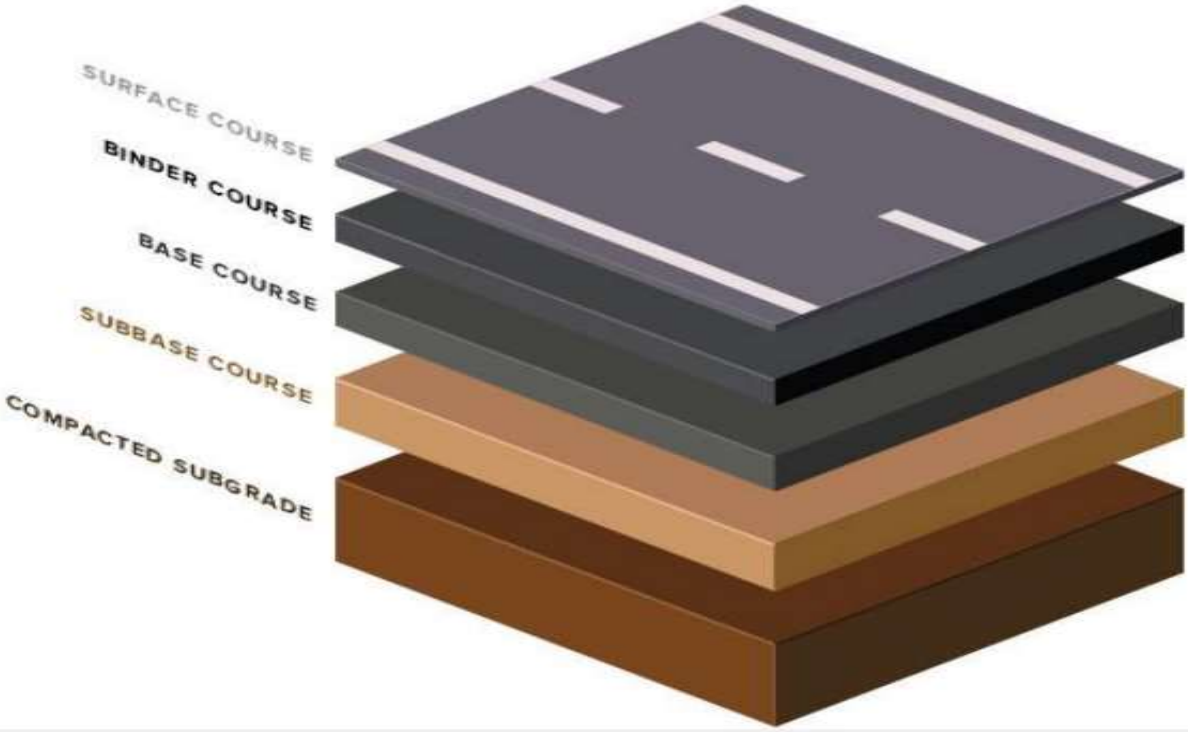


Figure 2.1: Vertical section of asphalt concrete pavement structure (Source: Google)

2.3. Common Types of Premix

The main types of premix are asphaltic concrete, bitumen macadam, and hot-rolled asphalt. Each type can be used in surfacing or base courses. The general properties and suitable specifications described below [14].

2.3.1. Asphaltic Concrete

Asphalt concrete is a composite material commonly used in construction projects such as road surfaces, airports, parking lots, and the core of embankment dams [22]. Asphalt mixtures have been used in pavement construction since the beginning of the twentieth century [23]. It consists of asphalt (used as a binder) and mineral aggregate mixed, then is laid down in layers and compacted. The mix is designed to have low air voids and low permeability to provide good durability and good fatigue behavior but this makes the material particularly sensitive to errors in proportioning, and mix tolerances are therefore very narrow [14].

2.3.2. Bitumen Macadam

This one is closed graded bitumen macadam is continuously graded mixes similar to asphaltic concrete but usually with a less dense aggregate structure. They have developed in the United Kingdom from empirical studies and are made to recipe specifications without reference to a format design procedure. Their suitability for different condition and with different materials may be questioned but, in practice, numerous materials including crushed gravels have been used successfully [24].

2.3.3. Bituminous Surfacing

This is particularly important for surfacing's laid on granular base courses. Mixes that are designed to have good durability rather than high stability are flexible and are likely to have "sand" and bitumen contents at the higher end of the permitted ranges. In areas where the production of sand-sized material is expensive and where there is no choice but to use higher stability mixes, additional stiffening through the aging and embrittlement of the bitumen must be prevented by applying a surface dressing [24].

2.4. Types of Asphalt

To be able to provide the best performance to different sectors, a large variety of asphalt mixes can be offered. Due to the different requirements e.g. a road needs to fulfill (high traffic, tough weather conditions, and other) the respective mix used needs to have sufficient stiffness and resistance to deformation to cope with the applied pressure from vehicle wheels on the one hand, yet on the other hand, the need to have an adequate flexural strength to resist cracking caused by the varying pressures exerted on them. Moreover, good workability during application is essential to ensure that they can be fully compacted to achieve optimum durability [25].

2.4.1. Cold Mix Asphalt

Cold mix asphalt is produced without heating the aggregate. This is only possible, due to the use of a specific bitumen emulsion which breaks either during compaction or during mixing. After breaking, the emulsion coats the aggregate and over time increases its strengths. Cold mixes are particularly recommended for lightly trafficked roads [25]. Cold mix is commonly used as a patching material and on lesser trafficked service roads.

2.4.2. Warm Mix Asphalt

A typical warm mix asphalt is produced at a temperature around 20 - 40 °C lower than an equivalent hot mix asphalt. Less energy is involved and, during the paving operations, the temperature of the mix is lower, resulting in improved working conditions for the crew and an earlier opening of the road [25].

2.4.3 Hot Mix Asphalt

HMA is the form of asphalt concrete most commonly used on high traffic pavements such as those on major highways, racetracks and airfields. It is also used as an environmental liner for landfills, reservoirs, and fish hatchery ponds [26]. Hot mix asphalt is produced at a temperature between 150 and 190 °C, it is the highest quality among the different types. Hot mix asphalt paving material consists of a combination of aggregates that are uniformly mixed and coated with asphalt cement (bituminous binder) [3]. HMA pavements serve in a multitude of traffic and environmental conditions, demanding that the materials and design meet specific engineering requirements. According to [20] HMA pavement mix types include:

- **Dense-graded mixes**: - A dense-graded mix is a well-graded HMA that has an even distribution of fine and coarse aggregate. Additionally, it consists of a dense HMA mixture of aggregates and asphalt binder. Properly designed and constructed mixtures are relatively impermeable. Dense-graded mixes are generally referred to by their nominal maximum aggregate size and can further be classified as either fine-graded or coarse graded. Fine-graded mixes have more fine sand size particles than coarse-graded mixes. It is suitable for all pavement layers and all traffic conditions.
- **Stone Matrix Asphalt (SMA)**: - sometimes called stone mastic asphalt, is a gap-graded HMA originally developed in Europe to maximize rutting resistance and durability in heavy traffic road. SMA has a high coarse aggregate content that interlocks to form a stone skeleton that resists permanent deformation. The stone skeleton is filled with mastic of bitumen and filler to which fibers are added to provide adequate stability of bitumen and to prevent drainage of the binder during transport and placement. SMA is often considered a premium mix because of higher initial costs due to increased asphalt contents and the use of more durable aggregates.

Typical SMA composition consists of 70−80% coarse aggregate, 8−12% filler, 6.0−7.0% binder, and 0.3 percent fiber. The deformation-resistant capacity of SMA stems from a coarse stone skeleton providing more stone-on-stone contact than with conventional dense graded asphalt (DGA) mixes [27].

- **Open-graded mixes**: - are designed to be permeable to water, which differentiates them from dense-graded and SMA mixtures that are relatively impermeable. These mixtures use only crushed stone or, in some cases, crushed gravel with a small percentage of manufactured sands.

2.4.3.1 Desirable properties of Hot Mix Asphalt (HMA)

The main objective in the design of the HMA mixture is to determine a cost-effective proportion of ingredients in the mixture and the mix design seeks to achieve a set of properties in the final HMA product. Some of the desirable properties of asphalt mixes are listed below with a brief description of each [28].

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

ii. **Workability**: - The mix must be capable of providing sufficient workability and hence permit efficient placement and compaction of the mix with reasonable effort without segregation, sacrificing stability, and performance.

iii. **Stability**: - The mix must provide sufficient stability under traffic loading through its service life. The stability of a mixture under traffic load is the amount of resistance to deformation.

iv. **Fatigue resistance**: The mix, as a paved road, must resist cracking effects that may induce due to repeated traffic loading over time. The cracking of mixes under repeated traffic loading over time is referred to as fatigue cracking.

v. **Skid resistance**: - HMA designed for surfacing should provide sufficient resistance to skidding.

vi. **Air voids content**: - There must be sufficient voids in the total compacted mixture to allow for a slight amount of additional compaction under traffic loading and a slight amount of asphalt expansion due to temperature increases without flushing, bleeding, and loss of stability.

vii. **Moisture damage resistance**: - HMA must be resistant to moisture-induced damages. This property is mainly influenced by the characteristics of aggregate with asphalt binder and air voids.

2.5 Components of Hot Mix Asphalt

2.5.1 Aggregate

Aggregate is the major component in HMA and the quality and physical properties of this material have a large influence on mix performance [17]. Because the amount of mineral aggregate in asphalt paving mixture is generally (90 to 95) percent by weight

Aggregates can be classified into three types according to their size distribution: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36 mm sieve i.e. it comprises the portion of the aggregates that have large particle sizes. According to [17] coarse aggregates used for making HMA should be produced by crushing sound, unweathered rock, or natural gravel. Gravel should be crushed to produce at least two fractured faces on each particle. Fine aggregates those that pass through the 2.36 mm sieve and are retained on the 0.075 mm sieve. That is the aggregate particles that can fill the voids created by the coarse aggregates in the mixture [29]. According to [30], Mineral filler is defined as that portion of the aggregate passing the 0.075 mm sieve. It consists of a very fine, inert mineral with the consistency of flour, which is added to the hot mix asphalt to improve the density and strength of the mixture. They can also be classified into two based on their ability to react with asphalt binder these are active fillers and inactive fillers.

2.5.1.1 Aggregate Gradation

The particle size distribution or gradation of an aggregate is one of the most important characteristics in determining how an aggregate will perform as a pavement material. In HMA, gradation helps to determine almost every important property including stiffness, stability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage [31]. Because of this, the primary concern in any mix design is the selection and combination of available aggregates to obtain a gradation within the required limits. Usually pavement design codes supply proposed aggregate gradations by an upper and a lower limit. It has been the custom for researchers and contractors to choose a gradation between these limits (in particular, the gradation that is located in the middle of the band is more preferable). Table 2.1 Shows that Gradation Limits of Dense Graded Asphalt Binder Course.

Table 2.1: Gradation Limits of Dense Graded Asphalt Binder Course (ASTM D3515)

Sieve Number (in.)	Sieve Size (mm)	Percentage By Weight Passing	
		Min	Max
1"	25	100	100
3/4"	19	90	100
1/2"	12.5	71	88
3/8"	9.5	56	80
NO.4	4.75	35	65
NO.8	2.36	23	49
NO.16	1.18	15	37
NO.30	0.6	10	28
NO.50	0.3	5	19
NO.100	0.15	4	13
NO.200	0.075	2	8
Bitumen Content (%)		4	10

2.5.1.2 Properties of Aggregates

During production, construction, and the service life of the road, the aggregates may be subjected to the effects of weather, climate, and a range of mechanical processes which together contribute to the deterioration in its physical condition. Therefore, when the construction of a road is necessary, it is important to obtain a material sufficiently durable to last the design life of the road so that its performance is not affected by deterioration or degradation of the material.

The qualities required of aggregates are described in terms of shape, hardness, durability, cleanliness, bitumen affinity, and porosity. In addition to these properties, the micro-texture of the aggregate particles will also strongly influence the performance of a compacted HMA layer. Smooth-surfaced river gravel, even partly crushed, may not generate as much internal friction as a crushed aggregate from particles having a coarse micro-texture. Therefore, aggregates should have the following characteristics for aggregates used in HMA [17]. Aggregates should be:

- Angular and not excessively flaky, to provide good mechanical interlock.
- Clean and free of clay and organic material.
- Resistant to abrasion and polishing when exposed to traffic.
- Strong enough to resist crushing during mixing and lying as well as in service.
- Non-absorptive since highly absorptive aggregate are wasteful of bitumen and also give rise to problems in mix the design.
- Have good affinity with bitumen, hydrophilic aggregates may be acceptable only where protection from water can be guaranteed or a suitable adhesion agent is used.

2.5.2 Asphalt binder (bitumen)

Bitumen is a category of organic liquids that are highly viscous, black, sticky, and wholly soluble in carbon disulfide [32]. Asphalt binder (bitumen) which holds aggregates together in HMA is the thick, heavy residue remaining after refining crude oil. Asphalt binders consist mostly of carbon and hydrogen, with small amounts of oxygen, sulfur, and several metals. This makes bitumen one of the most complex molecules found in nature. The physical properties of asphalt binders vary considerably with temperature. At high temperatures, asphalt binder is a fluid with a low consistency similar to that of oil. At room temperature, most asphalt binders will have the consistency of soft rubber. At sub-zero temperatures, asphalt binder can become very brittle. Many asphalt binders contain small percentages of polymer to improve their physical properties; these materials are called polymer modified binders. Most of asphalt binder specification was designed to control changes in consistency with temperature [29]. Generally, there are two sources of asphalt and these are: -

i. Natural asphalt is obtained from nature in that it is found in so-called “asphalt lakes” around the world. Pit Lake, Trinidad; Gard, Auvergne, Ain and Haute Savoie in France; Central Iraq; Butin Island, Indonesia, etc are some of the sources for natural asphalt.
ii. Petroleum asphalt is obtained during the refinery process of heavy crude oils. Asphalt used for road construction is mainly produced from the refinery process.

Asphalt Binder Characteristics

Generally, asphalt binder has the following five characteristic properties:

- Adhesion: - Bitumen has excellent adhesive qualities provided the conditions are favorable.
- Elasticity: - When one takes a thread of an asphalt binder from a sample and stretches or elongates it; it can return to a length close to its original length eventually. This property is referred to as the elastic character of bitumen.
- Plasticity: - when temperatures are raised, as well as when the load is applied to bitumen, the bitumen will flow, but will not return to its original position when load is removed. This condition is referred to as plastic behavior.
- Visco-elasticity: - Asphalt binder has a Viscoelastic character. Its behavior may be either viscous or elastic depending on the temperature or the load it is carrying.
- Aging: - refers to changes in the properties of asphalt binder over time, which is caused by an external condition [33].

2.5.3 Mineral Fillers

The term mineral filler is typically referred to as the fine mineral particle with physical size passing the 75 µm sieve. Mineral fillers are by-products of various stone crushing procedures, manifesting the feasibility of including them in the design of hot mix asphalt [30]. Conventionally, materials such as stone dust, hydrated lime, and cement are being utilized in asphalt mix composition as fillers since they deliver satisfactory performances in the mix. Over the years, several types of researches and studies have shown the high effect of fillers properties on the bituminous mastic performances. From a structural point of view, the presence of filler within the aggregates mixture enhances the reduction of intergranular voids [34].

2.6 Effect of Mineral Fillers on HMA

Many highway engineers and researchers have been motivated to identify paving materials that can reduce pavement damage and enhance the performance of asphalt pavements. Highway researchers aim to provide safe, economical, durable, and smooth pavements that are qualified to carry predicted loads. Filler, as one of the components in asphalt mixtures, plays an effective role in their properties and behavior, especially regarding binding and aggregate interlocking effects [18]. An inclusion of filler in the asphalt mix satisfies the aggregate gradation specification and influences the strength and volumetric requirements of the mix and also extends the bitumen to increase the bitumen volume in the mixture and reduce optimum bitumen content and material cost of the mix [35]. [36] Proved that mineral filler in asphalt mixture offers for the durability of the asphalt mixtures in the case of water action due to its physical characteristics, reducing the porosity of the granular structure and thereby making the access of water and air difficult.

Studies such as [37] proved that filler stiffens the bitumen to improve the mechanical properties of the mixture, and not only influences the ability of mixes to resist permanent deformation at high temperatures but also cracking resistance at low temperature and fatigue life at intermediate temperatures. Another researcher called [38] Fillers influences the constructability of mix by influencing its mixing and compaction temperature and also the thermal performance of asphalt mixes. Generally, Studies conducted by [39] elucidated that the properties of the mineral filler have a considerable influence on the properties of HMA mixtures because fines vary in terms of their gradation, particle shape, surface area, void content, mineral composition, and physicochemical properties, changing their effect on the properties of HMA mixtures.

2.7 Moisture Susceptibility of Hot Mix Asphalt

One of the desirable properties of bituminous mixtures is that the resistance to moisture-induced damages. Moisture is a primary cause of failure of asphalt mix because its presence could lead to its loss of structural strength and durability [40]. According to [41], moisture damage is defined as the loss of strength and durability in asphalt mixtures due to the effects of moisture. Moisture can damage the HMA in the following two ways: 1) loss of bond between the asphalt cement or mastic and the fine and coarse aggregate and 2) weakening of the mastic due to the presence of moisture. Six contributing factors have been attributed to causing moisture damage in HMA: detachment, displacement, spontaneous emulsification, pore-pressure induced damage, hydraulic scour, and environmental effects [41]. Water weakens the structure to a point where the mix can no longer sustain the traffic it was designed to support and finally fails under the repeated loading. The resistance to moisture damage under the presence of moisture in the mixture is a complex matter, and the degree mainly depends on the properties of each ingredient materials in the mixture, type and use of the mix, environment, traffic, construction practice, and the use of anti-strip additives [3]. Among these factors, aggregate response to asphalt cement underwater is primarily responsible for this phenomenon, although some asphalt cement is more subjected to stripping than others.

Many test methods have been developed in the past to predict the moisture susceptibility of HMA mix. The test methods mentioned below are not the only ones and other tests are still being used throughout the world.

A. Static-Immersion Test (AASHTO T182) – HMA mix is immersed in distilled water at 25^0c for (16 to 18) hours. The percentage of the total visible area of the aggregate which remains coated will be estimated as above or below 95%.

B. Lottman Test (NCHRP 246) – This is a strength test developed by Lottman under National Cooperative Highway Research Program 246. Nine specimen 102 mm in diameter and 64 mm high are compacted at expected field air void content. The specimens are divided into three, three specimens per group. Group 1 is the control group. Group 2 is vacuum saturated with water for 30 minutes. Groups 3 are also vacuum saturates subjected to freeze at -18^0c for 15 hours and thaw for 24 hours at 60^0c. All nine specimens are tested for resilient modulus or indirect tensile strength. Retained tensile strength (TSR) is the quotient of ITS of the conditioned specimen to ITS of the control specimen. A minimum TSR of 70% is used as a guideline.

C. Modified Lottman Test (AASHTO T283) – is proposed by Kandhal. It uses the Lottman test with some modification. The sample size is reduced to six and grouped into two containing three specimens. The specimens are compacted to (6 – 8) % air void. Group 1 is a control specimen while group 2 is vacuum saturated (55 to 80)% saturation with water and then subjected to one cycle freeze and thaw. All specimens are tested for ITS at 25^0c at a loading rate of 51mm/min. TSR is determined based on the Lottman test and a minimum value of 70% is usually specified.

D. Marshall Immersion Test (ASTM D1075) – Six Marshall specimens are prepared for this test. The specimens are grouped into two groups, each with three specimens. Group 1 is the control specimen maintained in the air at 25^0c while group 2 is immersed in water for 24 hr. at 60^0c. Group 2 specimens are then transferred to 25^0c water bath for 2 hrs. and compressive strength of both groups is determined. A value of at least 70% is specified as a requirement in many agencies. Superpave design guideline requires a minimum of 80% retained strength.

2.8 Waste Tires

The tire is a complex and high-tech safety product representing a century of manufacturing innovation, which is still on-going [42]. The raw materials used in tires are synthetic and natural rubber, nylon, polyester cord, carbon black, Sulphur, oil resin, and other chemicals. These constituents provide the tire with good strength to ensure adequate road holding properties under all conditions [43].

The tire is made up of three main component materials: (i) elastomeric compound, (ii) fabric, and (iii) steel. The structural skeleton of the tire is made up of fabric and steel; while the flesh of the tire is made up of rubber that is the material of the tread, sidewall, apexes, liner, and shoulder wedge.

Structurally, the main components of a tire are the tread, body, sidewalls, and beads the raised pattern in contact with the road is called the tread. The body gives the tire its shape and supports the tread. The beads hold the tire on the wheel and are metal-wire bundles covered with rubber. The main characteristics of tires include resistance to mold, mildew, heat, and humidity, retardation of bacterial development, resistance to sunlight, ultraviolet rays, some oils, many solvents, acids, and other chemicals. Other physical characteristics include non-biodegradability, non-toxicity, weight, shape, and elasticity. Many of these characteristics are disadvantageous in the tire's post-consumer life and create collection, storage, and/or disposal problems [44].

Figure 2.2: Tire structure, adapted from (Lo Presti., 2013).

2.8.1 Previous studies of waste tires in Asphalt Concrete

Due to the increasing trend of road usage by motorists, scrap tires have also been on the increase and these scrap tires pose a serious environmental concern as they are mostly left at the mercy of nature. Several types of research have focused on the reuse of waste tire rubber in asphalt pavements produced by the dry process to improve its engineering properties. The use of CR as a bitumen modifier has recently gained popularity. Besides, mechanical properties, the fatigue properties, crack resistance, and rutting performance of hot mix asphalt mixtures can be significantly improved with the addition of CR [45]. According to [46] have concluded that rubberized asphalt mixtures produced by dry process, have increased the elasticity of the mixture; it could enhance the bonding between binders and aggregates increasing fatigue life, and resistance to rutting, and could lead to a reduction of the thermal and reflecting cracking of these mixtures and study such by [47] showed that the addition of rubber at (10–15)% (by weight of the asphalt) by dry process caused a reduction in penetration into bitumen and softening point, while viscosity increased with CR content and decreased as the temperature was elevated. A rubberized dense asphalt mixture has resulted in lower Marshall Stability values than the virgin asphalt, while flowability increased with the increase of rubber content [46].

Rubber is the first by-product from ELT in terms of weight (about 70%) and it is recycled in several engineering fields. As reported by [48] it can be used in asphalt paving mixtures, Portland cement concrete, crash barriers, bumpers, artificial reefs, or as a light-weight filler. According to [49] studies using TDF fly ash as mineral filler were satisfied with the Korean standards of KSF 3501. The Marshall Stability of the asphalt mixture using TDF fly ash was higher than the standard criteria. It means that the HMA using TDF fly ash is enough to support the traffic loading and TDF fly ash is effective to improve the moisture resistance.

Study such by [50] Crumb Rubber Powder at 10% by the weight of mix, increased the Marshall properties of Bituminous Mixes. Waste tire rubber can be used in the Hot Mix Asphalt at 10%, as the partial replacement of traditional fillers, because the stability is found maximum and all other characteristics including flow value, air voids, %VMA, %VFB are obtained within the internationally specified ranges [51].

During the process of mixing the asphalt and the aggregate, the mastic asphalt filler forms because of the fineness of the filler. The interaction between the asphalt and the fillers results in certain mastic properties. Thereby, the performance of the mixture is affected [52].

2.8.2 Mixing Process of Recycled Tire Rubber in Asphalt Pavement

The basic processes used to add the crumb rubber into an asphalt paving material can be divided into two categories, the wet process and dry process [53].

A. The wet process - defines any method that adds the crumb rubber to the asphalt binder to produce a modified binder product. Rubber particles are mixed with bitumen at an elevated temperature before mixing with the hot aggregates. Modified binder from the wet process is termed asphalt rubber. In the wet process, the properties of the rubberized asphalt depend on various parameters such as the characteristics of the asphalt binder, and of the rubber particles – including size, percentage of rubber added, mixing temperature and mixing time.

B. The dry process - defines any method of adding crumb rubber directly into the hot mix asphalt mix; typically pre-blending of rubber particles with heated aggregate before the addition of the bitumen. In the dry process, the rubber acts more like an aggregate, and asphalt made by the dry process is rubberized asphalt. The aggregate and rubber particle are "dry" blended for approximately 15 seconds before the asphalt binder is added to the batch.

2.9 Tire Grinding Process

Processing is required to make tires usable as a modifier or additive. Tire rubber powder also known as crumb rubber is produced by shredding and grinding scrap tires into very small particles. In the process, most of the steel wires and reinforcing fibers of the recycled tires are removed. The two primary methods normally used to produce tire rubber powder are the ambient grinding and cryogenic fracturing processes [54].

The ambient grinding process starts cutting up the tires into smaller pieces with sharp cutting blades. The smaller pieces are then passed through shredders that grind and tear the rubber into smaller particles [53]. Ambient grinding can be classified in two ways: granulation and cracker mill. A granulator shreds and cuts the tire material with revolving steel plates into cubical, uniformly shaped particles with sizes ranging from 9.5mm to

0.425 mm. The cracker mill passes the material between rotating corrugated steel drums to produce irregular, elongated, torn particles with sizes ranging from 4.75 mm to 425 μm (No. 40 sieves). Finer crumb rubber (smaller than No. 40 sieves) can be produced with the micro mill [55].

Cryogenic fracturing involves cutting up the larger tire pieces into smaller, typically 50 mm particles, and using sharp steel cutters. Liquid nitrogen is used to increase the brittleness of these small pieces crumb rubber. Once frozen it can be ground to desired size. The fracturing process produces a large variety of sizes from very small, passing the 75 μm sieve, to larger 4 or 5 mm size particles. It is a bit faster operation resulting in the production of fine sieve size. Each process can produce crumb rubber of similar particle size, but the primary difference between them is the particle surface texture. Crumb rubber particles produced by the ambient process have an irregular shape with a rough texture due to the shredding action of the rubber particles. The crumb rubber particles resulting from the cryogenic process have smooth surfaces [54].

2.10 Chemical Composition of tire

The tire is made up mainly by rubber. The components of a tire manufactured by different manufacturers are very similar and its constitution varies a little between the car tires and heavy truck tires. Rubber consists of a complex mixture of elastomers, polyisoprene, polybutadiene and stirene-butadiene. Tires are made of rubber (60–65wt. %), carbon black (25–35wt. %), fillers (3 wt. %), and accelerators. Rubber is the main component in tires. Both natural and artificial rubbers are used for tire manufacturing. Fillers such as carbon black, carbon chalk are added to impart color to the tires [43]. The basic components are about the same and are provided in Table 2.2 below.

Table 2.2: compositions of tire rubber [53]

Component	Typical Range
Natural rubber	14 to 27%
Synthetic rubber	14 to 27%
Carbon black	28%
Steel, Fabric	14 to 15%
Processing oils	16 to 17%

3.10.1 Methods to Determine Chemical Composition

The method of correctly identifying an alloy is referred to as positive material identification (PMI). There are many different techniques used to determine alloy composition, but the two main techniques used in the PMI industry, x-ray fluorescence spectroscopy (XRF) and optical emission spectroscopy (OES).

A. X-ray fluorescence: is a well-established and powerful tool for nondestructive elemental analysis of virtually any material. It is widely used for environmental, industrial, pharmaceutical, forensic, and scientific research applications to determine the presence or absence and in some cases to measure the concentration of elemental constituents or contaminants. The fluorescent X-rays are in general measured by two types of detection systems: wavelength dispersive detection (WDXRF) and energy dispersive detection (EDXRF).

B. Optical emission spectroscopy: is a method of positive material identification (PMI) that creates a spark on the sample in the presence of argon gas. The spark excites the atoms within the sample. These excited atoms emit light at specific frequencies which are then used to precisely determine the composition of the alloy. Measurements can be taken without the use of argon gas at the expense of accuracy in the result. One of the major advantages of OES is its ability to measure the light elements that are not detectable by XRF. As such; OES is a very versatile method to determine the chemical composition of alloy [56].

2.11 Summary

This chapter describes the literature review about what the research was focused on. The review of literature includes basic concepts of hot mix asphalt which includes aggregates and asphalt binder, basic concepts of mineral fillers, the effect of mineral filler in hot mix asphalt, moisture susceptibility of hot mix asphalt and mixing process of waste tire powder in asphalt concrete and chemical composition of waste tire powder. Generally, as i realized from the literature review, the waste tire was used in asphalt concrete as fine and coarse aggregate. Basically, it has been used as a bitumen modifier and mineral filler.

CHAPTER THREE

RESEARCH MATERIALS AND METHODS

3.1 Introduction

The goal of this study was to evaluate the possible use of waste tire powder as mineral filler in hot mix asphalt. The effectiveness of the study was evaluated using the Marshall Mix design method to investigate the Marshal properties of bituminous mixtures prepared in the laboratory with the conventionally used filler materials namely crushed stone dust. The study starts with the preparation and investigation of the physical properties of the materials for the Marshall Mix. The materials used in the mixture include coarse aggregate, fine aggregate, crushed stone dust, waste tire powder and bitumen. All the above materials and the compacted specimen were subjected to various tests and conducted according to respective ERA, ASTM, AASHTO and BS testing standards. In addition, other performance tests were conducted to investigate the sensitivity of the control mix and mix containing waste tire powder. Finally the effect of waste tire powder on bitumen was evaluated using bitumen content of two above and below the optimum at 0.5% increment.

3.2 Study Area

The study area of this research was Jimma Town which is found in Jimma Zone, Oromia Regional State south-west of Ethiopia. Jimma is geographically located between 7° 38’52” and 7° 43’ 14” N latitude, and between 36° 48’ 00” and 36° 53’ 24” E longitude, with an estimated area of 19,506.24 km^2. Jimma town is located approximately at a distance of 350 Km away from the capital city of Ethiopia Addis Ababa in an area of average altitude of about 1780 m above mean sea level. It lies in the climatic zone locally known as Woyna-Dega.

3.3 Study Period

This study was conducted from September, 2020 to February, 2021.

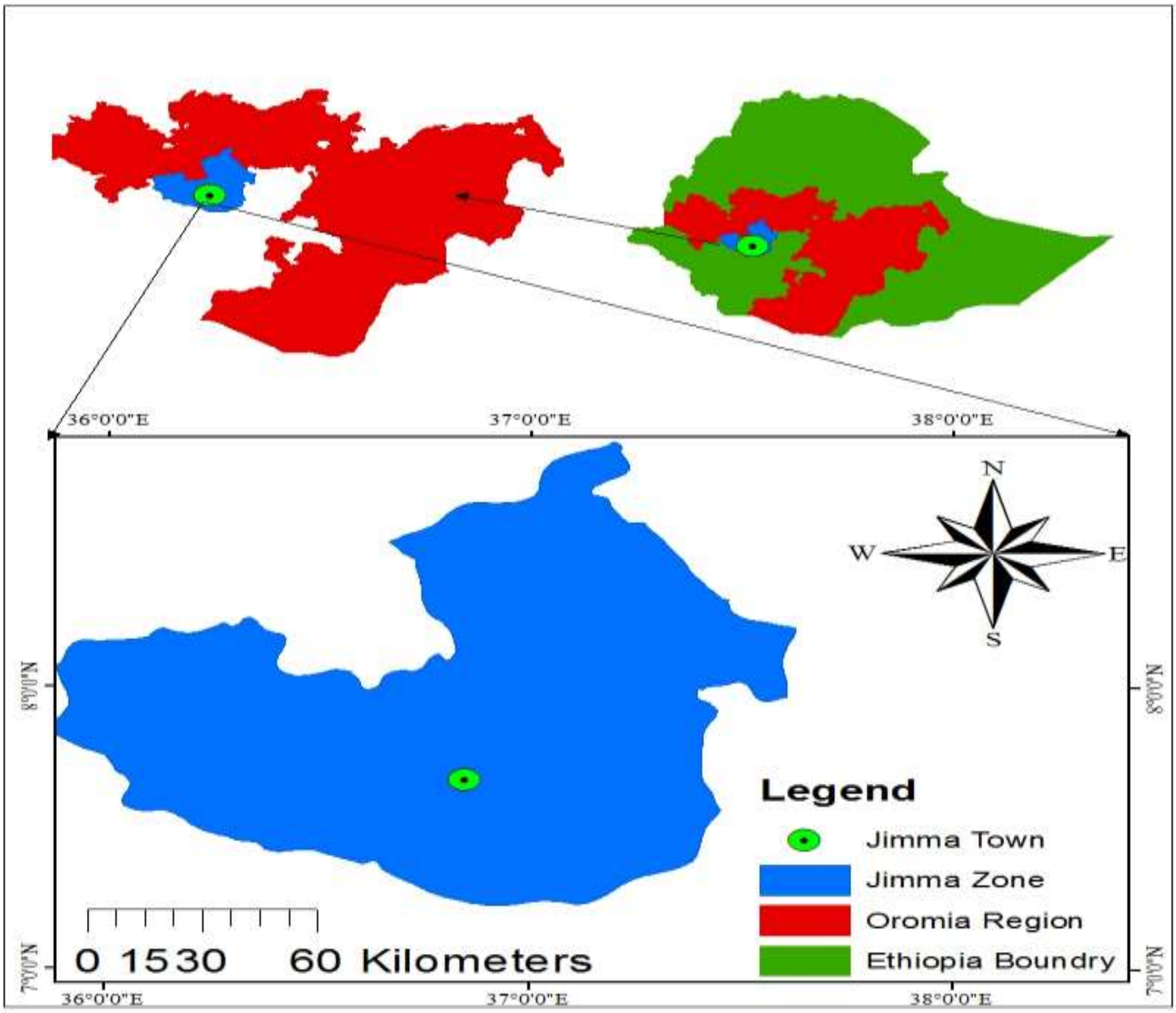


Figure 3.1: Study Area (ArcGIS 10.3.1).

3.4 Study Variables

3.4.1 Dependent Variable

- Performance of Hot Mix Asphalt with waste tire powder as filler.

3.4.2 Independent variables

- Physical properties of materials (Aggregates, Crushed stone dust, Bitumen, and Waste tire powder).
- Marshall Properties of materials (Stability, Flow, VIM, VMA, VFA, and Bulk specific gravity).
- Weight percentage of waste tire powder.
- Moisture susceptibility of waste tire powder.
- Effect of waste tire powder on bitumen content.

3.5 Materials

The raw materials which were used for performing this research work are;

- Aggregates (Course, and Fine).
- Bitumen (80/100 Penetration grade).
- Filler (Crushed Stone Dust, and Waste Tire Powder).

3.6 Research Design

This research was conducted using a laboratory experimental research design. To conduct the studies of the research effectively, a well-ordered design is formed step by step for a fruitful results. Following organizing a literature review of different previously published researches, the study investigate the possible use of waste tire powder as filler materials in asphalt mix design. The first step was data collection of materials that were used for mix design, and then the quality of the materials was tested in the laboratory using AASHTO, ASTM, and BS standard. After the quality test, gradation was prepared for fine and coarse aggregate. Subsequently, trial Marshall Mix design was performed for different filler and bitumen content to determine the OBC and OFC of the control mix. The standard Marshall specimens were prepared by applying 75 blows on each face according to ASTMD1559 with five different bitumen content (4%-6%) by weight of the total mix at 0.5% increments and three different conventional filler content namely crushed stone dust (5.0%, 6.0%, and 7.0%). After preparation of the HMA mixes, Marshall Stability and flow value were determined. Then volumetric properties of the asphalt mixes were calculated and the Marshall Design requirements criteria were checked by the design specification guideline. Subsequently, the Optimum Bitumen content (OBC) was obtained from the achieved results of specimens. Following the same procedure Marshall mix design as conventional one, another series was prepared at optimum bitumen content, using six varying contents (0% (control), 3.0%, 6.0%, 9.0%, 12.0%, 15.0%, and 18.0%) of Waste tire powder (by weight of optimum filler content) in the mixes to examine the possibility of this mineral filler on HMA and the Optimum percentage of Waste tire powder that to be used. Then, the effect of waste tire powder on moisture susceptibility of asphalt mixes was evaluated. Lastly the effect of waste tire powder on bitumen content was evaluated by preparing a mixes using pre-determined optimum replacement percentage at bitumen content of above and below the OBC.

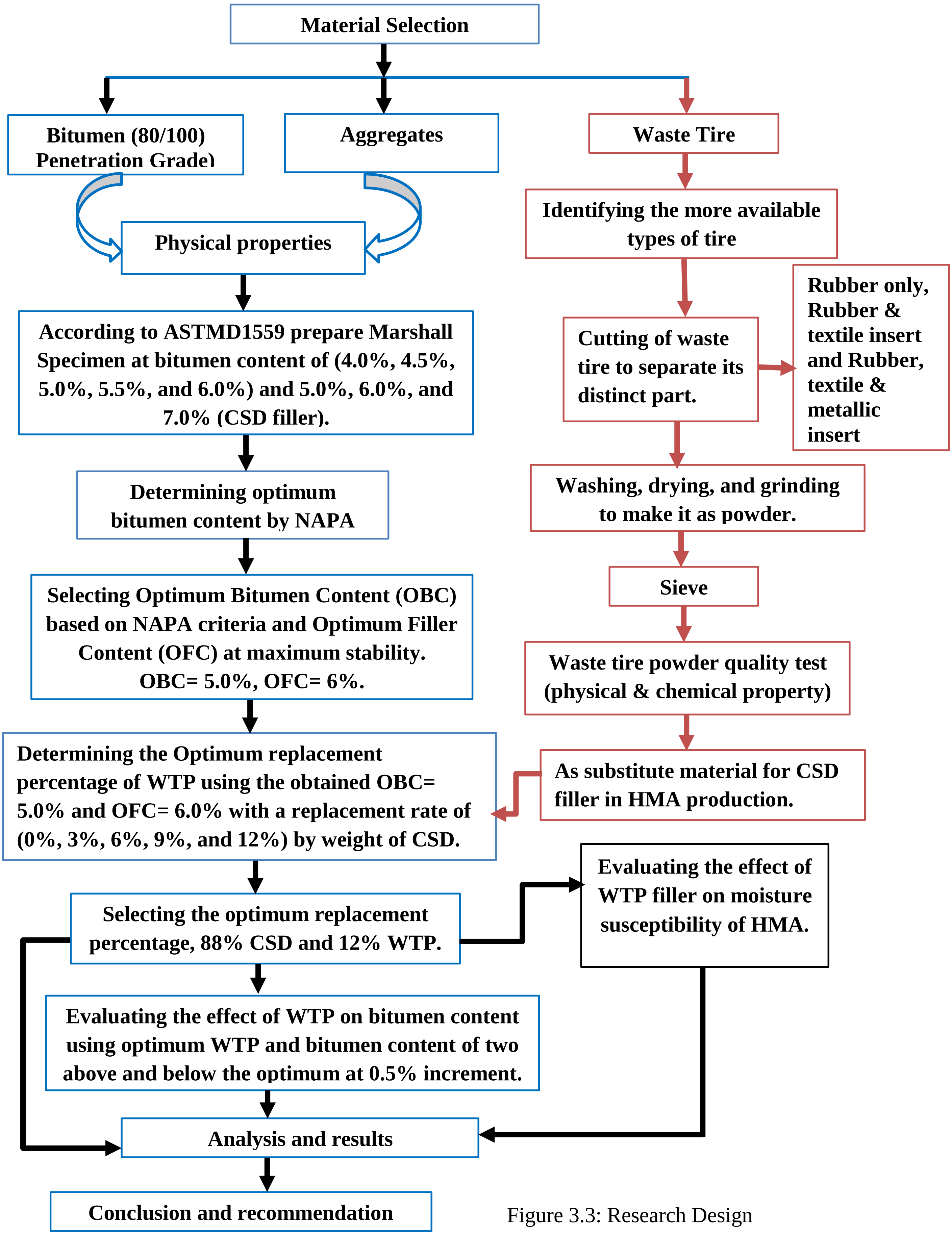


Figure 3.3: Research Design

3.7 Data Collection Methods

Different types of data were collected to accomplish this research. Those data are primary and secondary. Primary data include coarse and fine aggregates, bitumen, crushed stone dust, and waste tire rubber; the conventional materials were collected from a different source and Waste tire from tire retiring stock after identifying the more available types, and converted into powder in Horizon Addis Tire Share Company. Laboratory test were conducted to check the quality of material based on each standard. The secondary data were obtained from standard manuals, literatures, and different materials source which used for this research.

3.8 Sampling Techniques and Sample Size

3.8.1 Sampling Techniques

Purposive sampling is a non-probability method. This sampling technique was proposed based on the intention to perform laboratory tests on the required materials to design mixed such as coarse and fine aggregates, filler, and bitumen to investigate the possible use of waste tire powder as replacement of the conventionally used crushed stone dust filler in hot mix asphalt. This sampling technique has free distribution and adopted to help the researchers to select a unit sample from a population. Samples were reduced with a sample splitter or by quartering and weighting were used for sampling technique.

3.8.2 Sample Size

Sampling is the most important step in assuring that good quality materials are being used. The representative and the more available waste tire which were changed into powder were taken from tire retiring in Jimma town and Crushed stone dust filler and aggregates were obtained from Jimma road upgrading quarry site around Deneba area with different sizes of 13-25 mm, 6-13 mm, 3-6 mm, and 0-3 mm. The asphalt binder of 80/100 Penetration grade was also obtained from the Jimma road upgrading batching plant. The penetration grade was selected based on climatic conditions and their performance in past ever since it is a common type of asphalt that widely use in most road projects in our country to construct roads especially places where relatively mild climates like Jimma. Since a sample is just a small portion of the total material; the importance that the sample be representative of the material being delivered cannot be overemphasized and the sample should be prepared as per the specification. In conducting this research the sample size shall be quantified enough to execute the necessary trials in fulfilling the Marshall property design requirements for all laboratory work. Using that, a total of one hundred five (105) HMA specimens were prepared, Forty-five (45) HMA specimens to were prepared determine optimum bitumen content and optimum filler content, eighteen (18) specimens to determine the optimum replacement percentage of waste tire powder to be added in HMA, twelve (12) specimens to check the effect of waste tire powder on bitumen content, and the remaining thirty (30) specimens were prepared to evaluate the effect of waste tire powder filler on moisture susceptibility of asphalt mixes.

3.9 Data processing and analysis

The research was conducted first by performing physical properties and characteristics of aggregate, bitumen, and filler material through laboratory tests. Material preparations of specimens were performed in order to determine the optimum bitumen and filler content through the Marshall Properties and volumetric properties of each sample. The results of the laboratory tests were analyzed using excel by drawing different kinds of graphs and tables. Then, a comparison of test results with standard specification for surface course materials on the respective ERA, AASHTO, and ASTM standards was an important aspect of analysis. Finally, the results of the analysis were present according to the research objectives.

3.10 Data quality assurances

Pre-test of the available instruments were done before the main data collection period begin and the data were collected after gaining awareness on how to collect relevant data by principal investigators. Samples were collected from appropriate sources. Standard formats were used for recording test results to prevent loss of data.

3.11 Ethical Consideration

Before starting data collection an official letter was written by jimma institute of technology and send to Ethiopian Road Authority (ERA) and concerned local authorities in order to obtain the relevant sample and perform the relevant tests.

3.12 Tests and Materials Preparation

3.12.1 Mineral Aggregate Test and preparation

Aggregate is the main constituent in HMA, and the quality, physical properties of this material have a great influence on mix performance [17]. Due to this Aggregate gradation, shape, surface texture, water absorption, soundness, resistance to crushing, and impact loads have a great impact on a shear strength hot mix asphalt properties. Important properties and performance tests were conducted when selecting aggregates for the asphalt mix design. Table 3.1 below shows types of tests conducted to evaluate quality of used aggregate. The test results of aggregate properties are presented in Appendix A, in detail and summarized in chapter four of the paper.

Table 3.1: Laboratory tests and method to determine physical properties of Aggregate

Test	Test Description	Test Methods		Standard Specification
		AASHTO	BS	
Aggregate Test	Sieve analysis	AASHTO T-27		(ERA manual, 2013)
	Specific Gravity of Coarse Aggregate,%	AASHTO T-85		
	Specific Gravity of Fine Aggregate ,%	AASHTO T-84		
	Los Angles Abrasion ,%	AASHTO T-96		
	Aggregate Crushing Value ,%		BS 812, Part 110	
	Aggregate Impact Value ,%		BS 812, Part 112	
	Flakiness Index ,%		BS 812, Part 105	
	Water absorption ,%		BS 812, Part 2	

3.12.2 Asphalt Binder Test and Selection

Asphalt binder is the most commonly used material in pavement construction today because of its high engineering performance capabilities such as elasticity, adhesion, and water resistance. For this research bitumen of 80/100 was used and research and subjected to various laboratory tests to determine the physical properties. These tests are presented in Table 3.2 below. The test results of bitumen are presented in Appendix B, in detail and summarized in chapter four of the paper.

Table 3.2: Laboratory tests and method to determine physical properties of Bitumen

Test	Test Description	Unit	Test Methods	standard specification
Bitumen Test	Penetration	1/10mm	ASTM D 5	(ERA manual, 2013)
	Softening point	^oC	ASTM D 36	
	Ductility	cm	ASTM D 113	
	Specific gravity	Kg/cm^3	ASTM D 70	
	Flash point	^oc	ASTM D 92	

3.12.3 Physical Properties of Mineral Filler

Mineral fillers contain finely divided mineral matter such as rock dust, slag dust, hydrated lime, hydraulic cement, fly ash, loess, and other suitable mineral materials. The conventional filler used in this study, namely crushed stone dust. Laboratory tests were performed to evaluate crushed stone dust filler physical properties, which consisted of the gradation parameters, Plasticity Index, and Apparent Specific gravity. The laboratory tests were evaluated using AASHTO, and ASTM standard specification. According to the AASHTO standard, the mineral filler needs to be non-plastic and the plastic index is less than four.

3.12.3.1 Waste Tire Powder Test and preparation

The types of the tire which was used in this study could be taken from the Motorcars (station wagons) because the sample covers more than 80% of the other tire types in pieces and more than the other imported types of tires [57]. The sample tire was cut into distinct parts by using a knife, scissor, and other manual cutting instrument and the three distinct parts of the tire were obtained: Rubber only, Rubber and textile insert, and Rubber, metallic and textile insert Figure 3.3 (a). From these separated parts rubber only were taken for laboratory experiment because it is difficult to separate the rubber covered with steel wire and textile manually. The rubber was shredded into small pieces and convenient for effective conversion into powder. Then, the sample rubber tire particles were washed using tap water to remove dust and other impurity and dried in the open air as shown in the Figure 3.3 (b) below. Finally, the selected part was converted into powder using the ambient grinding method as shown in the Figure 3.3 (c), and then sieved in a 0.075 mm sieve. Figure 3.3 (d) below shows sieving the grinded rubber powder. Before using in mix preparation waste tire powder physical properties was determined using AASHTO, and ASTM standard specification. The conducted tests are gradation parameters, Plasticity Index, and Apparent Specific gravity.

(a) Separating rubber distinct part
Source: Ashenafi Kebede

(b) Washing of rubber tire
Source: Ashenafi Kebede

(c) Grinding of Rubber tire using grinding machine.
Source: Yohanise Melaku

(d) Sieving tire rubber powder.
Source: Bilisumma Lemi

Figure 3.4: Waste tire powder preparation.

3.12.3.2 Determining Chemical Composition of Waste Tire Powder

Determining the exact chemical composition is extremely important due to several reasons, for example it may be necessary to verify that a critical component is made from the correct alloy when a mill test certificate is unavailable or the validity of said certificate is in equation.

The method of correctly identifying an alloy is referred to as positive material identification (PMI). PMI can determine both the element composition (quantitative) and the grade of (qualitative). There are many different techniques used to determine alloy composition, but the two main techniques used in the PMI industry, x-ray fluorescence spectroscopy (XRF) and optical emission spectroscopy (OES). For this study analytical methods that were used to determine the chemical composition of waste tire powder are; lithium metaborate ($LiBO_{2}$)), Colorimetric analysis, Atomic absorption spectroscopy (AAS), Gravimetric, Fusion, and hydrogen fluoride (HF) attack.

3.13 Experimental Work (Marshall Tests)

3.13.1 Marshall Mix Design

The concept of Marshall Mix design methods was originally formulated by Bruce Marshall, formerly of the Mississippi Highway Department, and improved by the U.S Army Corps of Engineers. The Marshall method is applicable only to hot mix asphalt using penetration, viscosity, or PG graded asphalt binder or cement and containing aggregate with a maximum size of 25.0 mm (1 in.) or less.

The purpose of the Marshall method to is determine the optimum bitumen content for a particular blend of aggregate and also it provides information about the properties of the resulting pavement mix including density and void content which are used during pavement construction.

The Marshall method uses standard test specimen 64 mm high and 102 mm internal diameter. A series of specimens, each containing the same aggregate blend but varying in asphalt content from 4.0% to 6.0% with an increment of 0.5% was prepared using a specific procedure to heat, mix and compact the asphalt aggregate mixtures.

The procedure for the Marshall methods starts with the preparation of the test specimen. The Marshall Mix design method consists of the following basic steps:

- All materials proposed to use would meet the physical requirement of the specification.
- Aggregate blend combination meets the graduation requirements of the specification.
- Stability determination using the Marshall Stability and flow test.

- Volumetric calculations.
- Finally the required Optimum bitumen content selection from 4% air void is calculated.

3.13.2 Gradation of Coarse and Fine Aggregate

Aggregate gradation is one of the most important characteristics in designing hot mix asphalt mixture. It influences almost every important HMA property including stiffness, stability, durability, permeability, workability, fatigue resistance, skid resistance, and resistance to moisture damage and according to [31] studies, gradation affects permanent deformation of hot mix asphalt. Because of this, gradation is a primary concern in HMA mix design and must meet the requirement of ASTMD3515 standard specification.

The coarse and fine aggregate gradations were performed using sieve analysis. Sieve analysis involves passing the material through a series of sieves stacked with progressively smaller openings from top to bottom and then weighing the material retained on each sieve. The aggregate gradation is normally expressed as the percentage (by weight) of the total sample that passes through each sieve. It is determined by weighing the contents of each sieve following the sieve analysis and then calculating the percentage passing each sieve by one of several mathematical procedures. One method is to subtract the weight of the contents of each sieve from the weight of the material passing the previous sieve, resulting in the total weight passing each sieve. Available aggregate materials, coarse aggregate (13-25 mm), intermediate aggregate (6-13 mm and (3- 6 mm), fine aggregate (0- 3 mm), and filler. To achieve the aggregate gradation within the specification limit and to get the proper gradation proportioning were made using mathematical trial and error methods and also by plotting the graph is desirable. However, the first trial may not always meet the specified limits. In such cases, other combinations must be tried until a satisfactory one is obtained. In this research three gradations were prepared by varying the amount of conventionally used crushed stone dust filler 5.0%, 6.0%, and 7.0% (by weight of aggregate) using purposive sampling methods.

3.13.3 Hot Mix Asphalt specimen Preparation

Before going into the mixing procedures it necessary to prepare proper and enough materials for the whole works. Aggregates are the first oven-dried constant weight at 110 + 5^{o}c and each should be placed in a separate container.

In determining the design asphalt content for selected aggregate grading by Marshall Method, a series of test specimens was prepared for a range of different asphalt contents. The main materials that used for preparing the HMA mixture specimens are totally blended aggregates, filler, bitumen, oven, compactor, Marshall Mold with flat bottom metal (base plate) and collar, balance, mixer, pan and filter paper. Before mixing with bituminous binder 1200 g blended aggregates was dried in oven with a temperature of 160-170^{o}c for a minimum of 16 hours and bitumen also heated to 150^{0}C-170^{o}C. Also the Standard Marshall Molds were heated in an oven for a minimum of 8 hours. Subsequently the bitumen temperature were adjusted and the required amount of bitumen were added in (4.0%, 4.5%, 5.0%, 5.5%, and 6.0%) by weight of total mix as shown in Figure 3.4 (a) below, and then the pre-heated aggregates and bitumen are mixed properly until a homogeneous mix is obtained. The Figure 3.4 (b) shows Marshal Mold on oven.

(a) (b)

Source: Dejene Dereje Source: Asebew Almaw

Figure 3.5: (a) Adding heated bitumen on the mix. (b) Marshall Mold on oven

The mixture was then placed in the pre-heated mold with a collar and base then the mixture was spaded around the sides of the mold and a filter paper were placed both at the bottom and on the top of the sample and then compacted by a Marshall Compactor hammer having a weight of 4.5 kg and a free fall of 45.7 cm giving 75 blows on each side of the specimen with the standard Marshall hammer as specified in ASTM D1559 as shown in Figure 3.5 (a). The compacted specimens were removed from the molds after 24 hours using specimen extractor as shown below in the Figure 3.5 (b).

(a)

(b)

Source: Dejene Dereje

Source: Muluken Geremew

Figure 3.6: (a) Specimen on compaction. (b) Extrude the marshal specimen from the mold

The specimens were then weighted in dry air, weighted in water and saturated surface dry weight and height of the specimen were noted on the prepared sheet as shown below in the Figure 3.6 (b), and the bulk specific gravity of compacted specimens was determined according to the test procedure specified by ASTM 2726. After determination of the bulk specific gravity, bring the specimen to the desired temperature by immersing them in the water bath for 30 minutes at 60°C as shown below in Figure 3.7 (a). Then the specimens were subjected to Marshall Stability and flow test as per AASHTO T245-82. The cylindrical specimens were then compressed on the lateral surface at a constant rate of 50 mm/min. until the maximum load (failure) is reached. The load resistance and the corresponding flow value were recorded. Volumetric analysis was made for each series of test specimens after the completion of the stability and flow tests. The measured Marshall Stability value is corrected by means of a conversion factor. Note that the conversion was made on the basis of measured volume. The Figure 3.7 (b) below shows a specimen in the flow and stability testing machine.

(a) (b)

Source: Asebew Almaw Source: Muluken Geremew

Figure 3.7: (a) Compacted marshal specimen. (b) Measuring weight of specimen

(a) (b)

Source: Bilisumma Lemi Source: Dejene Dereje

Figure 3.8: (a) Removing specimen from water bath for test. (b) Specimen in marshal testing machine.

3.14 Determination of Optimum Bitumen Content

It is common practice to design the mix using the Marshall Test (ASTM D1559. The total mix designs to be carried out in the Marshall test are 3 (types of filler content) × 15 (samples for five bitumen and three samples for each bitumen content) = 45 specimens were prepared to determine OBC and optimum filler content. Marshall Properties of the asphalt mix such as stability, flow, and volumetric properties were obtained for various bitumen contents. Then, the following graphs were utilized to determine the optimum bitumen content for the mix.

- Air voids (Va) vs. Bitumen Content,
- Stability vs. Bitumen Content,
- Flow vs. Bitumen Content,
- Bulk Specific Gravity vs. Bitumen Content,
- Void in Mineral Aggregate (VMA) Vs. Bitumen Content,
- Voids Filled with Asphalt (VFA) vs. Bitumen Content.

3.14.1 Methods to Determine Optimum Bitumen Content

According to (Asphalt Institute, 2003) there are two commonly used methods to determine the optimum bitumen content:

Method I-NAPA Procedure

1. Determine the asphalt content which corresponds to the specification's median air void content (4 percent typically). This is the optimum asphalt content.

2. Determine the following properties at this optimum asphalt content by referring to the plots:

- Marshall Stability,
- VMA,
- Flow ,
- Bulk density, and
- Percent voids filled with Asphalt.

3. Compare each of these values against the specification values and if all are within the specification, then the preceding optimum bitumen content is satisfactory. If any of these properties is outside the specification range, the mixture should be redesigned.

Method 2-Asphalt Institute Method

1. Determine:

a. Asphalt content at maximum stability

b. Asphalt content at maximum density

c. Asphalt content at the midpoint of specified air void range (4 percent typically)

2. Average the three bitumen contents selected above.

3. For the average bitumen content, go to the plotted curves and determine the following properties: Stability, Flow, Air voids, and VMA.
4. Compare values from Step 3 with criteria for acceptability given in Table 3.3.

In this research work, the NAPA (National Asphalt Pavement Association) procedure was used. The reason for selecting this method was because of its commonly used. The optimum bitumen content (OBC) was obtained for the conditions the range of bitumen content which satisfied all the specification limits of design parameter (Va, VMA, VFA, flow, and stability) according to marshal criteria for asphalt concrete mix design (ERA Pavement Design Manual, 2002) shown in the Table 3.3.

Table 3.3: Marshall Criteria for asphalt concrete mix design (ERA, Pavement Design Manual, 2002)

Total Traffic (106 ESA)	**< 1.5**		**1.5 - 10.0**		**> 10.0**	
Traffic Class	**T1, T2, T3**		**T4, T5, T6**		**T7, T8**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
No. of blows of Marshall Compaction hammer	2*35		2*50		2*75	
Stability (KN)	3.5	-	6	-	7	-
Flow, (mm)	2	4	2	4	2	4
Percent Air Voids	3	5	3	5	3	5
Percent Voids filled with Asphalt (VFA)	70	80	65	78	65	75
Percent VMA (for 4% air voids and Nom. Max, Particle size of 19 mm)	13	-	13	-	13	-

3.15 Optimum Replacement Percentage of Waste Tire Powder

The optimum replacement ratio of waste tire powder was determined after the optimum bitumen content and optimum filler content were determined for the conventional materials. Then, by applying the same procedure Marshall Mix Design as of Conventional one, another series 18 specimens was prepared at optimum bitumen content and filler content at varying content (0% (control), 3.0%, 6.0%, 9.0%, 12% 15%, and 18%) of waste tire powder by weight of conventionally used optimum crushed stone dust filler and laboratory tests were carried out using Marshall Stability test. All mixtures were prepared with the same binder content and the same aggregate source of the conventional mix. Then, the Marshall Stability properties of these replaced asphalt mix such as stability, flow, bulk specific gravity, and volumetric properties i.e. Va. VMA and VFA were determined and checked according to the standard specification of (ERA, pavement design manual, 2013 and Asphalt Institute, 2003). Finally, the Optimum replacement percentage of waste tire powder has obtained the mixes having maximum stability, maximum bulk density, and air void (Va) within the allowed range of specifications [58].

3.16 Volumetric Properties of HMA Mixes

For convenience, mix components are blended in proportion by mass and expressed as percentages of the complete mix. The volume of the mix is affected by; The proportions of the different aggregates and filler, the specific gravity of the different materials, where porous aggregate is present, the amount of asphalt binder absorbed, and the amount of non-absorbed asphalt binder.

Fundamentally, mix design is meant to determine the volume of bitumen and aggregates necessary to produce a mixture with the desired properties since weight, measurements are typically much easier; weights are taken and then converted to volume by using specific gravities. The properties that are to be considered include the theoretical maximum specific gravity (Gmm), the bulk specific gravity (Gmb), percentage of voids in the total mix (VTM), percentage volume of bitumen (Vb), percentage void in mineral aggregate (VMA), percentage voids filled with asphalt (VFA), and Effective bitumen content (Pbe). Figure 3.8 below show a phase diagram of the bituminous mix.

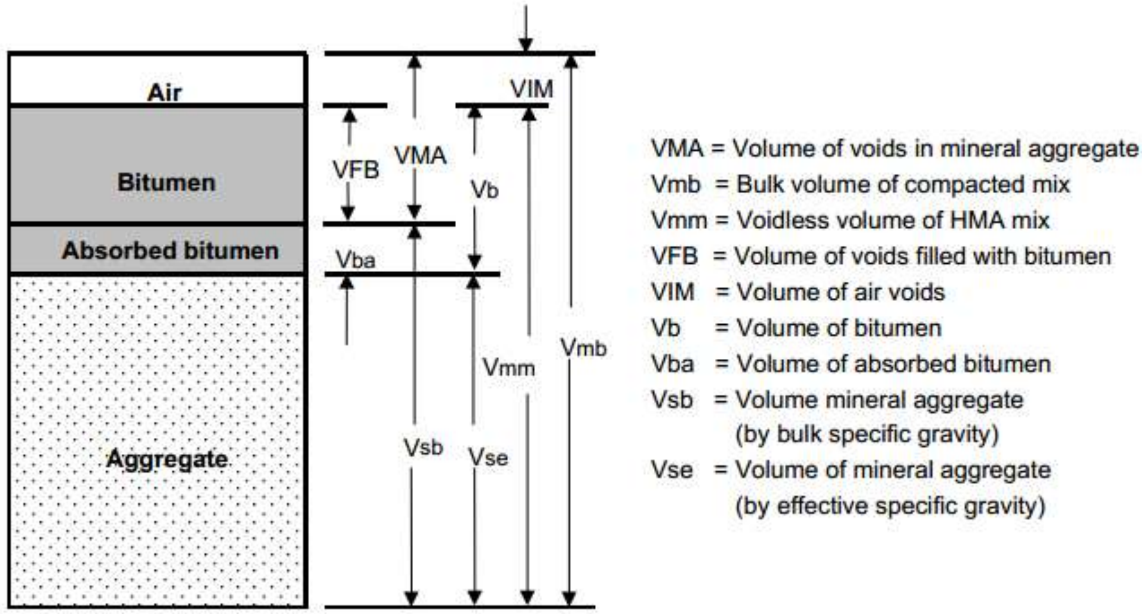


Figure 3.9: Phase diagram of the bituminous mix (Asphalt Institute Manual Series No.2 (Ms-2), Sixth Edition).

3.16.1 Air Voids (Va)

It is the total volume of the small pockets of air between the coated aggregates particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture. A certain percentage of air voids is necessary for the finished HMA to allow for a slight amount of compaction under traffic and a slight amount of asphalt expansion due to temperature increases. The allowable percentage of air voids in laboratory specimens is (3-5) percent for surface and base courses, depending on the specific design.

The durability of asphalt pavement is a function of the air void content. Therefore, designing and maintaining the proper air void content in HMA and other mix types are important for several reasons. When air void contents are too high, the pavement may be too permeable to air and water, resulting in significant moisture damage and rapid age hardening. When air void contents are too low, the asphalt binder content may be too high, resulting in a mixture prone to rutting, bleeding, and shoving. It is calculated as:

$$Va = 100 * \frac{Gmm - Gmb}{Gmm} \quad \text{Eq. 3.1}$$

Where: Va = Air voids in compacted mixture,

Gmm= maximum specific gravity of paving mixture,

Gmb= bulk specific gravity of compacted mixture

3.16.2 Voids in Mineral Aggregates (VMA)

It is the volume of intergranular void space between the aggregate particles of a compacted paving mixture. It includes the air voids and the volume of bitumen not absorbed into the aggregate. VMA is a volumetric measurement expressed as a percentage of the total bulk volume of a compacted mix.

VMA represents; the space that is available to accommodate the effective volume of asphalt (i.e., all of the asphalt except the portion lost by absorption into the aggregate) and the volume of air voids necessary in the mixture. The more VMA in the dry aggregate, the more space is available for the films of asphalt. The durability of the mix increases with the film thickness on the aggregate particles. Therefore, specific minimum requirements for VMA are recommended and specified as a function of the aggregate size.

Table 3.4: Void in the mineral aggregate (ERA manual)

Nominal maximum particle size (mm)	7.5	28	20	14	10	5
Minimum void in mineral aggregate, (%)	12	12.5	14	15	16	18

Minimum VMA is necessary to achieve an adequate asphalt film thickness, which results in durable asphalt pavement. Increasing the density of the gradation of the aggregate to a point where below minimum VMA values are obtained leads to thin films of asphalt and a low-durability mix. Therefore, economizing in asphalt content by lowering VMA is actually counter-productive and detrimental to pavement quality. It is calculated as:

$$VMA=100-\frac{Gmb}{Gsb}*Ps \quad \text{Eq. 3.2}$$

Where: VMA = voids in the mineral aggregate,

Gsb= bulk specific gravity of total aggregate e,

Gmb = bulk specific gravity of the compacted mixture,

Ps = aggregate content, percent by mass of total mixture.

3.16.3 Voids Filled with Asphalt (VFA)

It is the percentage of inter-granular void space between the aggregate particles (VMA) that contains or is filled with asphalt. VFA represents the volume of the effective bitumen content and is used to ensure that the effective asphalt part of the VMA in a mix is not too little (dry, poor durability) or too great (wet, unstable). The voids filled asphalt, VFA is the percentage of the integral void space between the aggregate particles (VMA) that are filled with asphalt. Mathematically void filled with asphalt is calculated as:

$$VFA = 100 * \frac{(VMA - Va)}{VMA} \quad \text{Eq. 3.3}$$

Where: VFA = Voids filled with asphalt, percent of VMA,

VMA = Voids in mineral aggregates, percent of the bulk volume,

Va = Air voids in compacted mixture, percent of total volume.

3.16.4 Theoretical maximum specific gravity of Un-compacted Specimen (Gmm)

The theoretical maximum specific gravity of an asphalt concrete mixture is the specific gravity of the mixture at zero air void content. It is one of the most difficult tests performed in paving materials laboratories and also one of the most important. Like bulk specific gravity, theoretical maximum specific gravity in and of itself does not affect the performance of a paving mixture. However, in designing a pavement mixture with a given aggregate, the maximum specific gravity (Gmm) was measured at each asphalt content and it is essential to calculate air voids and VMA. Theoretical maximum specific gravity is the ratio of the weight in air of a unit volume of the un-compacted bituminous paving mixture at a stated temperature to the weight of an equal volume of gas-free distilled water at a stated temperature. It is calculated as:

$$Gmm = \frac{A}{(A+B)+C} \quad \text{Eq. 3.4}$$

Where:

Gmm = Maximum Theoretical Specific Gravity is calculated as per ASTM D 2041

A = Mass of the dry sample in air, g

B = Mass of Jar Filled with Water, g, and

C = Mass of Jar Filled with Water + Sample, g

3.16.5 Bulk specific gravity of compacted specimen (Gmb)

Bulk specific gravity of a mixture refers to the specific gravity of a specimen of compacted mixture, including the volume of air voids within the mixture. The bulk specific gravity of a mixture refers to the specific gravity of a specimen of compacted mixture, including the volume of air voids within the mixture. It is equivalent to the mass of a given specimen in grams, divided by its total volume in cubic centimeters. The standard procedure for determining the bulk specific gravity of compacted asphalt concrete involves weighing the specimen in air and water. It is determined using a compacted specimen in the laboratory. The bulk specific gravity (Gmb) can be calculated using the following formula:

$$Gmb = \frac{A}{A - B} \quad \text{Eq. 3.5}$$

Where: Gmb= Bulk specific gravity of compacted specimen

A = Mass of the dry specimen in air, g

B = Mass of the saturated surface-dry specimen in air, g, and

C = Mass of the specimen in water, g.

3.17 Determination of the Effect of Waste Tire Powder on Bitumen Content

Waste tire powder can be obtained from waste tires through two principal processes (ambient and cryogenic). The waste tire powder used in this research was obtained by mechanical shredding at ambient temperature. The effect of WTP on bitumen content was determined after the optimum replacement percentage was determined for a series of the mix at OBC, and OFC. Then, using the same procedure Marshall Mix design that used for replacement determination, 12 HMA specimen were prepared two bitumen content below the optimum (4.0%, and 4.5%), and two bitumen content above the optimum(5.5%, and 6.0%) at 0.5% increment. All the mixes were prepared using the same materials as the conventional at the optimum replacement percentage of waste tire powder i.e. 12%. Then, the effect was evaluated using marshal stability, and volumetric properties in comparison to the control mix at the same bitumen content to the mix prepared with 12% WTP by weight of optimum filler content.

3.18 Moisture Susceptibility

In a tropical country like Ethiopia, moisture susceptibility is one of the most important distress mechanisms leading to premature failure of asphalt pavements, and it is known that the presence of moisture in a bituminous mix is a critical factor for failure.

A set of cylindrical samples were manufactured for each replacement percentage of waste tire powder i.e. (0%, 3.0%, 6.0%, 9%, and 12%) by weight of optimum filler content at the optimum bitumen content. The Hot Mix Asphalt samples were compacted at air-voids between (6 -8) %. To conduct this test a minimum of six specimens are prepared for each proportion. Each set was subdivided into two subsets with the same number of specimens in each subset. One subset, known as the "dry subset" or "unconditioned" while the other subset, known as the "wet subset" or "conditioned". The unconditioned group was stored at room temperature for two hours before the compressive strength was undertaken. The conditioned were is saturated between (55-80)% with water, and immersed in water at 60 ^{0}C for 24 hours and then moved to a water bath at 25^{0}c for two hours before the compressive strength test was performed.

After conditioning, the specimen were removed from water bath, and placed on its side between the bearing plates of the testing machine such that the load was applied along the diameter of the specimen with a loading rate of 2 in/min. The test was performed as per AASHTO –T283 standard. Indirect tensile strength is calculated as:

$$ITS = \frac{2 \times P}{\pi \times t \times D} \qquad \text{Eq. 3.6}$$

Where:

ITS = Indirect Tensile Strength (KPa),

P = Peak Load (KN),

t = Thickness of specimen (mm),

D = Diameter of specimen (mm).

In this study, the test results of the conditioned specimens can be used to indicate moisture susceptibility. A higher TSR value typically indicates that the mixture will perform well with a good resistance to moisture damage (lower moisture susceptibility). The tensile strength ratio (TSR) is a common parameter to evaluate moisture susceptibility.

The tensile strength ratios (TSR) of the specimens in each set were determined as follows:

$$TSR=\frac{ITS_W}{ITS_D}*100 \quad \text{Eq. 3.7}$$

Where:

TSR = the tensile strength ratio (%),

ITS_W = the average tensile strength of four conditioned (wet) specimens (KPa),

ITS_D = the average tensile strength of four unconditioned (dry) specimens (KPa).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General

This chapter discusses the laboratory test results and the interpretations of the results. Before going to the preparation of the specimen the quality of used materials were tested based on the respective ASTM, AASHTO, BS, and ERA standard specifications. Then, preparation of the specimen, taking different tests, and recording test results were performed in three phases and the chemical composition of waste tire powder was determined. Firstly, Forty-five sets of bituminous mixtures were prepared using different bitumen content (4% - 6%) by 0.5% increment and 5%, 6%, and 7% of conventionally used crushed stone dust filler. Then, the results are analyzed to find out the optimum bitumen and filler content of the mixes. Secondly, using the obtained OBC Eighteen Marshall samples were prepared with waste tire powder at the rate of 0% (control), 3.0%, 6.0%, 9.0%, 12%, 15%, and 18% (by weight of optimum crushed stone dust). After conducting the Marshall test the result was analyzed to determine the optimum replacement of waste tire powder. Then, the moisture susceptibility of the mix was conducted by the use of Marshall Immersion. The test was conducted by preparing six Marshall Specimen for each mix at optimum bitumen content. The six samples are then divided into two groups of three specimens each conditioned and unconditioned. Finally, the effect of waste tire powder on bitumen content were checked by preparing twelve specimens using optimum percentage of waste tire powder with a bitumen content two above and below the optimum at 0.5% increment. The test results obtained in this thesis research are discussed under subsequent sections.

4.2.1 Aggregate physical Property

Important physical properties tests were conducted when selecting aggregates for the asphalt mix design. Table 4.1 presents quality assurance tests that were conducted on the aggregates include; sieve analysis, Aggregate crushing value, specific gravity, Los Angeles abrasion tests, Flakiness Index, and Aggregate impact value. All the results obtained from the conducted tests on aggregates were falls within the specification requirement value in the ERA Manual standard specification. Therefore, the assumed aggregate was found appropriate for preparing the HMA design.

Table 4.1 Physical properties of aggregate

Test	Test Method		Test Result				Specification Requirement
	AASHTO	BS	(13-25) mm	(6-13) mm	(3-6) mm	(0-3) mm	
Bulk dry S.G	AASHTO T 85-91		2.624	2.615	2.612	2.610	-
Bulk SSD S.G			2.676	2.668	2.664	2.669	-
Apparent S.G			2.763	2.755	2.754	2.774	-
Los Angeles Abrasion (LAA),%	AASHTO T96		15.85	-	-	-	<30
Aggregate Crushing value (ACV),%	BS 812, Part 110		17.56	-	-	-	<25
Aggregate Impact Value(AIV),%	BS 812, Part 112		16.70	-	-	-	<30
Flakiness Index	BS 812, Part 105		24.8	-	-	-	<45
Water Absorption,%	BS 812, Part 2		1.882	1.901	1.976	-	<2

4.2 Asphalt Binder Quality Test Result

The bitumen quality tests were conducted before the start of the mix design and the obtained test results are compared to the specifications set in ERA manual standard specification. The conducted tests include penetration, softening point, ductility, specific gravity, and flashpoint. According to test results shown in Table 4.2, the 80/100 penetration grade bitumen was fallen within the allowable boundary that is specified in ERA Manual code, 2013. Therefore, the material can be used in the preparation of the HMA mix design. Table 4.2 depicts the bitumen quality specification and summary of tests results that were carried out for this research work which includes; penetration, softening point, ductility, specific gravity, and flash point. The detailed works for each bitumen test result are shown in Appendix B.

Table 4.2: Bitumen quality test result

No	Test Description	Unit	Test Method	Average Test Result	Specification Requirement (ERA,2013)
1	Penetration@25^{o}C	1/10mm	ASTMD5	87.6	80-100
2	Softening Point	^{o}C	ASTMD36	48.5	42-51
3	Ductility@25^{o}C	Cm	ASTMD113	109.0	>75
4	Specific gravity@25^{o}C	Kg/cm^3	ASTMD70	1.015	-
5	Flash Point	^{o}C	ASTMD92	298.4	>219

4.3 Physical Properties of Mineral Filler

The fillers used in this research study are crushed stone dust and waste tire powder, which was obtained by grinding waste tire rubber. The physical properties that affect the bituminous property such as gradation parameters, plasticity index, and apparent specific gravity were determined by a laboratory test. An apparent specific gravity test was conducted according to ASTM D854 using the Water Pycnometer method. Table 4.3 shows a summary of laboratory test results for crushed stone dust and waste tire powder.

Table 4.3: Laboratory test results for the two filler

Sieve No.	Unit	% Passing	% Passing	ASTM D242
		Crushed Stone dust	Waste Tire powder	
No. 30	%	100	100	100
No 50		100	97	95-100
No 200		100	75	70-100
Apparent specific gravity	Kg/m^3	2.717	1.18	N/A

N/A =Not Available

4.4 Chemical Composition of Waste Tire Powder

The result of chemical composition analysis conducted of waste tire powder is as shown in Table 4.4. According to ASTM C618 standard which specifies a material having combined weight of silica, aluminum and iron oxides of 50% by weight of fraction can be deduced to be class C. The obtained result show that the total sum of ($Si0_2$ + Al_20_3 + Fe_20_3 = 54.83%) and can be used as mineral filler in HMA design as a partial replacement of conventionally used crushed stone dust filler.

Table 4.4: Chemical composition of waste tire powder

Collector's Code	Waste Tire Powder (%)
Sio_2	32.76
Al_2O_3	12.23
Fe_2O_3	9.84
CaO	3.0
MgO	<0.01
Na_2O	<0.01
K_2O	<0.01
MnO	0.04
P_2O_5	0.06
TiO_2	<0.01
H_2O	0.6
LOI	40.54

4.5 Gradation of Coarse and Fine Aggregates

Aggregate gradation should satisfy the control points specified by the specification guideline for Particle Size distributions for AC wearing courses. Several terms used for stating the aggregate portions and filler are: Course aggregate, G-1 (13-25 mm), Intermediate Aggregate,G-2 (6-13 mm and 3-6 mm), Fine Aggregate, G-3 (0-3 mm) and Mineral Filler, G-4. Blending proportions of the different aggregates sizes to produce the desired combined gradation for asphalt binder course are shown in Table 4.5 below.

Table 4.5: Aggregate blending proportion

Filler Content	Mix Type and Blending Proportion					
	Coarse Aggregate (G-1)	Intermediate Aggregate (G-2)		Fine Aggregate (G-3)	Filler (G-4)	Combined
	13-25mm	6-13mm	3-6mm	0-3 mm	CSD	
5.0%	22.0	30.50	16.0	30.52	0.98	100.0
6.0%	22.0	30.50	16.0	29.50	2.00	100.0
7.0%	22.0	30.50	16.0	29.00	2.50	100.0

Table 4.5 above shows the blending proportions of the three filler for the Marshall Mixture preparation. Figure 4.1 through 4.3 shows aggregate gradation curves without waste tire powder with 19 mm maximum aggregate nominal size for three different percentages of fillers (5.0%, 6.0%, and 7.0%) by weight of total mix added to the mix of the prepared aggregate gradation. All the three aggregate gradation curves drawn in Figure 4.1 through 4.3 were prepared based on the standard specification of ASTM D3515 limits and the color that used to indicate the upper limit, lower limit, the proposed gradation, and middle value for the three Varying percentage of crushed stone dust fillers (5%, 6%, and 7%), are blue black, red, green, and broken black respectively. The proposed gradation is between the upper and lower limits of ASTM specification as shown in the figure above. Therefore, the proposed gradation meets the standard specification requirements.

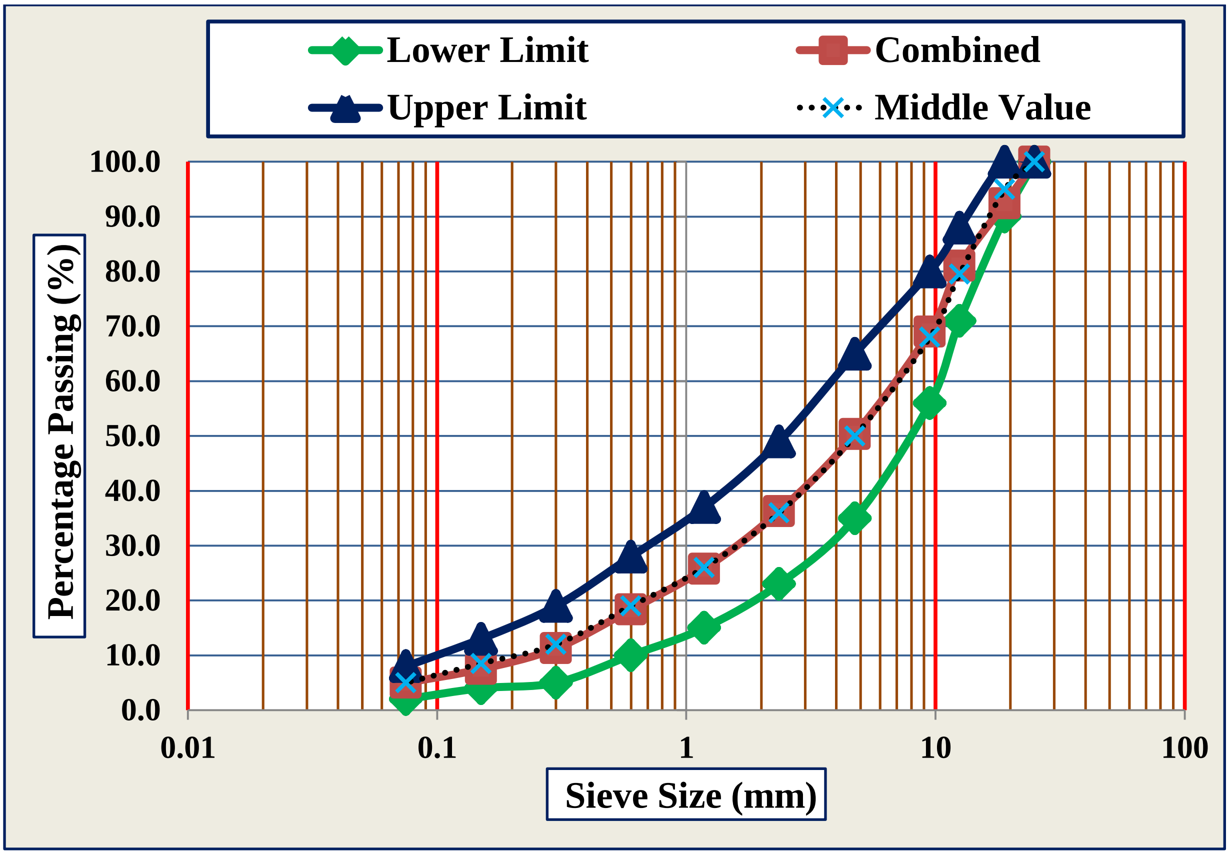


Figure 4.1: Aggregate gradation curve for 5% crushed stone dust

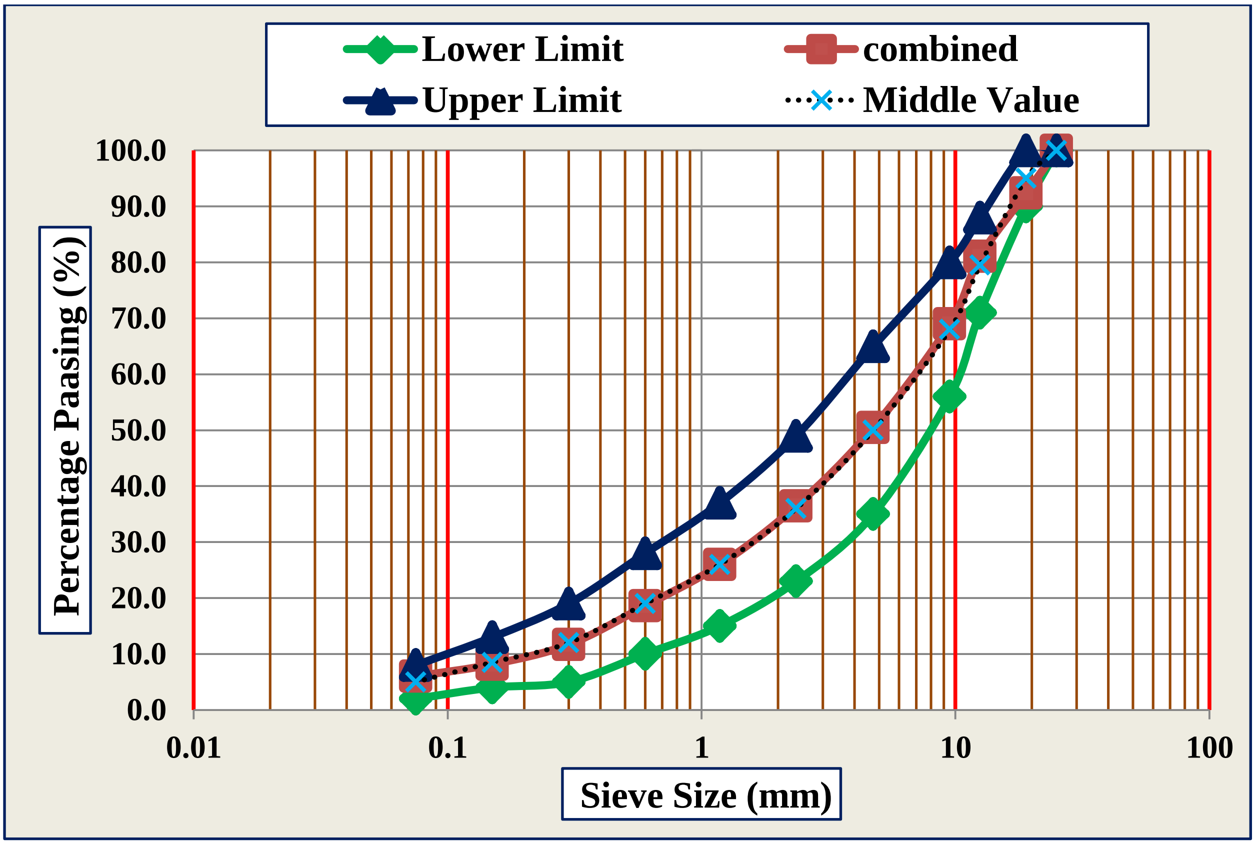


Figure 4.2: Aggregate gradation curve for 6.0% crushed stone dust

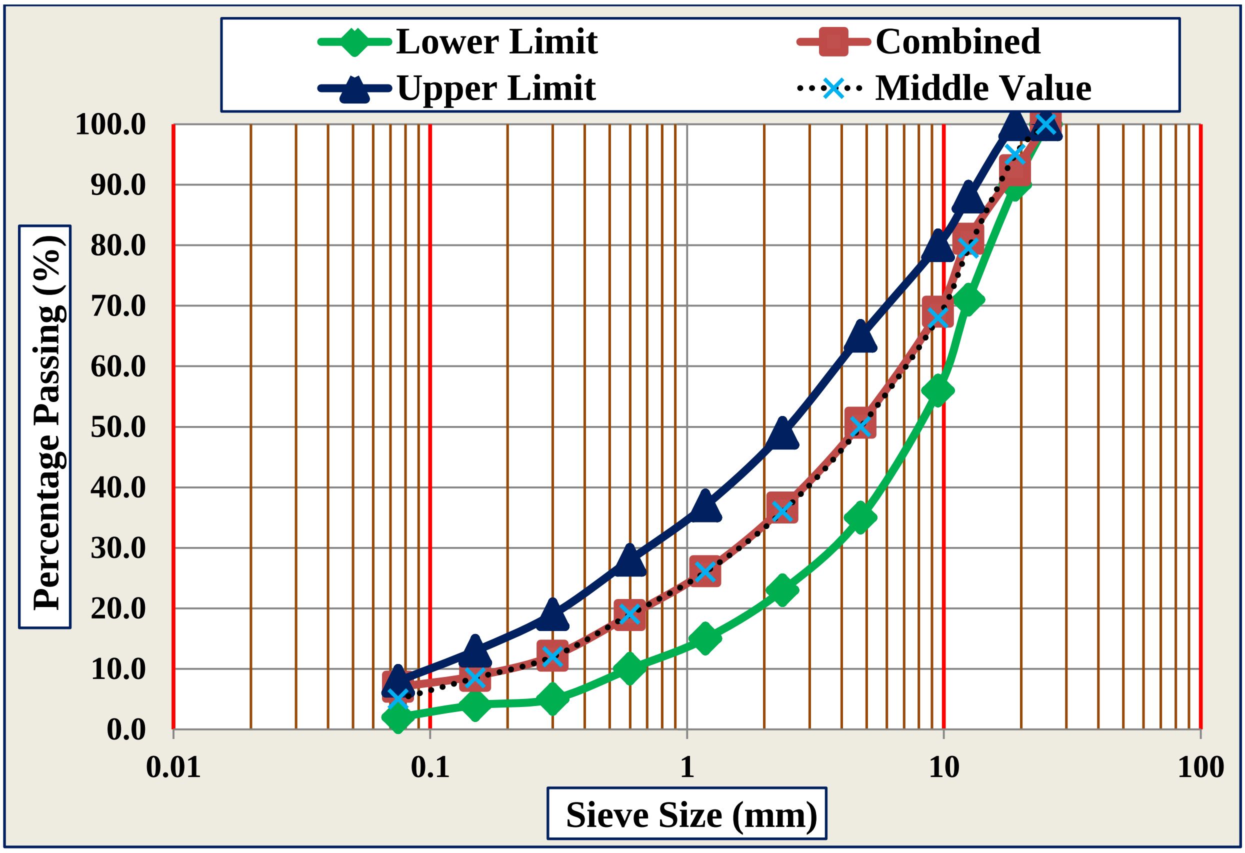


Figure 4.3: Aggregate gradation curve for 7.0% crushed stone dust

4.5 Analysis of Asphalt Mixture Properties

4.5.1 Marshall Test Results

Laboratory work results of the asphalt mix had been obtained and analyzed to succeed in the objective of the research. The total conventional sample was 15 samples with 3 samples for each percentage of conventionally used crushed stone dust filler at a rate of (5%, 6%, and 7%) by weight of aggregate and it was conducted for five different bitumen content (4.0%, 4.5%, 5.0%, 5.5% and 6.0%) of the total weight to determine the optimum bitumen content and optimum filler content. Each samples weight1200 gm.

Marshall Test results of the mixtures with different bitumen content with different varying filler content are presented in Table 4.6, 4.7, and 4.8. Further details are presented in Appendix (F). The relationships between bitumen content and the mixture properties such as Stability, Flow, VFB, VMA, Va, and Bulk specific gravity and the corresponding values are presented on the graph from Figure 4.4 through Figure 4.6.

Asphalt Institute recommended five mix design criteria for the Marshall Mix design method. These are maximum Marshall Stability, range of acceptable Marshall Flow, range of acceptable air voids, percent voids filled with asphalt (VFA), and a minimum amount of VMA.

The process of measuring the stability values from the standard 63.5 mm thickness were converted to an equivalent 63.5 mm value employing the conversion factor. The conversion was made based on either measured thickness or measured volume. It is possible while making the specimen the thickness slightly varies from the standard specification of 63.5 mm. Therefore, measured stability values need to be corrected to those which would have been obtained if the specimens had been exactly 63.5 mm. This is done by multiplying each measured stability value by an appropriated correlation factors as given in Appendix H.

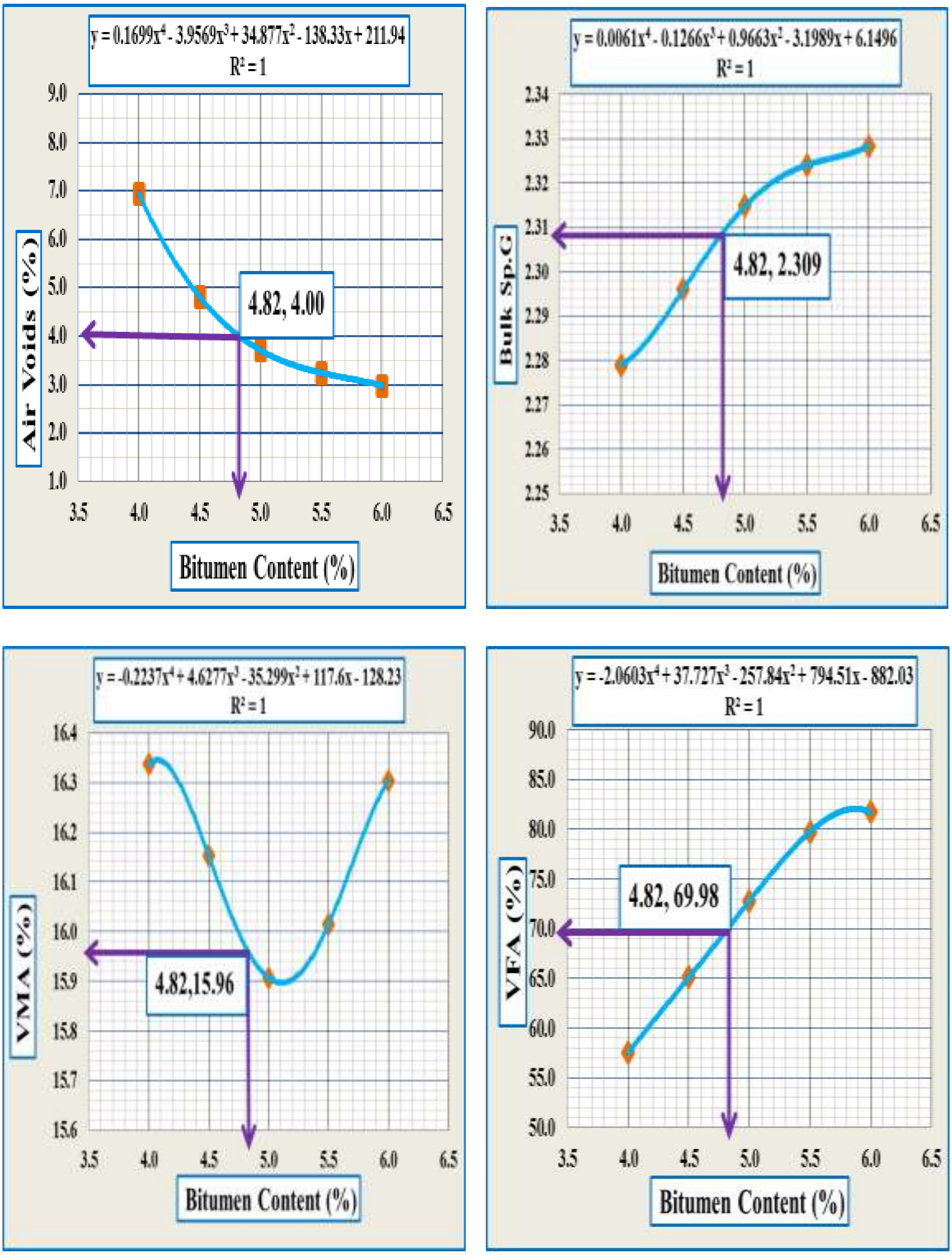
Table 4.6 shows the obtained laboratory test result of the Marshall properties of the mix at different bitumen content with 5.0% conventionally used crushed stone dust filler. The relationships between bitumen content and the mixture properties such as Stability, Flow, Air Voids, VFA, VMA, and Bulk specific gravity curves are plotted in Figure 4.4 by 4th order degree because the data points are five as shown in Table 4.6 below.

Table 4.6: Marshall Properties of asphalt mixes with 5.0% crushed stone dust.

Bitumen Content By weight of Total Mix, (%)	ρA (g/cm^3)	Air Voids (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
4.0	2.279	6.9	16.34	57.50	7.5	2.22
4.5	2.296	4.8	16.15	65.10	8.6	2.66
5.0	2.315	3.7	15.91	72.80	9.4	3.14
5.5	2.324	3.2	16.01	79.75	9.0	3.62
6.0	2.328	3.0	16.30	81.71	7.6	4.04

Figure 4.4 indicates the relationship between bitumen content and mixture properties with 5.0% conventionally used crushed stone dust filler. As shown in the figure the value of stability and the unit weight the total mix increases with increasing bitumen content up to a maximum and then gradually decrease while the bitumen content increase. The value of voids filled with asphalt (VFA) and flow increases with an increase of bitumen content. Whereas, the percent of voids in the mineral aggregate (VMA) decreases to the minimum

value then increases with higher bitumen content. According to the NAPA mix design method criteria, the mix to have 4% air voids at optimum bitumen content. Following this specified standard the observed optimum bitumen content in the Figure 4.4 are equal to 4.82% (by weight of the total mix).



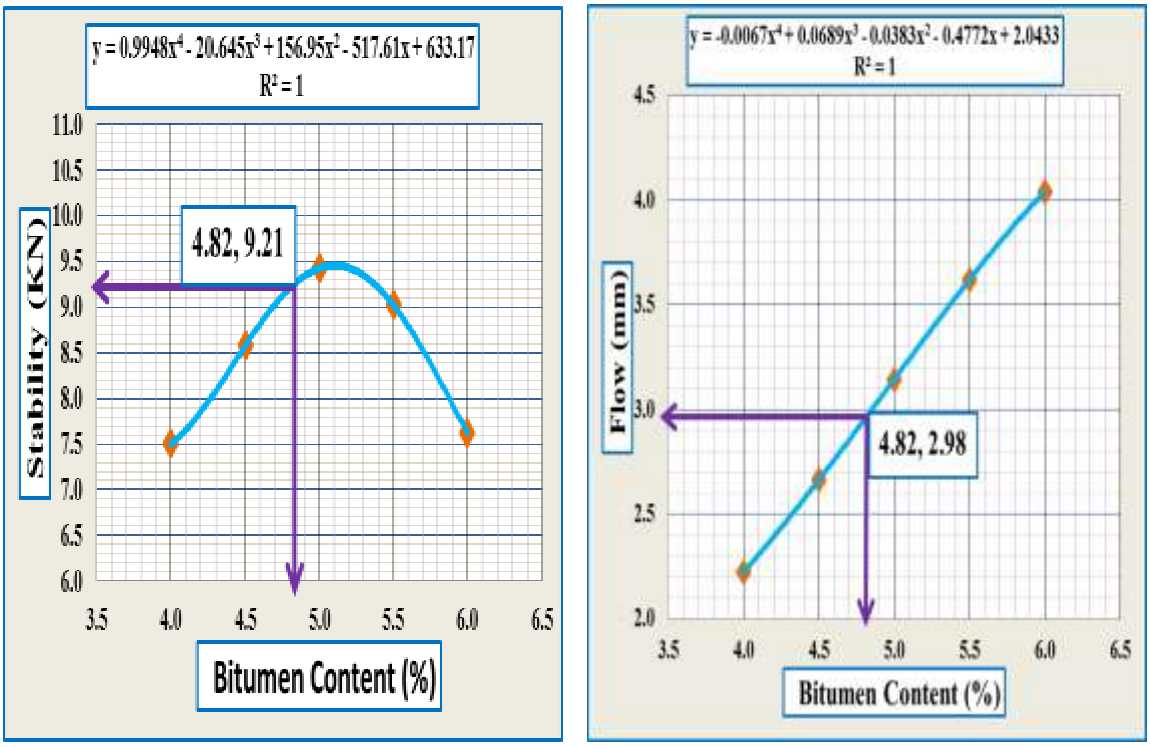


Figure 4.4: OBC and the properties of mixtures with 5.0 % crushed stone dust filler.

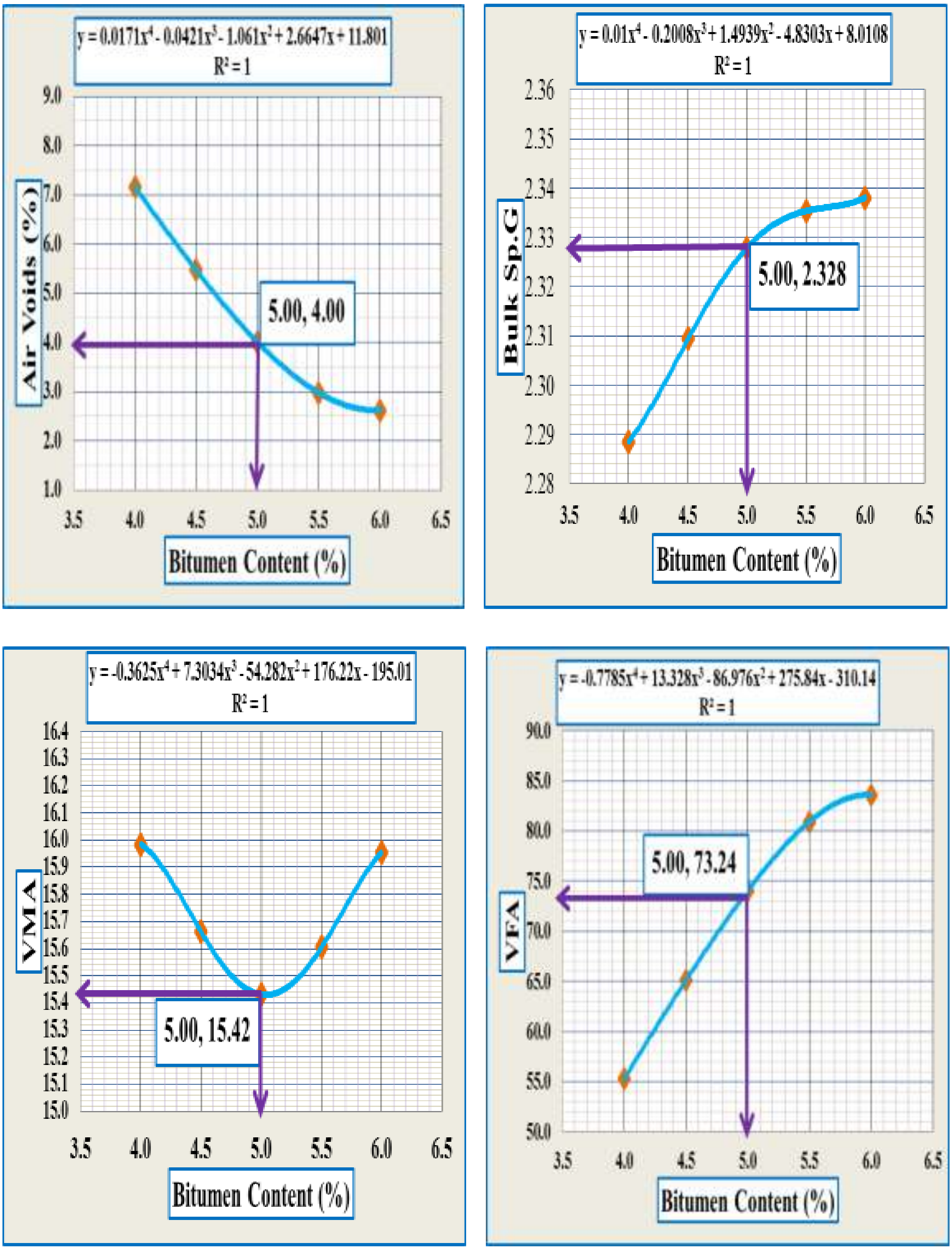
Table 4.7 present the obtained laboratory test result of the Marshall properties of the mix at different bitumen content with 6.0% conventionally used crushed stone dust filler. The relationships between bitumen content and the mixture properties such as Stability, Flow, Air Voids, VFA, VMA, and Bulk specific gravity curves are plotted in Figure 4.5 by 4th order degree because the data points are five as shown in Table 4.7 below.

Table 4.7: Marshall Properties of asphalt mixes with 6.0% crushed stone dust.

Bitumen Content By wt. of Total Mix, %	ρA (g/cm^3)	Air Voids (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
4.0	2.289	7.16	15.98	55.28	7.58	2.44
4.5	2.309	5.47	15.66	65.12	9.26	2.80
5.0	2.328	4.0	15.43	74.05	10.38	3.12
5.5	2.335	2.98	15.61	80.95	9.47	3.47
6.0	2.338	2.62	15.95	83.57	7.68	3.79

Figure 4.5 shows the relationship between bitumen content and mixture properties with 6% conventionally used crushed stone dust filler. From the figure shown below the optimum bitumen content of the mix which resulted in 4.0% air voids of the specification

is 5.0%. The over-all curve correlation between bitumen content and the Marshall properties for 6.0 % crushed stone dust filler is similar to 5.0% crushed stone dust filler.



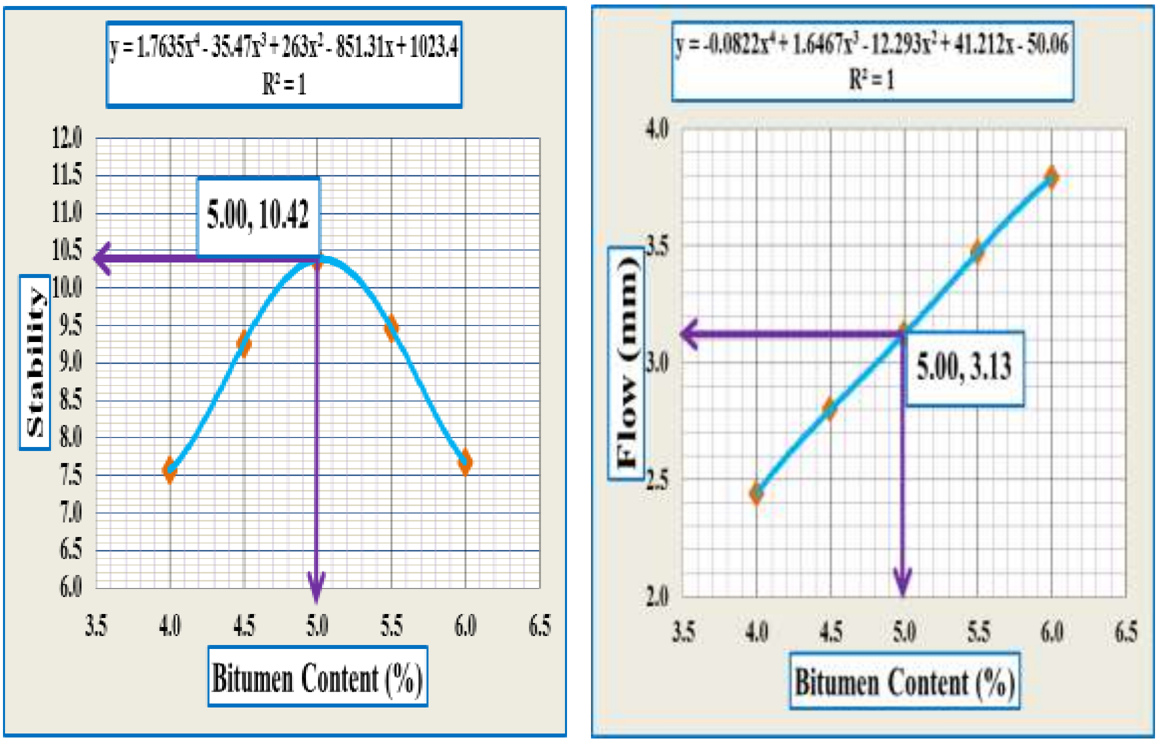


Figure 4.5: OBC and the properties of mixtures with 6.0 % crushed stone dust filler.

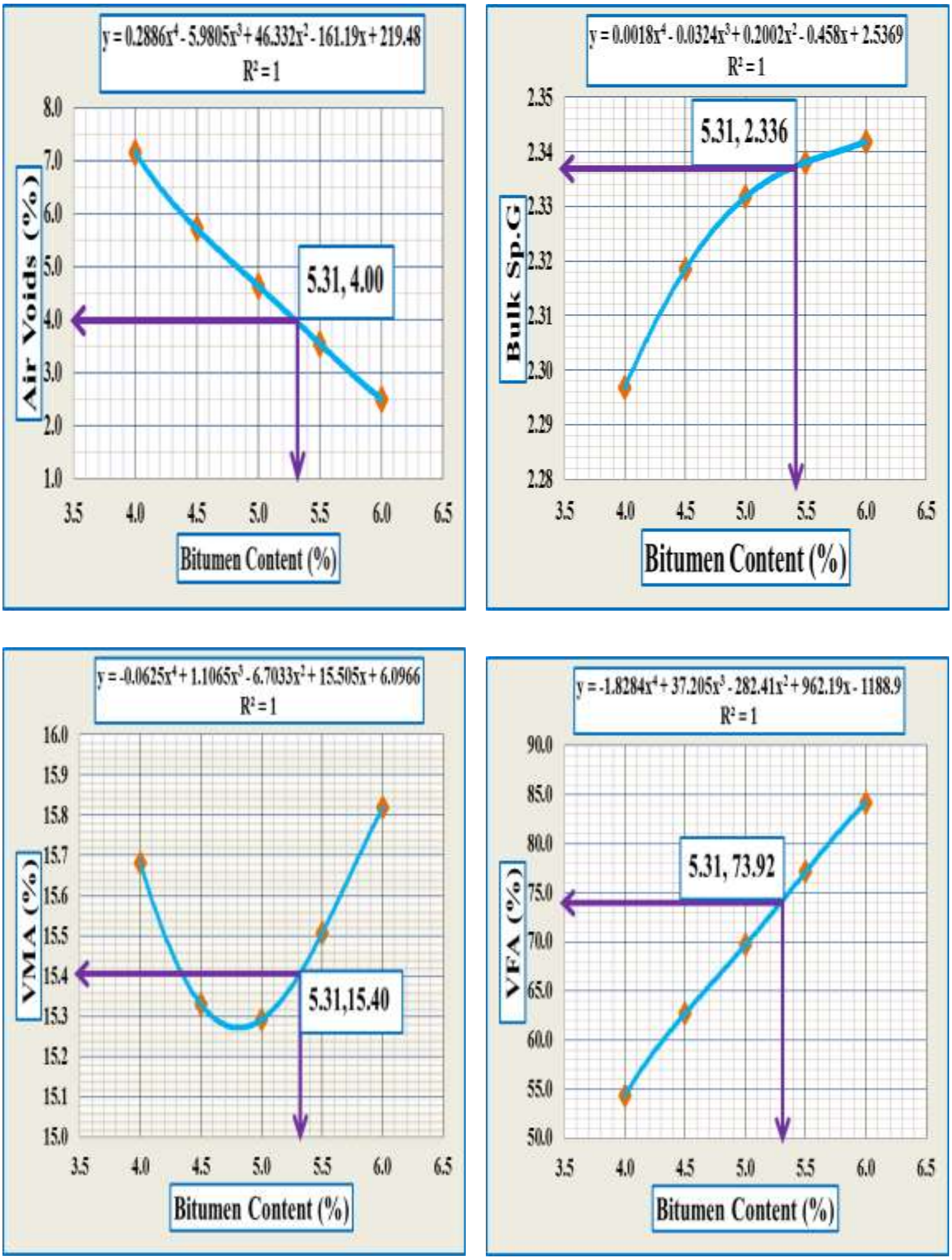
Table 4.8 shows the obtained laboratory test result of the Marshall properties of the mix at different bitumen content with 7.0% conventionally used crushed stone dust filler. The relationships between bitumen content and the mixture properties such as Stability, Flow, Air Voids, VFA, VMA, and Bulk specific gravity curves are plotted in Figure 4.6 by 4th order degree because the data points are five as shown in Table 4.8 below.

Table 4.8: Marshall Properties of asphalt mixes with 7.0% crushed stone dust.

Bitumen Content By weight of Total Mix, (%)	ρA (g/cm^3)	Air Voids (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)
4.0	2.30	7.16	15.68	54.38	7.43	2.31
4.5	2.32	5.72	15.33	62.73	9.06	2.72
5.0	2.33	4.63	15.29	69.70	10.21	3.15
5.5	2.34	3.54	15.51	77.15	9.82	3.59
6.0	2.34	2.50	15.82	84.18	8.96	4.10

Figure 4.6 shows the relationship between bitumen content and mixture properties with 7.0% conventionally used crushed stone dust filler. As shown in the figure the optimum

bitumen content of the mix which resulted in 4.0% air voids of the specification is 5.31%. The over-all curve correlation between bitumen content and the Marshall properties for 7.0 % crushed stone dust filler is similar to the curve of 5.0% and 6.0% crushed stone dust filler.



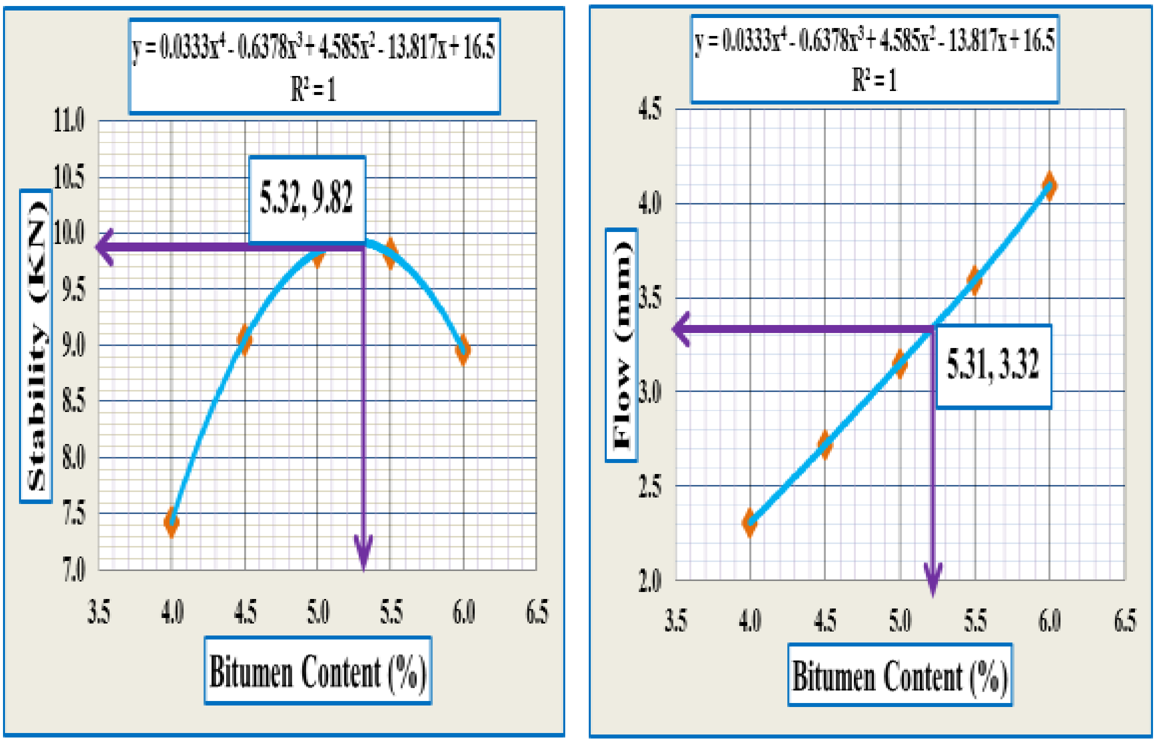


Figure 4.6: OBC and the properties of mixtures with 7.0 % crushed stone dust filler.

4.5.2 Determining the optimum Bitumen Content

In this research, laboratory work was conducted to determine the optimum bitumen for the control mix by varying amounts of bitumen content and filler content using the Marshall Test (ASTM D1559). Accordingly, the OBC was obtained by the method of the National Asphalt Pavement Association (NAPA). These methods recommend making the plotting curves as presented in Figure 4.4 to 4.6. The OBC is determined by finding the bitumen content which corresponds to the median air void 4.0% of the specification. Having this bitumen content Marshall Stability, Flow, VFA, VMA, and Bulk specific gravity was determined as shown in Figures 4.4, 4.5, and 4.6. The obtained values were compared with the specification values and all are within the specification of (ERA, 2013 and Asphalt Institute, 2003). Depending on the result, the optimum bitumen content at 4.0% air voids is 4.82%, 5.0%, and 5.31% by weight of total mix for the respective 5.0%, 6.0%, and 7.0% CSD.

Table 4.9 summarizes the bitumen content corresponding to the standard specification criteria. The obtained bitumen content and volumetric properties of the mixtures are included in the table. Based on this the Marshall result for stability, flow, VMA, VFA and bulk specific gravity of the asphalt mix at 4.82% OBC and 5.0% crushed stone dust filler is (9.21 KN, 2.98 mm, 15.96%, 69.98%, and 2.309 gm/cm^3) respectively. Therefore, it indicates that the mix at 5.0% crushed stone dust filler satisfied the criteria of ERA and Asphalt Institute standards.

Table 4.9: Marshall Properties of the asphalt mix with 4.82% OBC and 5.0% CSD filler

Mix Property	Unit	Values Obtained	ERA Specification Limits		Asphalt Institute Limits		Status
			Lower	Upper	Lower	Upper	
Bitumen	%	4.82	4	10	4	10	OK!!
Air Voids	%	4.0	3	5	3	5	OK!!
VMA	%	15.96	Min 13	-	Min 13	-	OK!!
VFA	%	69.98	65	75	65	75	OK!!
Stability	KN	9.21	Min 7.0	-	Min 8.006	-	OK!!
Flow	mm	2.98	2	4	2	3.5	OK!!
Bulk Specific Gravity	gm/cm^3	2.309	-	-	-	-	-

Table 4.10 summarizes the bitumen content corresponding to the standard specification criteria. The obtained bitumen content and volumetric properties of the mixtures are included in the table. Based on this, the Marshall result for stability, flow, VMA, VFA and bulk specific gravity of the asphalt mix at 5.0% OBC and 6.0% crushed stone dust filler is (10.42 KN, 3.13 mm, 15.42%, 73.24%, and 2.328 gm/cm^3) respectively. Hence, it indicates that the mix at 6.0% crushed stone dust filler satisfied the criteria of ERA and Asphalt Institute standards.

Table 4.10: Marshall Properties of the asphalt mix with 5.0% OBC and 6.0% CSD filler

Mix Property	Unit	Values Obtained	ERA Specification Limits		Asphalt Institute Limits		Status
			Lower	Upper	Lower	Upper	
Bitumen	%	5.0	4	10	4	10	OK!!
Air Voids	%	4.0	3	5	3	5	OK!!
VMA	%	15.42	Min 13	-	Min 13	-	OK!!
VFA	%	73.24	65	75	65	75	OK!!
Stability	KN	10.42	Min 7.0	-	Min 8.006	-	OK!!
Flow	mm	3.13	2	4	2	3.5	OK!!
Bulk Specific Gravity	gm/cm^3	2.328	-	-	-	-	-

Table 4.11 summarizes the bitumen content corresponding to the standard specification criteria. The obtained bitumen content and volumetric properties of the mixtures are included in the table. Based on this the Marshall result for stability, flow, VMA, VFA and bulk specific gravity of the asphalt mix at 5.31% OBC and 7.0% crushed stone dust filler is (9.82 KN, 3.32 mm, 15.40%, 73.92%, and 2.336 gm/cm^3) respectively. Hence, it indicates that the mix at 7.0% crushed stone dust filler satisfied the criteria of ERA and Asphalt Institute standards.

Table 4.11: Marshall Properties of the asphalt mix with 5.31% OBC and 7.0% CSD filler

Mix Property	Unit	Values Obtained	ERA Specification Limits		Asphalt Institute Limits		Status
			Lower	Upper	Lower	Upper	
Bitumen	%	5.31	4	10	4	10	OK!!
Air Voids	%	4.0	3	5	3	5	OK!!
VMA	%	15.40	Min 13	-	Min 13	-	OK!!
VFA	%	73.92	65	75	65	75	OK!!
Stability	KN	9.82	Min 7.0	-	Min 8.006	-	OK!!
Flow	mm	3.32	2	4	2	3.5	OK!!
Bulk Specific Gravity	gm/cm^3	2.336	-	-	-	-	-

4.5.3 Comparison of OBC at Percentage Mix Proportion of CSD Filler

The percentage of fillers that were used to determine the control mix using Marshall Mix design methods were 5.0%, 6.0%, and 7.0% crushed stone dust filler by weight of aggregate. For each percentage of crushed stone dust filler, 45 specimens were prepared at five different bitumen content. Summary of the Marshall properties at three different crushed stone dust filler and the specification were shown in Table 4.12.

The obtained result of the Marshall properties for the control mix at 5.0%, 6.0%, and 7.0% crushed stone dust filler by weight of aggregate with the optimum bitumen content of 4.82%, 5.0%, and 5.31% respectively. The Marshall stability and the flow values for the three filler content were within the range of ERA and Asphalt institute specification standard. Also, the volumetric properties of the three filler content meet the specification range. In this study, the mixture with higher Marshall Stability from the three filler content is selected as the optimum filler content and optimum bitumen content. So, the laboratory result of the Marshall stability for 5%, 6%, and 7% filler content is 9.21 KN, 10.42 KN, and 9.82 KN respectively. It indicates that 6.0% of crushed stone dust filler has maximum stability than the other. So that, 6.0% CSD filler and the respective 5.0% bitumen content were selected as the optimum filler content and optimum bitumen content. These results were used to determine the optimum replacement ratio of crushed stone dust with waste tire powder and the relationship of variables with waste tire powder content. Also, used to evaluate the moisture susceptibility of asphalt mixes, and the effect of waste tire powder on bitumen content.

Table 4.12: OBC and Marshall Properties of the three percentages of mix proportions.

Mix Properties	Crushed Stone Dust			Suggest Marshall Criteria	
	5%	6%	7%	ERA Specf.	Asphalt Institute
Bitumen,%	4.82	5.0	5.31	4-10%	4-10%
Air Voids,%	4.0	4.0	4.0	3-5%	3-5%
VMA,%	15.96	15.42	15.40	Min13	Min13
VFA,%	69.98	73.24	73.92	65-75%	6-75%
Stability,KN	9.21	10.42	9.82	Min 7KN	Min 8.006
Flow, mm	2.98	3.13	3.32	2-.4	2-3.5
Bulk Specific Gravity, gm/cm^3	2.309	2.328	2.336	-	-

4.6 The Relationship of Marshall Properties with Waste Tire Powder Filler Material

The introduction of waste tire powder as a replacement of conventionally used crushed stone dust filler in HMA has been evaluated using previously determined 5.0% optimum bitumen content and 6.0% optimum filler content. The possibility and the effect of replacing crushed stone dust with WTP on the Marshall stability and volumetric properties were evaluated by adding a different percentage of WTP to asphalt mix at a 3% incremental rate, (0%, 3.0%, 6.0%, 9.0%, 12%, 15%, and 18%) by weight of conventionally used crushed stone dust filler. Table 4.13 shows the different proportions of mineral aggregate and filler with varying percentages of waste tire powder.

Table 4.13: Mix Proportion of Asphalt Concrete Mixtures Prepared by using different filler content and their proportion of used aggregate.

Sample Name	Coarse Aggregate	Intermediate Aggregate		Fine Aggregate	% of Crushed Stone Dust	% of Waste Tire Powder	Filler (CSD +WTP),%
	(13-25mm)	(6-13mm)	(3-6mm)	(0-3mm)			
Control Sample	7.62	23.40	18.50	44.48	6.0	0 (0%)	6.0 (100%)
WTP1	7.62	23.40	18.50	44.48	5.82(97%)	0.18(3.0%)	6.0(100%)
WTP2	7.62	23.40	18.50	44.48	5.64(94%)	0.36(6.0%)	6.0(100%)
WTP3	7.62	23.40	18.50	44.48	5.46(91%)	0.54(9.0%)	6.0(100%)
WTP4	7.62	23.40	18.50	44.48	5.28(88%)	0.72(12%)	6.0(100%)
WTP5	7.62	23.40	18.50	44.48	5.10(85%)	0.90(15%)	6.0(100%)
WTP6	7.62	23.40	18.50	44.48	4.92(82%)	108(18%)	6.0(100%)

Table 4.13 present mix design proportion including coarse aggregates (13-25 mm) 7.62%, intermediate aggregates (6-13 mm) 23.40% and (3-6 mm) of 18.50%, fine aggregates (0 - 3 mm) 44.8% and mineral fillers (0.075 mm size) 6.0%. A total of 18 Marshall specimens of mixture each weighing 1200g were prepared using seven different percentage of waste tire powder content, 0% (control), 3.0%, 6.0%, 9.0%, 12%, 15%, and 18% (by weight of optimum filler content) and 5.0% bitumen content (by weight of total mix). The Marshall test was used to evaluate the specimens. Table 4.14 summarizes Marshall Properties of asphalt mixes with WTP at 5.0% of constant bitumen content. Further details are presented in Appendix F.

Table 4.14: Marshall Property of asphalt mix with WTP at 5.0% bitumen content

% of Replacement Rate	OBC	CSD and WTP By % of Total Mix	ρA (gm/cm^3)	Air Voids (%)	VMA (%)	VFA (%)	Stability (KN)	Flow (mm)	Marshall Quotient (KN/mm)
0% (Control Mix)	5.0	6.0% CSD +0% WTP	2.331	4.33	15.33	71.79	10.36	3.23	3.21
3%	5.0	5.82% CSD + 0.18%WTP	2.318	4.28	15.78	72.88	10.40	2.94	3.54
6%	5.0	5.64% CSD + 0.36%WTP	2.322	4.19	15.66	73.27	10.45	2.84	3.67
9%	5.0	5.46% CSD + 0.54%WTP	2.324	4.10	15.58	73.71	10.48	2.90	3.61
12%	5.0	5.28% CSD + 0.72%WTP	2.327	4.00	15.46	73.96	10.53	2.97	3.55
15%	5.0	5.10% CSD + 0.90%WTP	2.324	4.21	15.58	72.97	10.21	3.06	3.34
18%	5.0	4.92% CSD + 1.08%WTP	2.322	4.44	15.64	71.63	9.66	3.12	3.10

Table 4.14 shows summary of the Marshall Mix results with different percentage of conventionally used crushed stone dust filler and waste tire powder at the optimum bitumen content of 5.0%. The properties of the asphalt mixtures with varying content of tire powder will be discussed under following sections.

4.6.1 Marshall Stability – Waste Tire Powder Content Relationship

The stability is defined as the maximum load resistance that the specimen will achieve at 60°C under specified conditions. The mixture should have an adequate mix stability to prevent unacceptable distortion and displacement when traffic load is applied. Figure 4.7 below shows the relationship between Marshall Stability, and waste tire powder content. As it is seen from the figure the stability of the mix with waste tire powder increased as the replacement percentage of WTP content increases until it reaches maximum stability, then decreases. The results show that maximum stability of 10.53 KN at 12% content of waste tire powder in the mixes at 5.0% optimum bitumen content. The stability of the mixes with waste tire powder is higher as compared to the control mixes at the optimum bitumen content. All the value of stability has achieved the requirement of Asphalt Institute, 2003, and ERA, 2013.

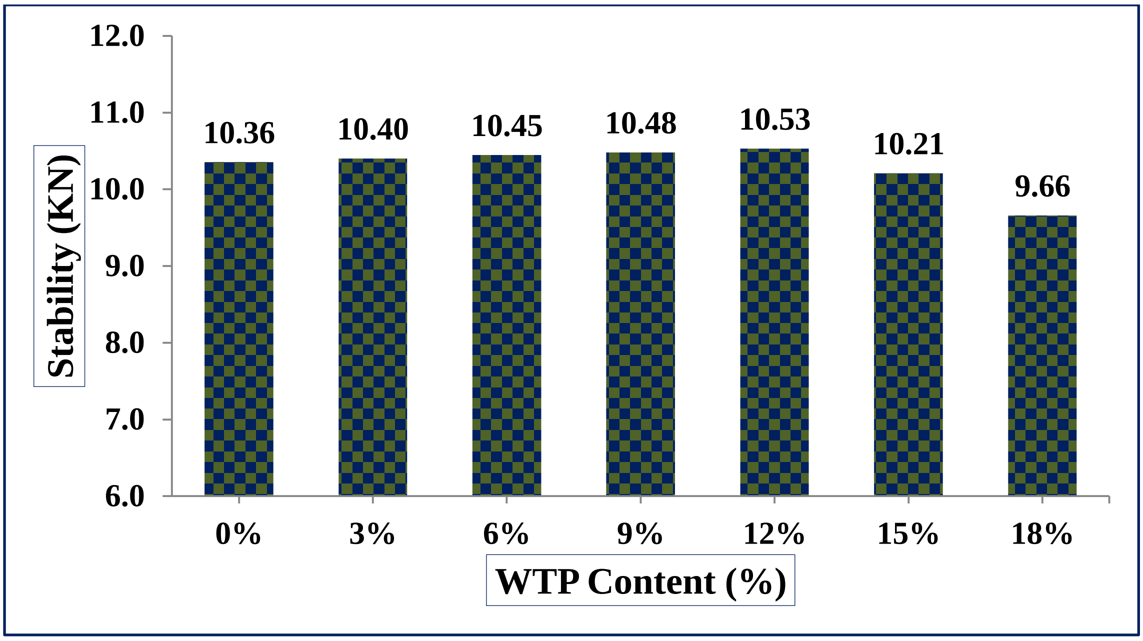


Figure 4.7: Stability value versus waste tire powder content relationship at 5.0% OBC.

4.6.2 Flow – Waste Tire Powder Content Relationship

Flow refers that the vertical deformation of the sample (measured from the start of loading to the point at which stability begins to decrease) in 0.25 mm. 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. According to (ERA, Pavement Design Manual, 2002) the flow value is usually specified to be in the range of (2-4) mm for heavy traffic. Figure 4.8 shows the relationship between flow value and waste tire powder content. The flow value initially decreased and recorded minimum value of 2.84 mm at 6% WTP filler content then, gradually increased as the percentage of waste tire powder content increase but it has less value than the control mix. A maximum flow value of the mix found to be 3.12 mm but the maximum value of the control mix was 3.23 mm which is greater than the mix result containing waste tire powder. Since the flow value of the replacing mix was less than the control mix which can be ascribed that the bitumen content of the control mix is not sufficient to obtain greater flow value and it has some effect on durability, and may lead to cracking of the mix.

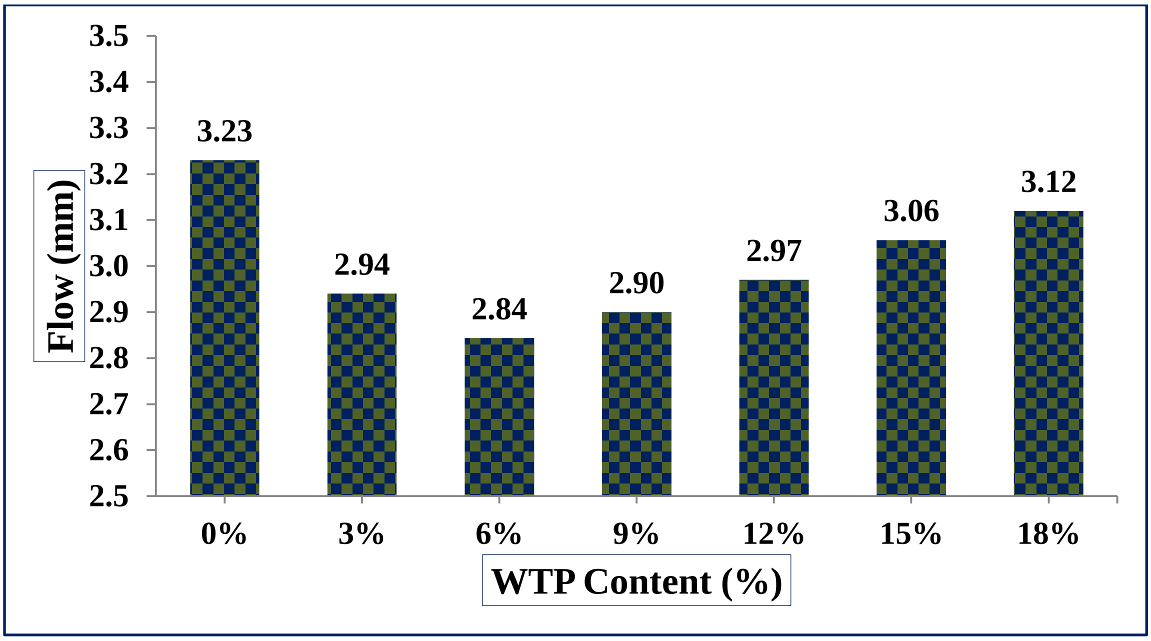


Figure 4.8: Flow value versus waste tire powder content relationship at 5.0% OBC.

4.6.3 Marshall Quotient (Stability to Flow Ratio)

Since Marshall Quotient (MQ) is an indicator of the resistance against the deformation of the asphalt concrete, MQ values are calculated to evaluate the resistance of the deformation of the asphalt concrete with a different percentage of waste tire powder filler, and can be calculated as the ratio of stability to flow. A higher value of Marshall Quotient indicates a stiffer mixture and, hence, indicates that the mixture is likely more resistant to permanent deformation. Figure 4.9 presents the relationship between the Marshall Quotient and WTP content. The result shows that the value of the Marshall Quotient initially increased as the waste tire powder content is increasing to a maximum value of 3.67KN/mm then decreased as the WTP content increases. Therefore, it can be concluded that the asphalt mix with a high value of WTP has less resistance to deformation and lower stiffness.

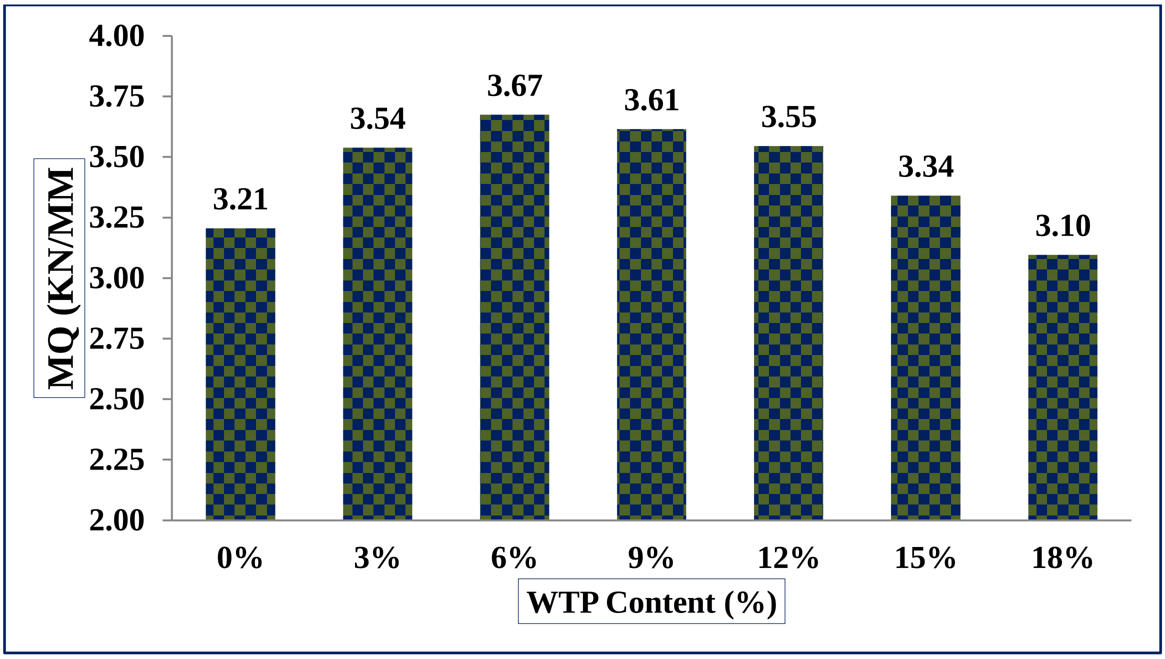


Figure 4.9: Marshall Quotient value versus waste tire powder content relationship at 5.0% OBC.

4.6.3 Bulk specific gravity – Waste Tire Powder Content Relationship

Figure 4.10 presents the relationship between bulk specific gravity and waste tire powder content. As shown on the graph below the bulk specific gravity increased with the increase of waste tire powder in the bituminous mix until it reaches a maximum at 12% of WTP content, then decline with a further increase of filler. The maximum bulk specific gravity of mixes containing waste tire powder is 2.327 gm/cm^3 at 12% waste tire powder content. The conventional mix has higher bulk specific gravity of 2.331 gm/cm^3 compared to mixes with waste tire powder because waste tire powder has lower specific gravity.

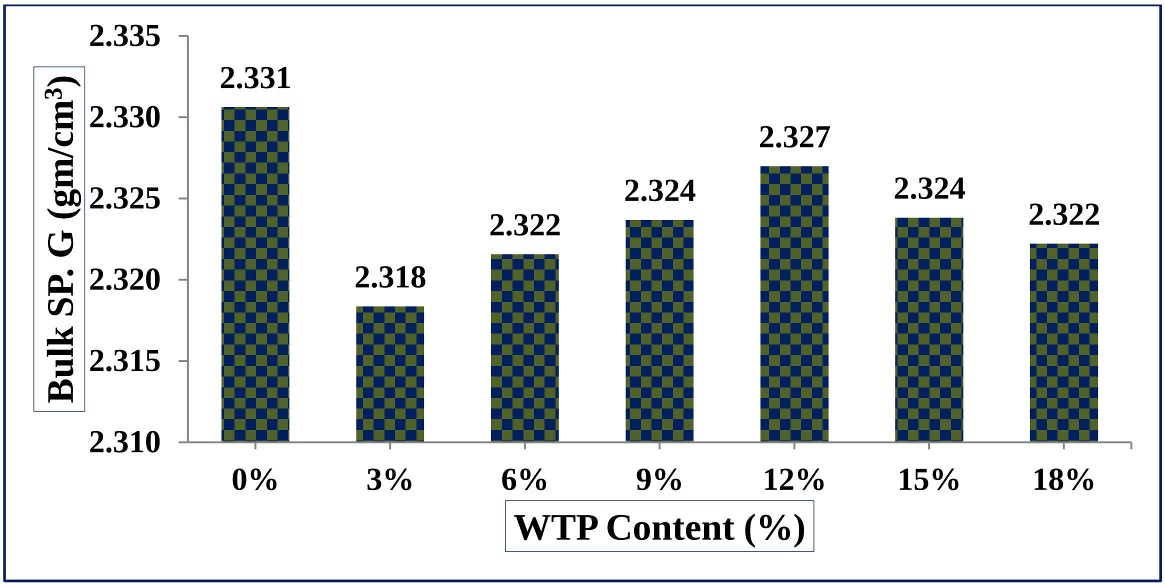


Figure 4.10: Bulk specific gravity value versus waste tire powder content relationship at 5.0% OBC.

4.6.4 Air Voids (Va) – Waste Tire Powder Content Relationship

Air voids in the mix refer to the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture. As observed in Figure 4.11 the air voids value of the bituminous mixes decreased gradually as the WTP filler content increases, the decrease is within the range given in (ERA, pavement design manual, 2002 and Asphalt Institute, 2003) which is (3-5)%. The value of air voids percentage at 12% filler content was 4.0% which is the median value of the specification.

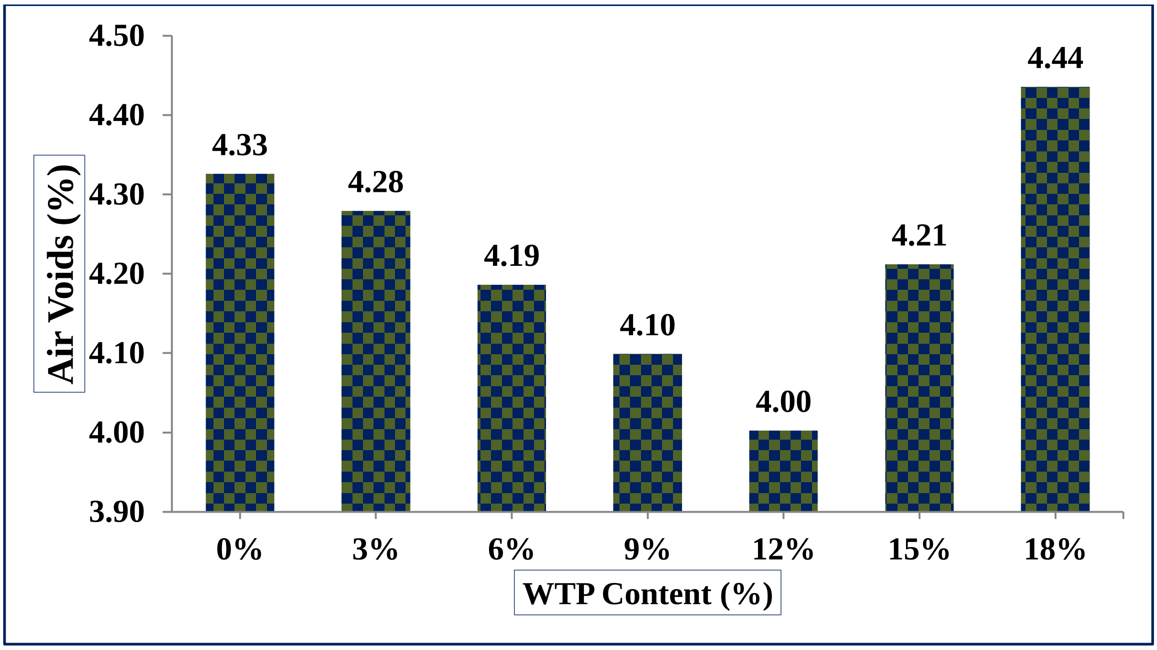


Figure 4.11: Air voids value versus waste tire powder content relationship at 5.0% OBC.

4.6.5 Void in Mineral Aggregate (VMA) – Waste Tire Powder Content Relationship

The voids in the mineral aggregates (VMA) refer to the percentage of void spaces between the granular particles in the compacted pavement mixture, including the voids and the volume occupied by the effective asphalt content. As displayed in Figure 4.12 below the VMA values decreases as the percentage of waste tire powder increase and reach to the minimum values then, increase as the filler content increases. The resulting decrease in the VMA value is due to partial replacement of mineral aggregates by WTP which increases the amount of filler resulting in reduction the void spaces between the granular particles in the compacted mix. Lower values of VMA result in fewer spaces to accommodate the required asphalt to produce a good coating and durable mix. The result shows that the minimum value of VMA was determined at 12% waste tire powder which is 15.46% but it is greater than 15.33 mm of the control mixes. Therefore, we can conclude that the control mixes result more durable mixes as compared to the mixes with waste tire powder. All the values of the VMA satisfy the required specification.

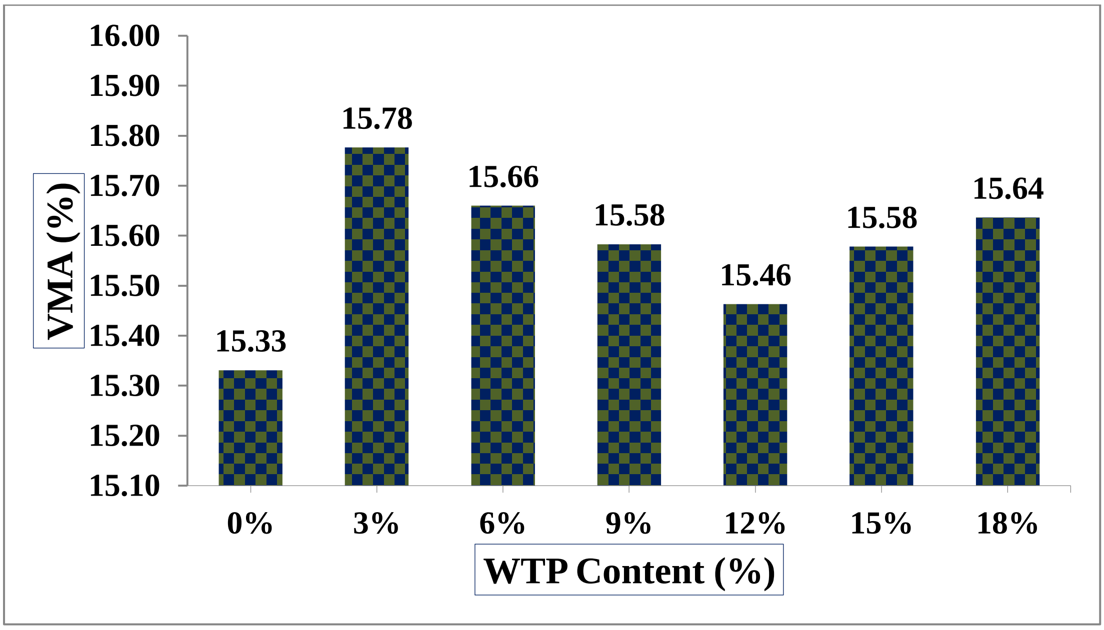


Figure 4.12: VMA value versus waste tire powder content relationship at 5.0% OBC.

4.6.6 Void Filled With Asphalt (VFA) – Waste Tire Powder Content Relationship

Figure 4.13 shows the relationship between the void filled with Asphalt and waste tire powder content. The result shows that the value of voids filled with asphalt increase to a value of 73.96% as the replacement percentage of WTP content increases to 12%. All the VFA values of the mix with a replacement percentage rate of (0% - 18%) fell within the standard specification (65-75). VFA represents the volume of effective bitumen content in the mixture. It is inversely related to air voids. The percent of air voids found minimum for 12% waste tire powder filler content but the value of VFA was maximum and it has higher values than the control mix at the same bitumen content.

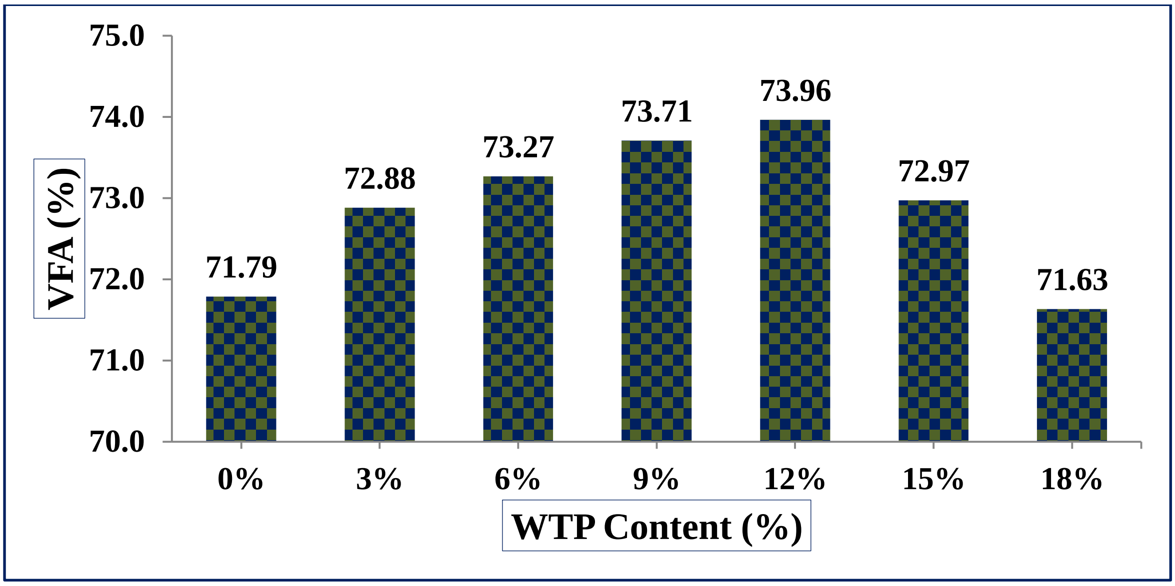


Figure 4.13: VFA values versus waste tire powder content relationship at 5.0% OBC.

4.7 Summary of Hot Mix Asphalt Properties

Table 4.15 below presents the summary of the properties of Hot Mix Asphalt at different replacement percentages of waste tire powder filler content.

Table 4.15: Properties of HMA with Different Percentage of Waste Tire Powder Content.

Property	Replacement Percentage of Waste Tire Powder						
	0%	3%	6%	9%	12%	15%	18%
OBC (%)	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Stability (KN)	10.36	10.40	10.45	10.48	10.53	10.21	9.66
Flow (mm)	3.23	2.94	2.84	2.90	2.97	3.06	3.12
Bulk- density (g/cm^3)	2.331	2.318	2.322	2.324	2.327	2.324	2.322
% Air Voids (Va)	4.33	4.28	4.19	4.10	4.00	4.21	4.44
% of Voids in Mineral Aggregate (VMA)	15.33	15.78	15.66	15.58	15.46	15.58	15.64
% of Voids Filled with Asphalt (VFA)	71.79	72.88	73.27	73.96	73.96	72.97	71.63

Table 4.15 above indicates the properties of stability, flow and volumetric properties of hot mix asphalt and their relationship with the replacement percentage of WTP.

4.8 Determination of Optimum Replacement Ratio of Waste Tire Powder in Hot Mix Asphalt

In determining optimum replacement Marshall Specimens were prepared using conventionally used crushed stone dust filler for determination of optimum proportion. According to [58] studies, a set of controls is recommended to obtain the optimum content that produces an asphalt mix with the best Marshall properties. The optimum replacement rate of the asphalt mix must satisfy the following three criteria: 1) Maximum stability, 2) Maximum specific gravity, and 3) Air Voids (%) within the allowed range of specifications. The relationship between the three Marshall Properties and filler content was presented in Figure 4.7, 4.10, and 4.11 and all the results satisfy the respective (ERA, 2002 and Asphalt institute, 2003) standard specification. As displayed in Figure 4.7 the maximum stability was 10.53 KN at 12% of waste tire powder and also the maximum bulk specific gravity was recorded at 12% replacement rate which is 2.327 gm/cm^3. Figure 4.10 represents the air voids percentage at various waste tire powder content, at 12% WTP filler content the corresponding air voids value was 4.0% which is the median air voids in the specifications. Based on the above discussion 12% waste tire powder (by weight of optimum filler content) with 5.0% bitumen content (by weight of total mix) meet the standard specifications criteria (maximum stability, maximum bulk density, and air voids at the median of the range). Therefore, 12% was adopted as the optimum replacement percentage of waste tire powder.

The comparison of Marshall properties with the optimum replacement of 12 % waste tire powder (by weight of optimum filler content) with the local specification (ERA, Pavement Design Manual, 2002, and International specification Asphalt Institute Manual, 2003) was presented in the Table 4.16.

Table 4.16: Marshall Properties of the asphalt mix with optimum WTP content.

Marshal Method Mix Criteria	(12%) Replaced Asphalt Mix	(ERA Pavement Design,Manual,2002) Specification		(Asphalt Institute,2003) Specification		Remark
		Heavy Traffic		Heavy Traffic		
		Min	Max	Min	Max	
No. of Blow	2*75	2*75		2*75		Satisfied!!
Stability,KN	10.53	7	-	8.006	-	Satisfied!!
Flow, mm	2.97	2	4	2	3.5	Satisfied!!
Percent Air Voids,%	4.00	3	5	3	5	Satisfied!!
VMA,%	15.46	13	-	13	-	Satisfied!!
VFA,%	73.96	65	75	65	75	Satisfied!!

Table 3.16 shows the asphalt mix prepared at the optimum replacement percentage of waste tire powder which is 12% (by weight of optimum filler content) or 5.28% CSD and 0.72% WTP (by weight of aggregate). The result shows that all the Marshall and volumetric properties satisfy the local (ERA, Pavement Design Manual, 2002) and international, (Asphalt Institute Manual, 2003) specification. Accordingly, it is possible to use waste tire powder filler in hot mix asphalt at 12%, by weight of conventionally used crushed stone dust filler or 0.72% by weight of one specimen mixture of aggregates.

4.9 Relationship between Waste Tire Powder and Bitumen Content

The main factor that affects the bitumen content of asphalt concrete mix are characteristics of aggregate such as gradation and absorption. The amount of absorption mainly varies depending on the type of aggregate used. In this study effect of waste tire powder on the bitumen content was evaluated using the optimum replacement percentage of waste tire powder, 12%, and bitumen content of two bitumen content above the optimum and two bitumen content below the optimum at 0.5% increment which is (4.0%, 4.5%, 5.5%, and 6.0%) and using the optimum filler content of 6.0% crushed stone dust. It is evaluated using Marshall Stability and volumetric properties. The result obtained was analyzed relative to the control mix for the respective bitumen content prepared using 12% waste tire powder by weight of optimum filler content. Table 4.17 shows the Marshall Properties result for 4.0%, 4.5%, 5.5%, and 6.0% bitumen content at 12% WTP.

The laboratory test results are shown in Figure 4.14 to 4.19 at optimum CSD filler content (6%), and optimum WTP content (12%). The Marshall Stability, flow, and volumetric properties result of the control mix with 6.0% crushed stone dust at 5.0% bitumen content was presented in Table 4.7.

Table 4.17: Marshall Result of 12% WTP at different bitumen content

Bitumen Content, (%)	Optimum WTP, (%)	CSD and WTP By % of Total Mix	Marshall result containing 12% WTP					
			Stability, (KN)	Flow, (mm)	Bulk Sg., (g/cm^3)	Air Voids, (mm)	VMA, (mm)	VFA, (mm)
4.0	12.0	5.46% CSD + 0.54%WTP	7.84	2.07	2.300	5.76	16.14	64.31
4.5	12.0	5.46% CSD + 0.54%WTP	9.37	2.54	2.314	4.77	15.76	69.77
5.0	12.0	5.46% CSD + 0.54%WTP	10.53	2.97	2.327	4.00	15.46	73.96
5.5	12.0	5.46% CSD + 0.54%WTP	8.71	3.10	2.332	3.49	15.72	74.92
6.0	12.0	5.46% CSD + 0.54%WTP	6.82	3.37	2.342	2.82	15.81	79.24

Table 4.17 above shows the Marshall Stability, flow, and volumetric properties result of the mix prepared with optimum replacement percentage of WTP at bitumen content of two above and below the optimum with 0.5% increment. The effect of WTP on asphalt mixes at varying content of bitumen will be discussed under following sections.

4.9.1 Marshall Stability – Bitumen Content Relationship

Figure 4.14, shows the relationship between stability and bitumen content of the control mix and asphalt mixes prepared at optimum replacement percentage of waste tire powder. As observed in the figure below the stability increased as the bitumen content increased, and reached maximum at optimum bitumen content then decreased while the bitumen content is increased two above the optimum at 0.5% increment. Asphalt mixes prepared with the optimum replacement percentage of WTP, (12% by weight of OFC) gotten higher stability (7.84 KN, and 9.37 KN) as compared to the control mix result (7.58 KN, and 9.26 KN) prepared at (4.0%, and 4.5%) bitumen content respectively but the control mix yields higher stability (9.47 KN, and 7.68 KN) in comparison to the obtained result with OWTP content (8.71 KN, and 6.82 KN) at the respective 5.5% and 6.0% bitumen content. The control mixes has attained lesser stability (10.38 KN) relative to the stability value obtained for the mix prepared with OWTP (10.53 KN). The results are then compared to the available standard specification. Therefore, all the samples fulfill the minimum stability value of 7.0 KN for heavy traffic volume as per ERA, 2013 specification except mixes prepared with OWTP at 6.0% bitumen content. The result obtained at 4.0% and 6.0% did not fulfill the minimum stability value of 8 KN for high traffic volume as per the Asphalt institute Ms-2 standard.

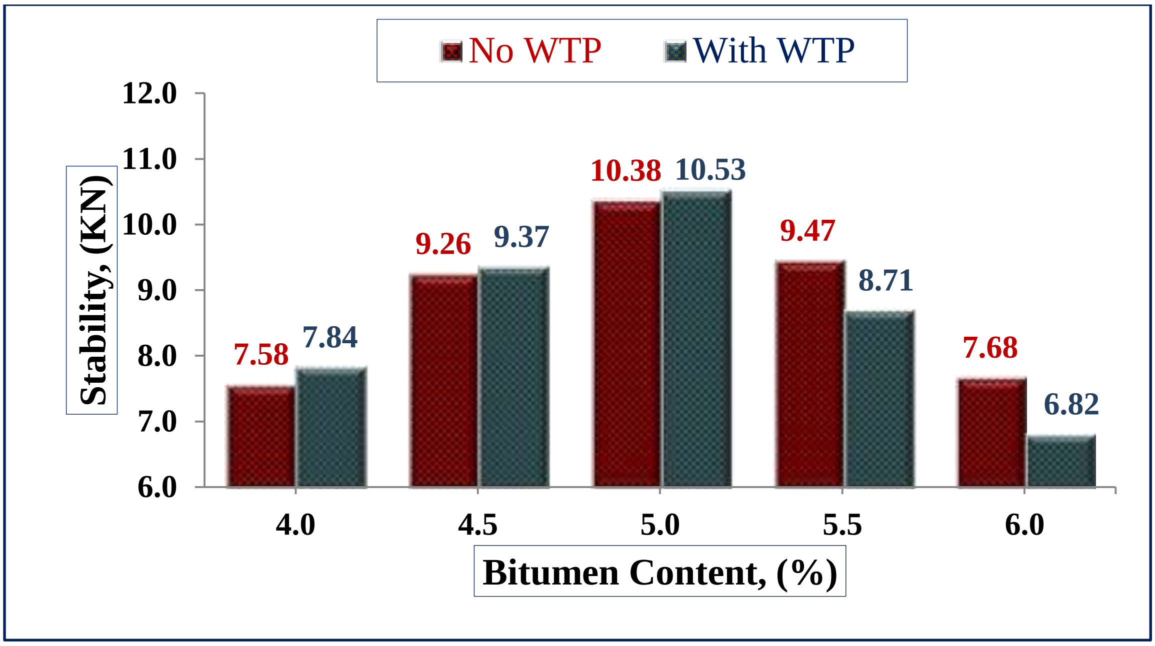


Figure 4.14: Stability value versus bitumen content relationship.

4.9.2 Flow – Bitumen Content Relationship

The combined graph of flow with bitumen content shows the flow value increases with increasing the bitumen content both for the control mix and a mix prepared with 12% OWTP. However, the flow value of a mix containing WTP has less than the flow value of the control mixes. This may be due to the reason that friction between aggregate particles increases with lesser asphalt binder films and the property of the material has high absorption. As shown on the Figure 4.15 the recorded flow value in the two cases meet the specified range of (ERA, pavement design, 2002) but the flow value for 4.0% bitumen content with optimum replacement percentage yields minimum value which nearly approach to lower range of the specification.

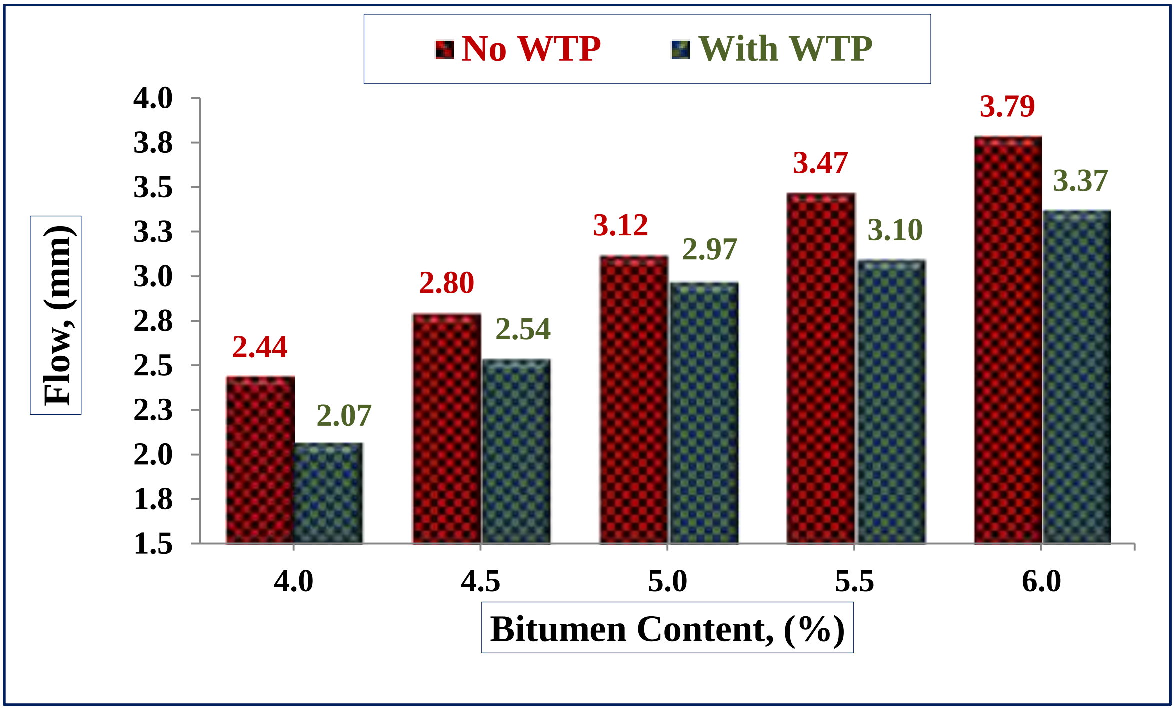


Figure 4.15: Flow value versus bitumen content relationship.

4.9.3 Bulk Specific Gravity – Bitumen Content Relationship

Figure 4.16, shows the relationship between Bulk Specific Gravity and Bitumen Content of the two cases. The test result shows that Bulk Specific Gravity slightly increases with increasing bitumen content. As displayed on the figure below the bulk specific gravity of a mix prepared with WTP is less than the obtained result of the control mix for all bitumen content except 6.0%. It can be concluded that WTP powder has slightly influenced the unit weight of the asphalt concrete mixes but 6.0% has higher bulk specific gravity value. Among the whole bitumen content proportion 6.0% bitumen content has higher bulk specific gravity value both for the control mix and a mix prepared with optimum replacement percentage, (12%) of WTP.

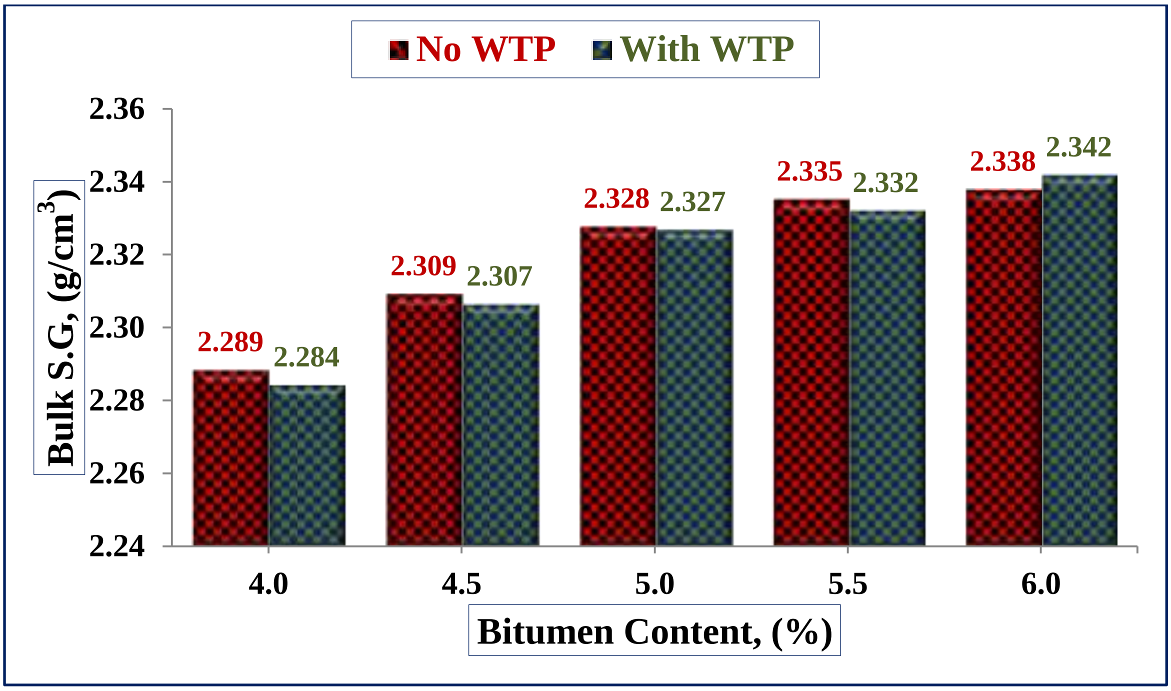


Figure 4.16: Bulk specific gravity value versus bitumen content relationship.

4.9.4 Air Voids (Va) – Bitumen Content Relationship

The durability of asphalt pavement is a function of the air void content of the HMA pavement. The lower air voids provide, the less permeable the mix develops. Figure 4.17, shows the relationship between air voids, and bitumen content. As indicated in the figure, the air voids decreases as bitumen content increases. The result show that the control mix has higher air voids value (7.16%, and 5.47%) as compared to air voids value of a mix prepared with OWTP, (12% by weight of OFC), (5.76%, and 4.77%) at a bitumen content of (4.0%, and 4.5%) respectively but the mix above the OBC, the control mixes has lesser air voids value (2.98%, and 2.62%) in comparison to the recorded result for mix containing OWTP (3.49%, and 2.82%) in the respective bitumen content (5.5%, and 6.0%). All the air voids values of a control mixes and a mixes with OWTP is meet the required standard specification (3-5) given by (ERA, 2013, and Ms-2) but at 4.0% bitumen content of the two mixes and 4.5% of the control mix is not within the specified range.

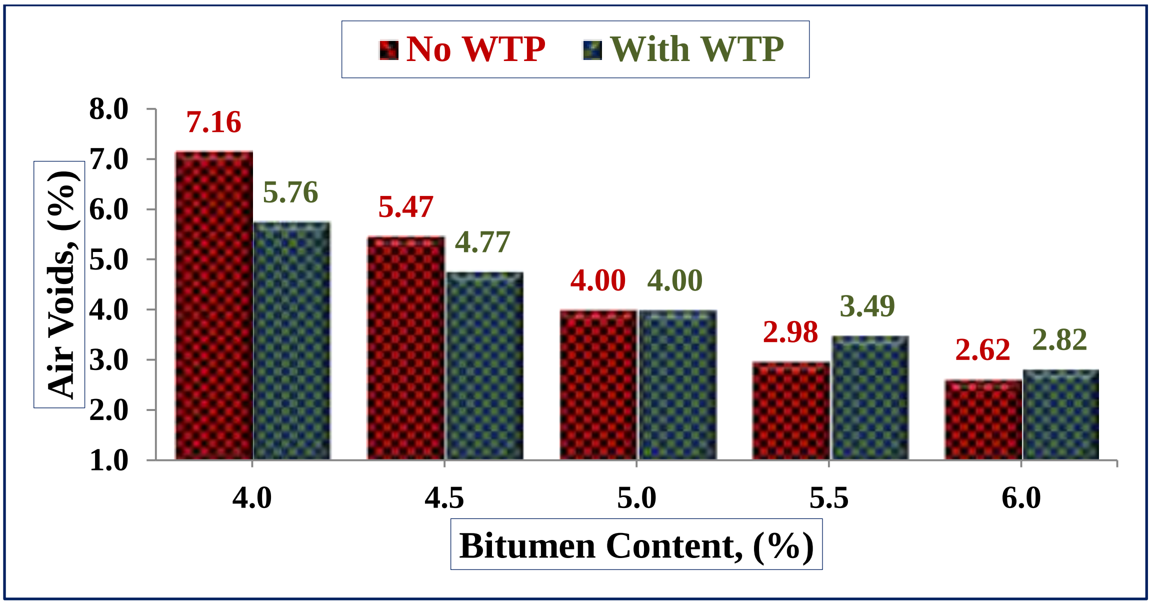


Figure 4.17: Air voids value versus bitumen content relationship.

4.9.5 Void in Mineral Aggregate (VMA) – Bitumen Content Relationship

Figure 4.18, presents the relationship between void in mineral aggregate and bitumen content. As the result displayed on the graph all the percentage of VMA decrease while the bitumen content increases up to the OBC and then increase with bitumen content both for the control mixes and a mix prepared with OWTP. Lower values of VMA result in less spaces to accommodate the required asphalt to produce good coating and durable mix. Consequently, all void in mineral aggregate fall within local (ERA, pavement design manual, 2013), and international (Asphalt Institute, 2003) standard specification i.e.>13.

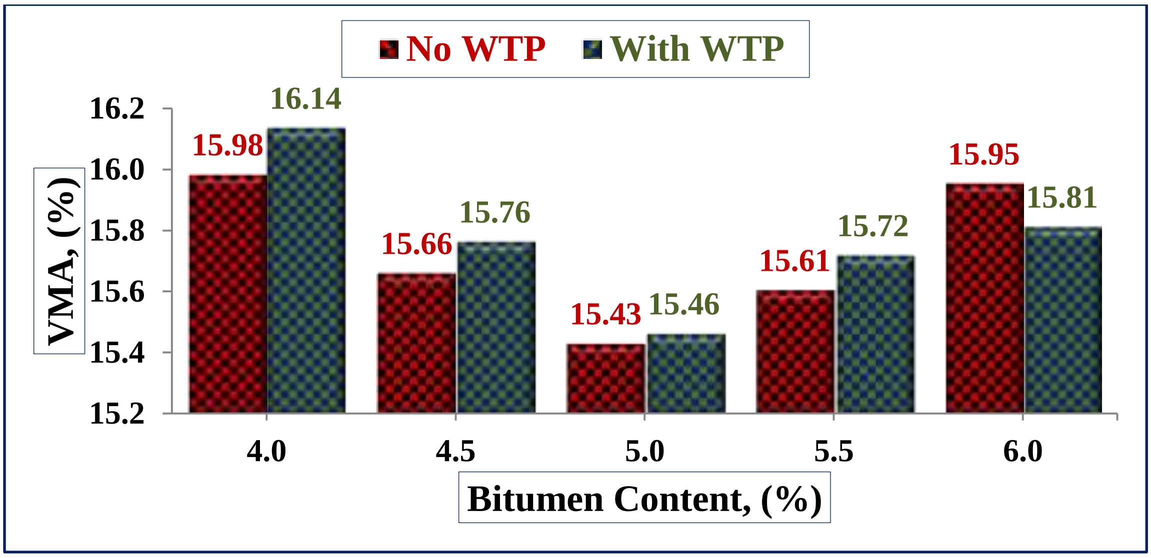


Figure 4.18: Void in Mineral Aggregate value versus bitumen content relationship.

4.9.6 Void Filled With Asphalt (VFA) – Bitumen Content Relationship

The Voids Filled with Asphalt, (VFA) is the percentage of the voids in the mineral aggregate that contain bitumen. If the VFA value too low, there is no enough bitumen to provide durability of the HMA. In other words, if the amount of VFA is over the specification limit lower voids maybe obtained than the required. Hence, VFA is very significant design property of asphalt concrete. As indicated in the Figure 4.19, below the amount of VFA increases as the bitumen content increases. All mixes prepared with optimum waste tire powder fulfill the VFA criteria, (65 – 75) %, at their respective bitumen content except at bitumen content of 6.0%. But the control mixes meet the specification at bitumen content of 4.0%, and 4.5%. The VFA value the control mixes at bitumen content of 5.5%, and 6.0% is not achieve the standard specification limits.

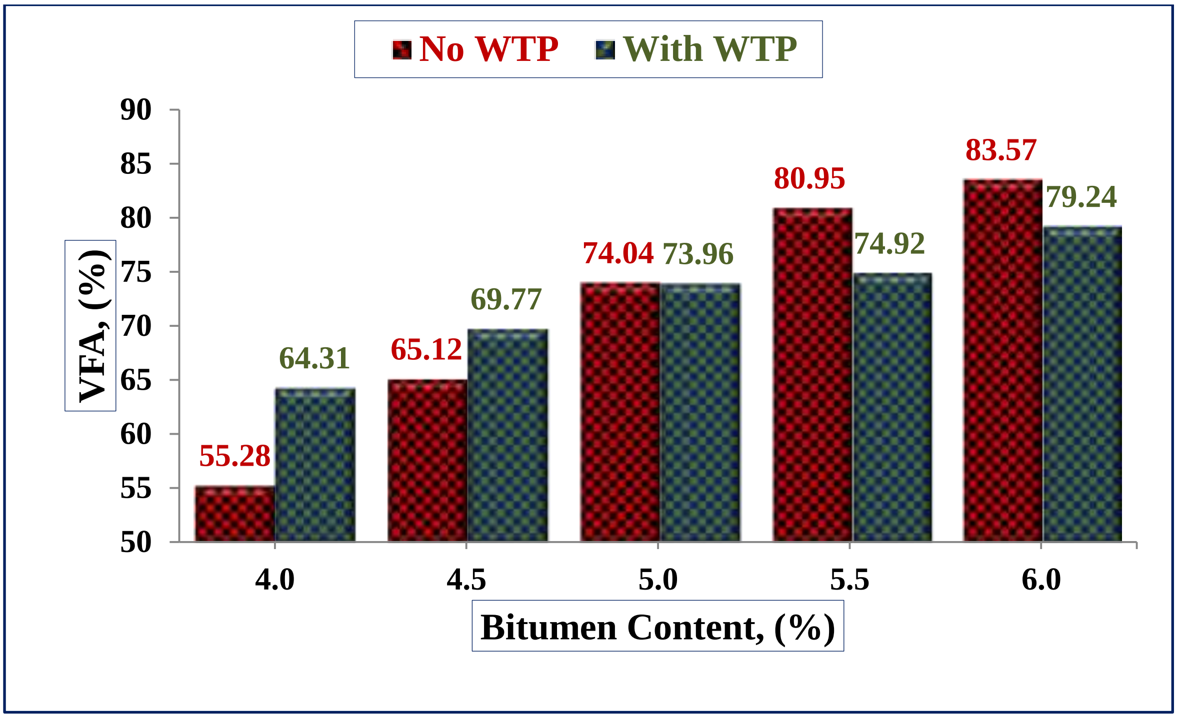


Figure 4.19: Void filled with asphalt value versus bitumen content relationship.

4.10 Effects of Waste Tire Powder on Moisture Susceptibility of HMA

The tensile strength ratio (TSR) is a common parameter that is used to evaluate the moisture susceptibility of asphalt mix. It is dependent on the results of the indirect tensile strength (ITS) of the two cases (conditions and unconditioned). In this study, the samples were prepared for each replacement percentage of waste tire powder i.e. 0% (control), 3.0%, 6.0%, 9.0%, and 12% (by weight of OFC) using OBC. Table 4.18 below shows a summary of the laboratory test results of the specimen prepared for moisture susceptibility. See the detail works in Appendix G.

Table 4.18: Summary of Moisture Susceptibility of HMA

WTP Content (%)	OBC (%)	OFC (%)	Gmm	**Dry Sample**			**Wet Sample**				**Avg. TSR (%)**
				Avg. Gmb	Avg. Air Void (%)	Avg. ITS (KPa)	Avg. Gmb	Avg. Air Void (%)	Saturation (%)	Avg. ITS (KPa)	
0.0	5.0	6.0	2.446	2.276	7.0	856.2	2.270	7.2	67.5	660.7	77.16
3.0			2.442	2.274	6.9	877.3	2.274	6.9	74.4	703.9	80.24
6.0			2.438	2.272	6.8	892.1	2.276	6.7	66.1	733.4	82.20
9.0			2.441	2.267	7.1	911.8	2.270	7.0	66.2	777.5	85.27
12.0			2.443	2.274	6.9	933.9	2.268	7.2	70.3	809.1	86.64

Table 4.18 shows the result of dry and wet samples of the specimen subjected to moisture susceptibility with different replacement ratio of waste tire powder. Figure 4.20 indicates the indirect tensile strength results for dry and wet specimens at different percentage of waste tire powder content. The indirect tensile strength results of dry samples have different values as compared to wet specimens. From the result shown in figure above HMA mix which contains waste tire powder generates higher indirect tensile strength both at the dry and wet (moisture conditioned) cases. The average indirect tensile strength results prepared at (0%, 3.0%, 6.0%, 9.0%, and 12%) for the dry and wet specimen are (856.2 KPa, 877.3 KPa, 892.1 KPa, 911.8 KPa, and 933.9 KPa) and (660.7 KPa, 703.9 KPa, 733.4 KPa, 777.5KPa, and 809.1 KPa) respectively. It is visible that the indirect tensile strength value increase as the waste tire powder content increase. The highest

indirect tensile strength for wet samples were recorded at a WTP content of 12% which is equal to 809.1 KPa, and the dry sample value was 933.9 KPa at WTP content of 12%. In the two cases, the control group of the mixes shows the lowest indirect tensile strength with a value of (856.2 KPa and 660.7 KPa) for dry and wet samples respectively.

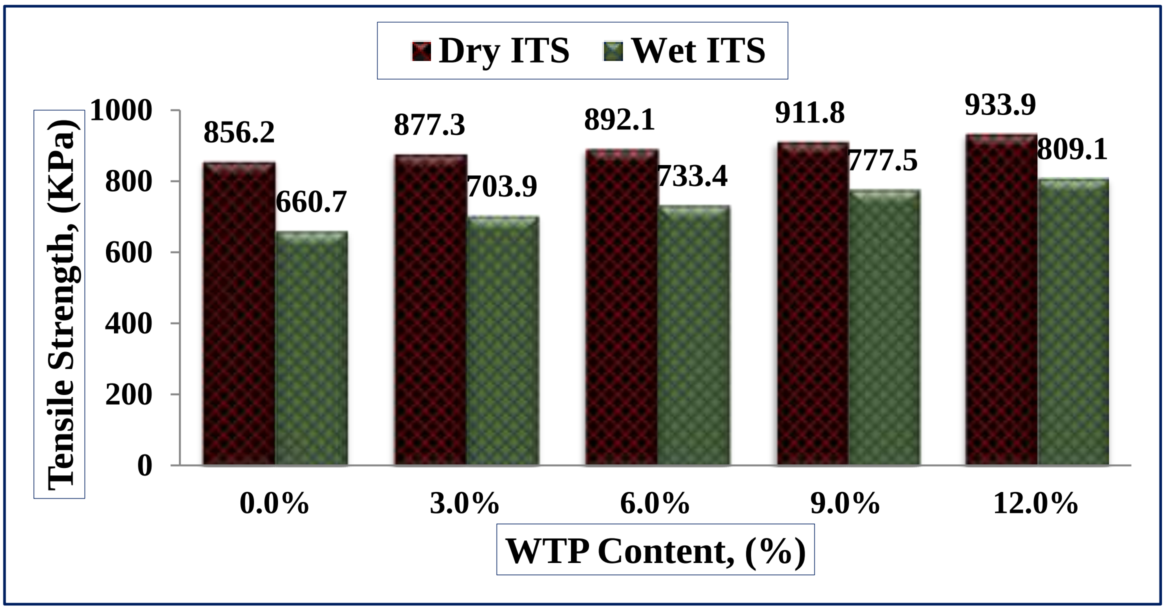


Figure 4.20: Dry and Wet Indirect Tensile Strength of HMA at Different WTP Content

4.10.1 Tensile Strength Ratios (TSR)

Tensile strength ratio (TSR) is a method used to analyze the indirect tensile strength data. It is calculated by dividing the indirect tensile strength value of the wet specimen by the dry specimen. The results of TSR for all WTP content are shown in Table 4.18. Figure 4.21 shows the Tensile strength ratio (TSR) of the control mixes, and mixes prepared with varying percentage of WTP. The average TSR of HMA mixes prepared at (0%, 3.0%, 6.0%, 9.0%, and 12%) waste tire powder content by weight of OFC at OBC are (77.16%, 80.24%, 82.20%, 85.27%, and 86.64%) respectively. Most agencies use a minimum value of TSR = 70% in the moisture sensitivity test for HMA mixtures. Therefore, all the results are within the required limit. The TSR rises with the increase of WTP content until the optimum replacement percentage (12%) with TSR equal to 86.64% which is the maximum value and 77.16% is the minimum TSR value which is recorded at the control group. In general, the TSR of HMA mixes with no waste tire powder exhibit lower TSR than a mix prepared with WTP. But, all of the specimens are not sensitive to the action of water and WTP improves the resistance of water-induced damage.

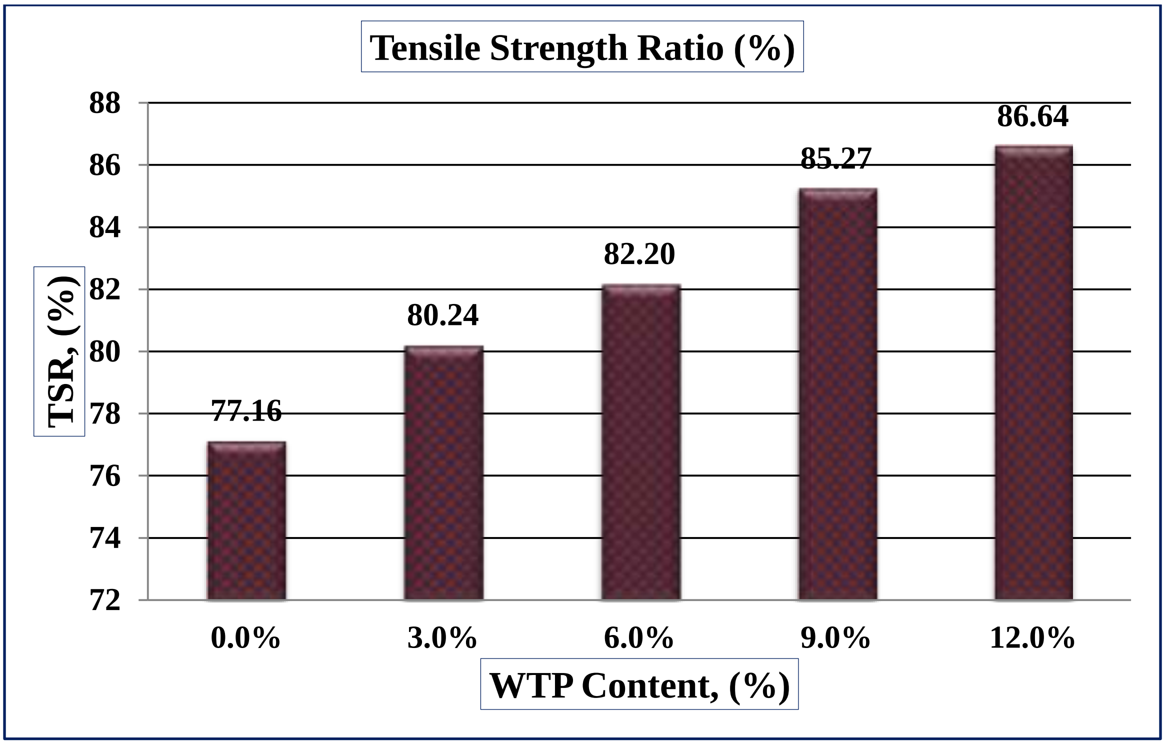


Figure 4.21: Tensile Strength Ratio of HMA

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

This research study aimed to investigate the possible use of waste tire powder as mineral filler in Hot Mix Asphalt (HMA) to enhance the mechanism of using locally available waste materials.

To meet the objective of the study, all the necessary quality tests of aggregate, bitumen, crushed stone dust, and waste tire powder were conducted using standard testing procedures and a detailed laboratory investigation was conducted to determine Marshall Stability and flow with corresponding volumetric properties and moisture sensitivity of mixes. Based on the results of laboratory tests and analysis the conclusions are drawn as follows.

5.1 Conclusion

1. The laboratory results of the conventional materials that used in this study i.e. aggregate, bitumen, and crushed stone dust satisfied the relevant standard specification. Also waste tire powder conform specification for use as filler material in HMA. Therefore, waste tire powder can be used in asphalt mixes.
2. To determine the optimum bitumen content and optimum filler content an experimental test consisting of 45 samples with five different amounts of bitumen content (4%, 4.5%, 5.0%,5.5%, and 6.0%) by weight of total mix and three different percentage of conventionally used crushed stone dust filler content (5.0%, 6.0%, and 7.0%) by weight of aggregate was prepared.
3. The optimum filler content for the control mix was 6.0% with a maximum stability value of the three filler content and the respective bitumen content is 5.0%.
4. The optimum replacement percentage of waste tire powder was determined based on the requirement of maximum stability, maximum bulk density, and air voids at the mid of the specification. The test result shows that the mix containing 12% WTP (by weight of optimum filler content) with a bitumen content of 5.0% fulfill the specified requirement. Therefore, 12% should be optimum WTP content to be partially replaced with CSD in asphalt concrete mixes.
5. The results of waste tire powder to bitumen content indicated that waste tire powder has visible effect at 4.0%, and 6.0% bitumen content. Considering all test

results for stability, flow, Va, VMA, VFA, and Bulk specific gravity, 4.5%, and 5.5% bitumen content can also be used as optional bitumen content with OWTP and OFC but 4.0%, and 6.0% fail the Marshall properties criteria.

6. The Tensile Strength Ratio value linearly increased as the WTP filler content increased. Mixes prepared with waste tire powder filler provide better resistance to moisture induced damage.

7. Therefore, it is generally concluded that waste tire powder can be used as filler materials instead of most commonly used crushed stone dust filler.

5.2 Recommendation

In Ethiopia, even though the construction industry is booming these days, it is still in its infant stage and needs much more effort to be made on the different construction materials. The awareness about the different crushed stone dust replacing materials and their advantages is negligible, implying more work to be done in the area. Especially road agencies are recommended to exercise newly investigated filler materials.

Therefore, based on the findings of this research, the following recommendations are forwarded:

- This study investigates the effect of the optimum waste tire powder on each of bitumen content. Therefore, further investigation is needed to determine optimum bitumen content for each replacement rate.
- From the investigations conducted, it will be greatly satisfactory to partially replace WTP up to 12% content with 6.0% crushed stone dust filler at a bitumen content of 5.0% in HMA. It is recommended that further research should be carried out to investigate the cost effectiveness of WTP for use as fillers in asphalt concrete mix.
- In this research ambient grinding method was used to process tire rubber into powder, further research needed to carry out by using cryogenic process.
- Further studies are recommended to use two or more different types of waste tire powder using 60/70 penetration grade bitumen.

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APPENDIXIES

Appendix A: - Physical Properties of Aggregates

Test Methods: BS 812, Part 110

A.1. Aggregate Crushing Value

Test No.	1	2
Size of aggregates ,mm	10-14	10-14
Maximum load applied ,KN.	400	400
Duration of testing ,mm.	10	10
Mass of aggregate before test, passing 14(12.5) mm and retained on 10(9.5) mm sieves, M1 (gm).	2674.6	2714.3
Mass of aggregate after test, passing 2.36 sieves, M_2 (gm).	448.2	498.3
Aggregate crushing Value, ACV(%) = $(M_2/M_1)*100$	16.76	18.36
Average ACV(%) = $(Test_1 + Test_2)/2$	**17.56**	

Test Methods: BS 812, Part 112

A.2. Aggregate Impact Value

S.No.	Details	Unit	Trial No.	
			1	2
1	Weight of cylindrical measure,(a)	gm	772.3	772.3
2	Weight of cylindrical measure plus aggregates sample,(b)	gm	1145.6	1136.5
3	Total weight of aggregates filling the cylindrical measure,(A)=a-b	gm	373.3	364.2
4	Weight of aggregates passing the 2.36 mm sieve after the test, (B)	gm	58.6	64.5
5	Weight of aggregate retained on 2.36mm sieve after the test, (C)	gm	314.7	299.7
6	Aggregate impact value (AIV) = B/A*100	%	15.70	17.71
Average Value (%)			**16.70**	

A.3. Los Angeles Abrasion Test

Test Method: AASHTO T96					
Sieve Size		Weight (gm)			
		A	B	C	D
Passing	Retained		………	………	………
37.5 mm	25.0 mm	1250±25	………	………	………
25 mm	19.0mm	1250±25	………	………	………
19 mm	12.5 mm	1250±10	**2500±10**	………	………
12.5 mm	9.5 mm	1250±10	**2500±10**	………	………
9.5 mm	6.3 mm	……...	………	2500±10	………
6.3 mm	4.75 mm	………	………	2500±10	………
4.75 mm	2.36 mm	………	………	………	5000±10
Total		5000±10	**5000±10**	5000±10	5000±10
No.of Revolution		500			
No. of Steel Balls		12	11	8	6

Sieve Size (mm)		Weight of Sample before test, (gm)	Weight of Retained on Sieve No.12 ,(gm)	Weight of passing Sieve No.12 ,(gm)	% Loss %
Passing	Retained				
37.5	25				
25	19				
19	12.5	2500.42			
12.5	9.5	2500.38			
9.5	6.3				
6.3	4.75				
4.75	2.36				
Total		**5000.80**	**4208**	**792.80**	**15.85**

A.4. Flakiness Index (BS 812, Part 105)

Sieves Nominal Apperture Size, (mm).	Mass of test portion, (gm).	Mass of agg. Passing on the flakiness gauge, (gm).	Flakiness index, (%)	Weighted average for flakiness index
13.2 - 19.0	1568.3	402.4	25.7	13.4
9.5 - 13.2	758.5	157.6	20.8	5.2
6.3 - 9.5	687	186.4	27.1	6.2
Total weight	3013.8	746.4		
Flakiness Index (%)	**24.8**			

A.5. Specific Gravity and Absorption of Course Aggregate, G-1 (13mm-25mm)

Test Method: AASHTO T 85-91				
Trial		1	2	Average
Description	Unit			
A. Mass of oven-dry sample in air	g	2516	2526.8	2521.4
B. Mass of SSD sample in air	g	2563.7	2574	2568.85
C. Mass of saturated sample in water	g	1605.3	1614.5	1609.9
Temperature	^{o}c	25	25	25
k		0.9989	0.9989	0.9989
Bulk Specific Gravity (Oven dry) SG_d = A*K/(B-C)		2.622	2.631	**2.624**
Bulk Specific Gravity (SSD) SG_{ssd} = B*K/(B-C)		2.672	2.680	**2.676**
Apparent Specific Gravity Sg = A*K/(A-C)		2.760	2.767	**2.763**
Water Absorption Aw = (B-A)*100/A	%	1.896	1.868	**1.882**

A.6. Specific Gravity and Absorption of Intermediate Aggregate, G-2 (6mm-13mm)

Test Method: AASHTO T 85-91				
Trial		1	2	Average
Description	Unit			
A. Mass of oven-dry sample in air	g	2385.9	2402.1	2394
B. Mass of SSD sample in air	g	2432	2447	2439.5
C. Mass of saturated sample in water	g	1519.6	1532.4	1526
Temperature	^{o}c	25	25	25
k	..	0.9989	0.9989	0.9989
Bulk Specific Gravity (Oven dry) SG_d = A*K/(B-C)		2.612	2.624	**2.615**
Bulk Specific Gravity (SSD) SG_{ssd} = B*K/(B-C)		2.663	2.673	**2.668**
Apparent Specific Gravity Sg = A*K/(A-C)		2.751	2.759	**2.755**
Water Absorption Aw = (B-A)*100/A	%	1.932	1.869	**1.901**

A.7. Specific Gravity and Absorption of Fine Aggregate, G-3 (3mm-6mm)

Test Method: AASHTO T 85-91				
Trial		1	2	Average
Description	Unit			
A. Mass of oven-dry sample in air	g	2174.1	2162.2	2168.15
B. Mass of SSD sample in air	g	2216	2206	2211
C. Mass of saturated sample in water	g	1386.6	1377.1	1381.85
Temperature	^{o}c	25	25	25
k	..	0.9989	0.9989	0.9989
Bulk Specific Gravity (Oven dry) SG_d = A*K/(B-C)		2.618	2.606	**2.612**
Bulk Specific Gravity (SSD) SG_{ssd} = B*K/(B-C)		2.669	2.658	**2.664**
Apparent Specific Gravity Sg = A*K/(A-C)		2.758	2.751	**2.754**
Water Absorption Aw = (B-A)*100/A		1.927	2.026	**1.976**

A.8. Specific Gravity and Absorption of Fine Aggregate, G-4 (0-3mm)

Trial		1	2	Average
Description	Unit			
A. Mass of oven-dry sample in air	g	474.5	474.8	474.65
B. Mass of SSD sample in air	g	485.1	485.6	485.35
C. Mass of Pycnometer +water	g	735	734	734.5
D. Mass of Pycnometer +water +sample	g	1038.2	1038.2	1038.2
Temperature	^{o}c	25	25	25
k	..	0.9989	0.9989	0.9989
Bulk Specific Gravity (Oven dry) SG_d = A*K/B-(D-C)		2.606	2.615	**2.610**
Bulk Specific Gravity (SSD) SG_{ssd} = B*K/B-(D-C)		2.664	2.674	**2.669**
Apparent Specific Gravity Sg = A*K/A-(D-C)		2.767	2.780	**2.774**

Appendix B: - Bitumen Quality Test

B.1. Penetration

Penetration	Test Method	Test No.	Test Temperature (°C)	Time of Test (Sec.)	Test load (g)	Reading Date (0.1mm)			Average (0.1mm)
						1st	2nd	3rd	
	ASTMD5	1	25	5	100	86.0	87.8	89.0	87.6
		2	25	5	100	88.8	89.9	87	88.6
		3	25	5	100	85.6	86	88.7	86.8
Average									**87.6**

B.2. Softening Point of Bitumen

Softening Point	Test Method	Test No.	Temp.when starting heating, (°C)	Record of liquid Temp in beaker			Softening point
				4min	5min	6min	
	ASTMD36	1	6		5min		48.87
		2	6		5min		48.22
Average :							**48.55**

B.3. Ductility Test Result of Bitumen

Ductility	Test Method	Test No.	Test Temperature(°C)	Speed (cm/min)	Ductility (cm)	Average (cm)
	ASTMD113	1	25	5	112	**109**
		2	25	5	109	
		3	25	5	106	

B.4. Test Record of Flash Point and Specific Gravity

No.	Test Description	Test Methods	Test Results
1	Flash Point	AASHTO T 48	298.40
2	Specific Gravity	AASHTO T 228	1.015

Appendix C: Properties of filler

C.1. Physical Properties of Crushed Stone Dust

`	Crushed Stone Dust		ASTMD242
Trial No.	1	2	
A. Mass of oven-dry sample in air, g	25	25	
B. Mass of Pycnometer +water, g	129.2	125.8	
C. Mass of Pycnometer +water +sample, g	145.1	141.5	
Apparent specific gravity @22^{o}c Sg=A*K/(A+B-C)	2.746	2.687	
Average	**2.717**		**-**
Plastic Index	**NP**		≤4

C.2. Physical Properties of Waste Tire Powder

Sieve No.	Unit	% Passing	% Passing	ASTM D242
		Crushed Stone dust	Waste Tire powder	
No. 30	%	100	100	100
No 50		100	97	95-100
No 200		100	75	70-100
Apparent specific gravity	Kg/m^3	2.717	1.18	N/A
PI,(Plastic Index)	-	NP	NP	≤4

C.3.Chemical Properties of Waste Tire Powder

	GEOLOGICAL SURVEY OF ETHIOPIA	Doc.Number: GLD/F5.10.2	Version No: 1
	GEOCHEMICAL LABORATORY DIRECTORATE		Page 1 of 1
Document Title:	Complete Silicate Analysis Report	Effective date:	May, 2017

Issue Date: -11/02/2021

Customer Name :-Asebew Alemaw

Request No:- GLD/RO/540/21

Report No:- GLD/RN/133/21

Sample type :- Crumb Rubber

Sample Preparation: - 200 Mesh

Date Submitted :-01/01/2021

Number of Sample:- One (01)

Analytical Result: In percent (%) Element to be determined Major Oxides & Minor Oxides

Analytical Method: $LiBO_2$ FUSION, HF attack, GRAVIMETERIC, COLORIMETRIC and AAS

Collector's Code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
Waste Tire Powder	32.76	12.23	9.84	3.0	<0.01	<0.01	<0.01	0.04	0.06	<0.01	0.6	40.54

Note: - This result represent only for the sample submitted to the laboratory.

Analysts	Checked By	Approved By	Quality Control
Lidet Endeshaw	Tizita Zerene	Yohannes Getachew	Gosa Haile
Nigist Fikadu			
Habtamu Alehegn			

Appendix D: Particle Size Distribution and Aggregate Blending Proportion

D.1. Particle Size Distribution of Coarse Aggregate, G-1 (13 mm-25 mm)

Dry Sample Weight (g)		3810.0	
After Wash Dry Sample (g)		3798.0	
Sieve Size(mm)	Mass of Retained Sample (g)	Cumulative Passing (g)	Cumulative Passing (%)
25	0.0	3810.0	100.0
19	1320.0	2490.0	65.4
12.5	1872.0	618.0	16.2
9.5	424.6	193.4	5.1
4.75	176.4	17.0	0.4
2.36	3.0	14.0	0.4
1.18	2.0	12.0	0.3
0.6		12.0	0.3
0.3		12.0	0.3
0.15		12.0	0.3
0.075		12.0	0.3
Pan	0.0		
Wash Lose	12.0		
Total	3810.0		

D.2. Particle Size Distribution of Intermediate Aggregate, G-2 (6 mm-13 mm)

Dry Sample Weight (g)		4120.0	
After Wash Dry Sample (g)		4106.0	
Sieve Size(mm)	Mass of Retained Sample (g)	Cumulative Passing (g)	Cumulative Passing (%)
25	0.0	4120.0	100.0
19	0.0	4120.0	100.0
12.5	70.0	4050.0	98.30
9.5	1264.3	2785.7	67.6
4.75	2132.7	653.0	15.8
2.36	530.0	123.0	3.0
1.18	80.0	43.0	1.0
0.6	23.0	20.0	0.5
0.3	6.0	14.0	0.3
0.15		14.0	0.3
0.075		14.0	0.3
Pan	0.0		
Wash Lose	14.0		
Total	4120.0		

D.3. Particle Size Distribution of Intermediate Aggregate, G-3 (3 mm-6 mm)

Dry Sample Weight (g)		3560.0	
After Wash Dry Sample (g)		3538.0	
Sieve Size(mm)	Mass of Retained Sample (g)	Cumulative Passing (g)	Cumulative Passing (%)
25	0.0	3560.0	100.0
19	0.0	3560.0	100.0
12.5	0.0	3560.0	100.0
9.5	58.0	3502.0	98.37
4.75	363.2	3138.8	88.17
2.36	2209.3	929.5	26.11
1.18	366.1	563.4	15.83
0.6	274.6	288.8	8.11
0.3	177.2	111.6	3.13
0.15	67.6	44.0	1.24
0.075	22	22.0	0.62
Pan			
Wash Lose	22.0		
Total	3560.0		

D.4. Particle Size Distribution of Fine Aggregate, G-4 (0-3 mm)

Dry Sample Weight (g)		1960.0	
After Wash Dry Sample (g)		1710.0	
Sieve Size(mm)	Mass of Retained Sample (g)	Cumulative Passing (g)	Cumulative Passing (%)
25	0.0	1960.0	100.0
19	0.0	1960.0	100.0
12.5	0.0	1960.0	100.0
9.5	0.0	1960.0	100.0
4.75	4.0	1956.0	99.80
2.36	10.5	1945.5	99.26
1.18	548.2	1397.3	71.29
0.6	393.5	1003.8	51.21
0.3	404.3	599.5	30.59
0.15	215.0	384.5	19.62
0.075	128.5	256.0	13.06
Pan	6	250.0	12.76
Wash Lose	250		
Total	1960		

D.5. Aggregate Gradation for 5.0% filler (crushed stone dust)

Aggregate gradation for filler 5.0% Crushed Stone Dust						
Sieve Size (mm)	Weight Retained, (gm)	Percent Retained, (%)	Percent pass, (%)	Combined asphalt aggregate specification limit		Median
				Lower limit	Upper limit	
25.0	0	0	100	100	100	100
19.0	91.4	7.62	92.38	90	100	95
12.50	136.0	11.33	81.05	71	88	79.5
9.50	144.8	12.07	68.98	56	80	68
4.75	224.0	18.67	50.32	35	65	50
2.36	168.4	14.03	36.28	23	49	36
1.18	126.0	10.50	25.78	15	37	26
0.600	89.0	7.42	18.37	10	28	19
0.300	85.0	7.08	11.28	5	19	12
0.150	45.5	3.79	7.49	4	13	8.5
0.075	29.9	2.49	5.00	2	8	5
Pan	60	5.00	0.00			
Total	1200	100				

D.6. Aggregate Gradation for 6.0% filler (crushed stone dust)

Aggregate gradation for filler 6.0 % Crushed Stone Dust						
Sieve Size(mm)	Weight Retained, (gm)	Percent Retained, (%)	Percent pass, (%)	Combined asphalt aggregate specification limit		Median
				Lower limit	Upper limit	
25.0	0	0	100	100	100	100
19.0	91.4	7.62	92.38	90	100	95
12.50	136	11.33	81.05	71	88	79.5
9.50	144.8	12.07	68.98	56	80	68
4.75	222	18.50	50.48	35	65	50
2.36	168.4	14.03	36.45	23	49	36
1.180	126	10.50	25.95	15	37	26
0.600	88	7.33	18.62	10	28	19
0.300	83	6.92	11.70	5	19	12
0.150	42.5	3.54	8.16	4	13	8.5
0.075	25.9	2.16	6.00	2	8	5
Pan	72	6.00	0.00			
Total	1200	100				

D.7. Aggregate Gradation for 7.0% filler (crushed stone dust)

Aggregate gradation for filler 7 % Crushed Stone Dust						
Sieve Size (mm)	Weight Retained (gm)	Percent Retained, (%)	Percent pass, (%)	Combined asphalt aggregate specification limit		Median
				Lower limit	Upper limit	
25.0	0	0	100	100	100	100
19.0	91.4	7.62	92.38	90	100	95
12.50	136	11.33	81.05	71	88	79.5
9.50	144.8	12.07	68.98	56	80	68
4.75	220	18.33	50.65	35	65	50
2.36	168.4	14.03	36.62	23	49	36
1.18	126	10.50	26.12	15	37	26
0.600	87	7.25	18.87	10	28	19
0.300	81	6.75	12.12	5	19	12
0.150	39.5	3.29	8.83	4	13	8.5
0.075	21.9	1.83	7.00	2	8	5
Pan	84	7.00	0.00			
Total	1200	100.00				

D.8. Percentage Passing and Blending proportion of Asphalt Mix for 5.0% CSD.

TYPE	Sieve										
	25	19	12.5	9.5	4.75	2.36	1.18	0.5	0.3	0.15	0.075
13-25mm	100.0	65.4	16.22	5.1	0.4	0.4	0.3	0.3	0.3	0.3	0.3
6-13mm	100.0	100.0	98.30	67.6	15.8	2.9	1.0	0.5	0.3	0.3	0.3
3-6mm	100.0	100.0	100.0	98.46	87.48	25.51	16.07	8.35	2.90	1.26	0.65
0-3mm	100.0	100.0	100.0	100	99.69	99.08	71.61	51.90	31.66	20.09	13.01
Filler	100.0	100	100	100	100	100	100	100	100	100	100

TYPE	Blending, (%)	Suggested percentages for binder course aggregate mix for 5 % filler content									
13-25mm	22.0	22.0	14.38	3.57	1.12	0.10	0.08	0.07	0.07	0.07	0.07	0.07
6-13mm	30.5	30.5	30.50	29.98	20.61	4.82	0.90	0.30	0.15	0.10	0.10	0.10
3-6mm	16.0	16.0	16.00	16.00	15.75	14.00	4.08	2.57	1.34	0.46	0.20	0.10
0-3mm	30.52	30.52	30.52	30.52	30.52	30.43	30.24	21.86	15.84	9.66	6.13	3.97
Filler	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Combined	100	100.0	92.38	81.05	68.98	50.32	36.28	25.78	18.37	11.28	7.49	5.0

D.9. Percentage Passing and Blending proportion of Asphalt Mix for 6.0% CSD.

TYPE		Sieve										
		25	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.5**	**0.3**	**0.15**	**0.075**
13-25mm		100	65.4	16.2	5.1	0.4	0.4	0.3	0.3	0.3	0.3	0.3
6-13mm		100	100.0	98.30	67.6	15.8	3.0	1.0	0.5	0.3	0.3	0.3
3-6mm		100	100.0	100.00	98.37	88.17	26.11	15.83	8.11	3.13	1.24	0.62
0-3mm		100	100.0	100.00	100	99.80	99.26	71.29	51.21	30.59	19.62	13.06
Filler		100	100	100	100	100	100	100	100	100	100	100
TYPE	**Blending, (%)**	**Suggested percentages for binder course aggregate mix for 6 % filler content**										
13-25mm	**22.0**	22.0	14.38	3.57	1.12	0.10	0.08	0.07	0.07	0.07	0.07	0.07
6-13mm	**30.50**	30.5	30.5	29.98	20.62	4.83	0.91	0.32	0.15	0.10	0.10	0.10
3-6mm	**16.0**	16.0	16.0	16.00	15.74	14.11	4.18	2.53	1.30	0.50	0.20	0.10
0-3mm	**29.50**	29.5	29.5	29.50	29.50	29.44	29.28	21.03	15.11	9.02	5.79	3.85
Filler	**2.0**	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Combined	**100**	**100.0**	**92.38**	**81.05**	**68.98**	**50.48**	**36.45**	**25.95**	**18.62**	**11.7**	**8.16**	**6.0**

D.10. Percentage Passing and Blending proportion of Asphalt Mix for 7.0% CSD.

TYPE		Sieve										
		25	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
13-25mm		100.0	65.4	16.2	5.1	0.4	0.4	0.3	0.3	0.3	0.3	0.3
6-13mm		100.0	100.0	98.30	67.6	15.8	2.9	1.0	0.5	0.3	0.3	0.3
3-6mm		100.0	100.0	100.00	98.46	89.35	27.59	15.16	7.16	2.63	1.16	0.54
0-3mm		100.0	100.0	100.00	100	99.80	99.05	71.80	51.76	31.14	20.59	13.11
Filler		100	100	100	100	100	100	100	100	100	100	100
TYPE	**Blending, (%)**	**Suggested percentages for binder course aggregate mix for 7 % filler content**										
13-25mm	**22**	22.00	14.38	3.57	1.12	0.10	0.08	0.07	0.07	0.07	0.07	0.07
6-13mm	**30.5**	30.50	30.50	29.98	20.61	4.82	0.90	0.30	0.15	0.10	0.10	0.10
3-6mm	**16**	16.00	16.00	16.00	15.75	14.30	4.41	2.43	1.15	0.42	0.19	0.09
0-3mm	**29**	29.00	29.00	29.00	29.00	28.94	28.72	20.82	15.01	9.03	5.97	3.80
Filler	**2.5**	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Combined	**100**	**100.00**	**92.38**	**81.05**	**68.98**	**50.65**	**36.62**	**26.12**	**18.87**	**12.12**	**8.83**	**7.0**

Appendix E: Theoretical Maximum Specific Gravity of Uncompacted of Asphalt Mix.

E.1. Theoretical maximum specific gravity of uncompacted asphalt mix with 5.0% crushed stone dust filler.

Test Method: ASTMD2041-90										
BC	4.0%		4.5%		5.0%		5.5%		6.0%	
Trial NO.	1	2	1	2	1	2	1	2	1	2
A	1246	1249.6	1251	1263.4	1252.2	1261.5	1256.1	1250.6	1267.2	1260.8
B	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320
C	3040.1	3059.5	3036.8	3058.3	3033.8	3057.3	3036.4	3049.8	3042.1	3055.4
Gmm	2.448	2.450	2.419	2.406	2.402	2.407	2.403	2.401	2.400	2.400
Average Gmm	**2.449**		**2.412**		**2.404**		**2.402**		**2.400**	

E.2. Theoretical maximum specific gravity of uncompacted asphalt mix with 6.0% crushed stone dust filler.

Test Method: ASTMD2041-90										
BC	4.0%		4.5%		5.0%		5.5%		6.0%	
Trial NO.	1	2	1	2	1	2	1	2	1	2
A	1271.0	1254.6	1273.8	1249.1	1252.5	1265.5	1253.4	1257	1266.2	1259.8
B	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320
C	3056.3	3067.5	3061.5	3051.8	3038.8	3063.7	3036.7	3053.8	3041.6	3055.4
Gmm	2.455	2.474	2.472	2.415	2.424	2.425	2.412	2.403	2.400	2.402
Average Gmm	**2.465**		**2.443**		**2.425**		**2.407**		**2.401**	

E.3. Theoretical maximum specific gravity of uncompacted asphalt mix with 7.0% crushed stone dust filler.

Test Method: ASTMD2041-90										
BC	4.0%		4.5%		5.0%		5.5%		6.0%	
Trial NO.	1	2	1	2	1	2	1	2	1	2
A	1270.1	1257	1254.6	1260.4	1258.2	1261.8	1251.1	1254.5	1264.8	1259
B	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320
C	3058.8	3069.7	3048.8	3066.5	3044.8	3067.6	3040.4	3054.6	3041	3055.2
Gmm	2.470	2.478	2.466	2.453	2.436	2.454	2.435	2.413	2.401	2.404
Average Gmm	**2.474**		**2.459**		**2.445**		**2.424**		**2.402**	

E.4. Theoretical maximum specific gravity of bituminous paving mixtures at 6.0% Crushed stone Dust and at 5.0% OBC

OBC	5.0%													
Filler Proportion	100% CSD and 0% WTP		97% CSD and 3% WTP		94% CSD and 6% WTP		91% CSD and 9% WTP		88% CSD and 12% WTP		85% CSD and 15% WTP		82% CSD and 18% WTP	
Trial No.	1	2	1	2	1	2	1	2	1	2	1	2	1	2
A	1250	1256	1256	1252	1254	1256	1252.4	1254.5	1256.5	1254.8	1250.6	1248.4	1246	1249.6
B	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320
C	3044	3057	3042	3053	3041	3056	3039.8	3054.9	3044.7	3053.7	3040	3051.8	3038	3053.5
Gmm	2.453	2.419	2.429	2.414	2.430	2.415	2.429	2.414	2.441	2.408	2.435	2.417	2.438	2.421
Average Gmm	**2.436**		**2.422**		**2.423**		**2.422**		**2.424**		**2.426**		**2.430**	

E.5. Theoretical maximum specific gravity of bituminous paving mixtures at 6.0% Crushed stone Dust and 12% WTP at bitumen content of4.0%, 4.5%, 5.5%, and 6.0%

OBC	**4.0%**		**4.5%**		**5.0%**		**5.5%**		**6.0%**	
Filler Proportion	88% CSD and 12% WTP		88% CSD and 12% WTP		88% CSD and 12% WTP		88% CSD and 12% WTP		88% CSD and 12% WTP	
Trial No.	1	2	1	2	1	2	1	2	1	2
A	1254.3	1257	1258.4	1253.6	1256.5	1254.8	1258.4	1252.5	1261.5	1253.8
B	2303	2320	2303	2320	2303	2320	2303	2320	2303	2320
C	3042.5	3055.8	3044	3053.8	3044.7	3053.7	3037.8	3055.9	3042.7	3051.7
Gmm	2.436	2.412	2.432	2.412	2.441	2.408	2.403	2.425	2.418	2.401
Average Gmm	**2.424**		**2.422**		**2.424**		**2.414**		**2.410**	

Appendix F: Marshal Mix Design Test Result

F.1. Marshall Mix Design Result for the Control Asphalt Mix with 5.0% Crushed Stone Dust.

MARSHALL PROPERTIES OF BITOMINIOUS MIXTURE ASTMD1559/AASHTO T 245				S.G OF AGGREGATE	
				Fraction of size,mm	Gsb
Tested By:	Asebew Almaw	Percent of Crushed Stone Dust Filled By Weight of Total Mix : 5.0%		a. (13-25mm)	2.624
Description:	Binder Course			b.(6-13mm)	2.615
Purpose	Final Thesis			c. (3-6mm)	2.612
Marshall compaction:	2*75 Blows			d. (0-3mm)	2.61
Grade of Asphalt:	80/100	S.G of Asphalt :	1.015	e. Filler	....
Bulk S.G of Aggregate	2.615			Combined (Gsb)	2.615

Asphalt Content, %	Specimen Height,(mm)	Max.SG of the Mix,[Gmm]	Mass of Specimen in [g]			Volume of Specimen [Cm^3]	Bulk SG of Compacted Mix	Air Void %	% V.M.A	% V.F.A	Stability			Flow (mm)
			Air Dry	Water	SSD						Load (KN)	Factor	Adjusted Load (KN)	
A	B	C	D	E	F	G	H	I	J	K				
						F - E	D/G	(C-H)*100/D	100-[(100-A)*H/Gsb]	(J-I)*100/J				
4.0	70		1227.5	691.7	1229.9	538.2	2.281	6.87	16.27	57.78	7.73	0.93	7.2	2.34
	71.5		1231.6	694.6	1234.3	539.7	2.282	6.82	16.22	57.97	7.64	0.93	7.1	2.15
	69.5		1222.8	688.1	1225.8	537.7	2.274	7.14	16.51	56.76	8.84	0.93	8.2	2.18
Average	70.3	2.449	1227.3	691.47	1230.0	538.53	2.279	6.94	16.34	57.50	8.07		7.5	2.22
4.5	69		1229.2	693.8	1231.2	537.4	2.287	5.17	16.47	63.50	9.42	0.93	8.8	2.21
	69.5		1238.4	703.5	1240.6	537.1	2.306	4.41	15.80	66.70	7.93	0.93	7.4	2.66
	69.3		1234.1	698.3	1236.1	537.8	2.295	4.86	16.20	65.10	10.34	0.93	9.6	3.12
Average	69.3	2.412	1233.9	698.5	1236.0	537.43	2.296	4.81	16.15	65.10	9.23		8.6	2.66
5.0	68		1240.8	707.7	1242.6	534.9	2.320	3.51	15.73	71.40	8.67	0.96	8.3	3.04
	67.5		1240.0	706.8	1241.7	534.9	2.318	3.57	15.78	73.10	10.45	0.96	10.0	2.93
	67		1237.4	703.4	1239.9	536.5	2.306	4.06	16.21	73.90	10.67	0.93	9.9	3.46
Average	67.5	2.404	1239.4	705.97	1241.4	535.43	2.315	3.71	15.91	72.80	9.93		9.4	3.14
5.5	69.0		1243.6	710.6	1245.5	534.9	2.325	3.21	15.98	79.92	9.64	0.96	9.3	3.36
	67.5		1246.9	713.4	1248.30	534.9	2.331	2.95	15.76	81.27	8.42	0.96	8.1	3.46
	68.5		1240.3	707.3	1242.8	535.5	2.316	3.57	16.30	78.07	10.14	0.96	9.7	4.04
Average	68.3	2.402	1243.6	710.4	1245.5	535.10	2.324	3.25	16.01	79.75	9.40		9.0	3.62
6.0	67.5		1245.9	712.8	1247.7	534.9	2.329	2.95	16.27	81.88	8.06	0.96	7.7	3.88
	67.5		1242.6	710.1	1245.6	535.5	2.320	3.31	16.59	80.02	7.76	0.96	7.4	4.26
	67		1247.8	716.6	1250.9	534.3	2.335	2.69	16.05	83.23	8.02	0.96	7.7	3.98
Average	67.3	2.400	1245.4	713.2	1248.1	534.9	2.328	2.99	16.30	81.71	7.95		7.6	4.04

F.2. Marshal Mix Design Result for the Control Asphalt Mix with 6.0% Crushed Stone Dust.

MARSHALL PROPERTIES OF BITOMINIOUS MIXTURE ASTMD1559/AASHTO T 245				S.G OF AGGREGATE	
				Fraction of size,mm	Gsb
Tested By:	Asebew Almaw	Percent of Crushed Stone Dust Filled By Weight of Total Mix : 6.0%		a. (13-25 mm)	2.624
Description:	Binder Course			b.(6-13 mm)	2.615
Purpose	Final Thesis			c. (3-6 mm)	2.612
Marshall compaction:	2*75 Blows			d. (0-3 mm)	2.610
Grade of Asphalt:	80/100	S.G of Asphalt :	1.015	e. Filler	..
Bulk S.G of Aggregate	2.615			Combined (Gsb)	2.615

Asphalt Content, %	Specimen Height,(mm)	Max.SG of the Mix,[Gmm]	Mass of Specimen in [g]			Volume of Specimen [cc]	Bulk SG of Compacted Mix	Air Void %	V.M.A %	V.F.A %	Stability			Flow (mm)
			Air Dry	Water	SSD						Load (KN)	Factor	Adjusted Load (KN)	
A	B	C	D	E	F	G	H	I	J	K				
						F-E	D/G	(C-H)*100/C	100-[(100-A)*H/Gsb]	(J-I)*100/J				
4.0	70		1226.2	689.1	1227.8	538.7	2.276	7.66	16.44	53.41	8.82	0.93	8.2	2.22
	68.5		1229.4	692.6	1231.4	538.8	2.282	7.43	16.23	54.20	8.12	0.93	7.6	1.98
	68.2		1237.6	703.5	1239.8	536.3	2.308	6.38	15.28	58.24	7.51	0.93	7.0	3.12
Average	68.9	2.465	1231.1	695.1	1233.0	537.93	2.29	7.16	15.98	55.28	8.15		7.6	2.44
4.5	71.2		1235.0	699.8	1238.1	538.3	2.294	6.09	16.21	62.45	8.96	0.93	8.3	3.12
	69.5		1240.8	706.6	1242.5	535.9	2.315	5.22	15.44	66.17	10.75	0.96	10.3	2.44
	69		1237.4	704.9	1238.6	533.7	2.319	5.09	15.33	66.76	9.52	0.96	9.1	2.84
Average	69.9	2.443	1237.73	703.77	1239.73	535.97	2.31	5.47	15.66	65.12	9.74		9.3	2.80
5.0	68.0		1246.9	713.7	1249.3	535.6	2.328	4.00	15.42	74.08	10.74	0.96	10.3	2.42
	68.5		1241.4	709.5	1242.8	533.3	2.328	4.01	15.43	74.02	11.58	0.96	10.8	3.53
	68.4		1244.7	712.8	1247.5	534.7	2.328	4.01	15.43	74.04	10.49	0.96	10.1	3.42
Average	68.3	2.425	1244.33	712.00	1246.5	534.5	2.33	4.00	15.43	74.05	10.94		10.4	3.12
5.5	66.5		1247.5	715.7	1248.3	532.6	2.342	2.69	15.36	82.49	10.83	0.96	10.4	4
	68.0		1243.9	710.8	1245.50	534.7	2.326	3.35	15.93	78.97	9.78	0.96	9.4	3.44
	67.6		1245.4	714.8	1247.6	532.8	2.337	2.89	15.53	81.40	8.97	0.96	8.6	2.98
Average	67.4	2.407	1245.6	713.8	1247.1	533.37	2.335	2.98	15.61	80.95	9.86		9.5	3.5
6.0	67.5		1252.5	718.9	1254.8	535.9	2.337	2.66	15.99	83.38	9.02	0.96	8.4	3.41
	67.5		1248.9	717.4	1251.6	534.2	2.338	2.63	15.96	83.53	7.45	0.936	7.0	4.34
	67		1250.5	718.2	1252.8	534.6	2.339	2.58	15.92	83.81	8.01	0.96	7.7	3.62
Average	67.3	2.401	1250.6	718.2	1253.1	534.9	2.338	2.62	15.95	83.57	8.16		7.7	3.79

F.3. Marshal Mix Design Result for the Control Asphalt Mix with 7.0% Crushed Stone Dust.

MARSHALL PROPERTIES OF BITOMINIOUS MIXTURE ASTMD1559/AASHTO T 245				S.G OF AGGREGATE	
				Fraction of size,mm	Gsb
Tested By:	Asebew Almaw	Percent of Crushed Stone Dust Filled By Weight of Total Mix : 7.0%		a. (13-25mm)	2.624
Description:	Binder Course			b.(6-13mm)	2.615
Purpose	Final Thesis			c. (3-6mm)	2.612
Marshall compaction:	2*75 Blows			d. (0-3mm)	2.610
Grade of Asphalt:	80/100	S.G of Asphalt :	1.015	e. Filler	..
Bulk S.G of Aggregate	2.615			Combined (Gsb)	2.615

Asphalt Content, %	Specimen Height,(mm)	Max.SG of the Mix,[Gmm]	Mass of Specimen in [g]			Volume of Specimen [cc]	Bulk SG of Compacted Mix	Air Void %	V.M.A %	V.F.A %	Stability			Flow (mm)
			Air Dry	Water	SSD						Load (KN)	Factor	Adjusted Load (KN)	
A	B	C.D	DE	EF	FG	GH	HI	IJ	JK	KL				
						F-E	D/G	(C-H)*100/C	100-[(100-A)*H/Gsb]	(J-I)*100/J				
4.0	71		1237.2	702.3	1239.8	537.5	2.30	6.96	15.50	55.08	7.96	0.93	7.4	2.16
	68.5		1234.8	696.8	1238.2	541.4	2.28	7.81	16.27	51.99	8.13	0.93	7.6	2.52
	69		1240.3	706.4	1243.8	537.4	2.31	6.71	15.27	56.05	7.87	0.93	7.3	2.24
Average	69.5	2.474	1237.43	701.8	1240.60	538.8	2.297	7.16	15.68	54.38	7.99		7.4	2.31
4.5	68.5		1243.1	709.2	1246.8	537.6	2.312	5.97	15.55	61.65	9.62	0.93	8.9	2.77
	69.0		1245.4	712.5	1248.5	536	2.324	5.51	15.15	63.62	10.27	0.93	9.6	2.58
	69.5		1246.3	713.4	1250.7	537.3	2.320	5.67	15.29	62.91	9.32	0.93	8.7	2.81
Average		2.459	1244.93	711.7	1248.7	537.0	2.318	5.72	15.33	62.73	9.74		9.1	2.72
5.0	69		1242.1	710.9	1244.3	533.4	2.33	4.76	15.40	69.10	10.65	0.96	10.2	2.95
	68		1245.3	713.5	1247.5	534	2.33	4.62	15.28	69.76	9.67	0.96	9.3	3.34
	68.5		1248.0	716.6	1251.2	534.6	2.33	4.52	15.19	70.24	10.42	0.96	10.0	3.16
Average	68.5	2.445	1245.1	713.7	1247.7	534.00	2.332	4.63	15.29	69.70	10.25		9.8	3.15
5.5	68		1256.0	719.8	1258.3	538.5	2.33	3.78	15.71	75.95	10.46	0.93	9.7	3.13
	68		1254.2	719.2	1255.5	536.3	2.34	3.52	15.49	77.26	10	0.93	9.3	4.04
	68		1250.4	718.6	1252.2	533.6	2.34	3.33	15.32	78.27	10.86	0.96	10.4	3.61
Average	68	2.424	1253.5	719.2	1255.3	536.1	2.338	3.54	15.51	77.15	10.44		9.8	3.59
6.0	67		1256.2	720.7	1257.7	537	2.34	2.61	15.91	83.59	9	0.93	8.4	3.88
	69		1249.6	718.9	1251.4	532.5	2.35	2.30	15.65	85.28	9.94	0.96	9.5	4.16
	68.2		1257.8	722.6	1260.2	537.6	2.34	2.60	15.90	83.67	9.64	0.93	9.0	4.25
Average	68.1	2.402	1254.5	720.7	1256.4	535.7	2.3419	2.50	15.82	84.18	9.53		9.0	4.10

F.4. Marshal Mix Design Result With Waste Tire Powder and 6.0% Crushed Stone Dust (OFC) at 5.0% Bitumen Content (OBC).

`MARSHALL PROPERTIES OF BITOMINIOUS MIXTURE ASTMD1559/AASHTO T 245				S.G OF AGGREGATE		
				Fraction of size,m	Proportion,%	Gsb
Tested By:	Asebew Almaw	Combination of Waste Tire Powder and Crushed Stone Dust By Weight of Total Mix : 6.0%		a. (13-25mm)	22	2.624
Description:	Binder Course			b.(6-13mm)	30.5	2.615
Purpose	Final Thesis			c. (3-6mm)	16	2.612
Marshall compaction:	2*75 Blows			d. (0-3mm)	29.5	2.610
Grade of Asphalt:	80/100	S.G of Bitumen:	1.015	e. Filler	2	..
Bulk S.G of Aggregate	2.615			Combined, (Gsb)	100	2.615

Asphalt Content, %	Specimen Height, (mm)	Mineral Filler Type		Max.SG of the Mix, [Gmm]	Mass of Specimen in [g]			Volume of Specimen [cc]	Bulk SG of Compacted Mix	Air Void %	% V.M.A	% V.F.A	Stability			Flow (mm)	Marshal Quotient (Stability/Flow), (KN/MM)
					Air Dry	Water	SSD	G	H	I	J	K	Load (KN)	Factor	Adjusted Load (KN)		
A	B	Percent of Crushed Stone Dust	Percent of Waste Tire	C	D	E	F	F-E	D/G	(C-H)*100/D	100-[(100-A)*H/Gsb]	(J-I)*100/J					
5.0	68.5	100.0%	0%		1242.5	711.7	1245.5	533.8	2.328	4.45	15.44	71.19	10.48	0.96	10.1	3.16	3.18
	70.0	100.0%	0%		1245.7	713.5	1247.2	533.7	2.334	4.18	15.21	72.48	11.17	0.96	10.7	2.98	3.60
	68.0	100.0%	0%		1241.5	710.8	1243.6	532.8	2.330	4.35	15.35	71.69	10.71	0.96	10.3	3.55	2.90
Average	**68.8**			**2.436**	**1243.2**	**712.00**	**1245.4**	**533.43**	**2.331**	**4.33**	**15.33**	**71.79**	**10.79**		**10.36**	**3.23**	**3.21**
5.0	68.5	97%	3%		1242.1	712.6	1248.5	535.9	2.318	4.30	15.80	72.76	11.14	0.96	10.7	2.84	3.77
	69.0	97%	3%		1239.4	709.4	1244.9	535.5	2.314	4.44	15.92	72.11	10.86	0.96	10.4	2.72	3.83
	67.0	97%	3%		1237.6	707.9	1240.7	532.8	2.323	4.09	15.61	73.78	10.51	0.96	10.1	3.26	3.09
Average	**68.2**			**2.422**	**1239.7**	**710.0**	**1244.7**	**534.73**	**2.318**	**4.3**	**15.78**	**72.88**	**10.84**		**10.40**	**2.94**	**3.54**
5.0	69.0	94%	6%		1240.5	711.8	1246.2	534.4	2.321	4.20	15.67	73.21	10.64	0.96	10.2	2.65	3.85
	68.5	94%	6%		1238.9	709.6	1243.5	533.9	2.320	4.23	15.70	73.05	11.27	0.96	10.8	2.72	3.98
	70.0	94%	6%		1243.7	713.3	1248.7	535.4	2.323	4.130	15.61	73.54	10.74	0.96	10.3	3.16	3.26
Average	**69.2**			**2.423**	**1241.0**	**711.57**	**1246.1**	**534.57**	**2.322**	**4.2**	**15.66**	**73.27**	**10.88**		**10.45**	**2.84**	**3.67**
5.0	67.5	91%	9%		1238.5	710.9	1242.9	532.0	2.328	3.92	15.43	74.59	10.62	0.96	10.2	2.83	3.60
	69.0	91%	9%		1242.1	712.6	1246.5	533.9	2.326	3.98	15.48	74.27	11.18	0.96	10.7	2.71	3.96
	68.5	91%	9%		1240.3	709.3	1244.7	535.4	2.317	4.39	15.84	72.28	10.96	0.96	10.5	3.16	3.33
Average	**68.3**			**2.423**	**1240.3**	**710.9**	**1244.7**	**533.77**	**2.324**	**4.1**	**15.58**	**73.71**	**10.92**		**10.48**	**2.90**	**3.61**
5.0	67.5	88%	12%		1240.4	711.9	1245.3	533.4	2.325	4.07	15.52	73.80	10.89	0.96	10.5	3.38	3.09
	68.0	88%	12%		1241.7	713.1	1246.1	533	2.330	3.89	15.37	74.20	10.96	0.96	10.5	2.64	3.99
	68.0	88%	12%		1244.1	714.6	1249.5	534.9	2.326	4.05	15.50	73.89	11.06	0.96	10.62	2.89	3.67
Average	**67.8**			**2.424**	**1242.1**	**713.2**	**1247.0**	**533.77**	**2.327**	**4.00**	**15.46**	**73.96**	**10.97**		**10.53**	**2.97**	**3.55**
5.0	66.5	85%	15%		1240.3	711.7	1244.70	533.00	2.327	4.08	15.46	73.61	10.18	0.96	9.8	3.08	3.17
	67.5	85%	15%		1238.5	708.8	1243.20	534.40	2.318	4.47	15.81	71.72	10.95	0.96	10.5	3.15	3.34
	68.0	85%	15%		1240.7	712.1	1245.30	533.20	2.327	4.09	15.47	73.59	10.78	0.96	10.3	2.94	3.52
Average	**67.3**			**2.426**	**1239.8**	**710.9**	**1244.4**	**533.53**	**2.324**	**4.21**	**15.58**	**72.97**	**10.64**	**0.96**	**10.21**	**3.06**	**3.34**
5.0	69.50	82%	18%		1244.1	713.2	1248.90	535.7	2.322	4.43	15.63	71.67	10.06	0.96	9.7	3.23	2.99
	67.00	82%	18%		1239.6	708.5	1242.50	534.00	2.321	4.47	15.67	71.46	9.95	0.96	9.6	3.13	3.05
	69.00	82%	18%		1241.6	712.3	1246.80	534.50	2.323	4.41	15.61	71.77	10.18	0.96	9.8	3.00	3.26
Average	**68.5**			**2.430**	**1241.8**	**711.3**	**1246.1**	**534.7**	**2.322**	**4.44**	**15.64**	**71.63**	**10.06**		**9.66**	**3.12**	**3.10**

F.5. Marshal Mix Design Result With 12% Waste Tire Powder, and 6.0% Crushed Stone Dust (OFC) at Bitumen Content of two above and below the optimum.

MARSHALL PROPERTIES OF BITOMINIOUS MIXTURE ASTMD1559/AASHTO T 245				S.G OF AGGREGATE		
				Fraction of size,mm	Proportio	Gsb
Tested By:	Asebew Almaw	Combination of Waste Tire Powder and Crushed Stone Dust By Weight of Total Mix : 6.0%		a. (13-25mm)	22	2.624
Description:	Binder Course			b.(6-13mm)	30.5	2.615
Purpose	Final Thesis			c. (3-6mm)	16	2.612
Marshall compaction:	2*75 Blows			d. (0-3mm)	29.5	2.610
Grade of Asphalt:	80/100	S.G of Bitumen:	1.015	e. Filler	2	..
Bulk S.G of Aggregate	2.615			Combined, (Gsb)	100	2.615

Asphalt Content, %	Specimen Height, (mm)	Mineral Filler Type		Max.SG of the Mix, [Gmm]	Mass of Specimen in [g]			Volume of Specimen [cc]	Bulk SG of Compacted Mix	Air Void %	% V.M.A	% V.F.A	Stability			Flow (mm)
					Air Dry	Water	SSD						Load (KN)	Factor	Adjusted Load (KN)	
		Percent of Crushed Stone	Percent of Waste Tire					G	H	I	J	K				
A	B			C	D	E	F	F-E	D/G	(C-H)*100/C	100-[(100-A)*H/Gsb]	(J-I)*100/J				
4.0	68.0	88%	12%		1232.5	698.7	1237.7	539.0	2.287	5.67	16.05	64.70	8.14	0.93	7.9	2.22
	69.5	88%	12%		1234.2	700.2	1239.9	539.7	2.287	5.66	16.05	64.74	8.27	0.93	8.3	1.92
	67.0	88%	12%		1230.8	696.8	1236.7	539.9	2.280	5.95	16.31	63.50	7.84	0.93	7.3	2.08
Average	**68.2**			**2.424**	**1232.5**	**698.57**	**1238.1**	**539.53**	**2.284**	**5.76**	**16.14**	**64.31**	**8.08**		**7.84**	**2.07**
4.5	67.5	88%	12%		1240.1	708.6	1245.2	536.6	2.311	4.58	15.60	70.63	8.86	0.93	8.51	2.54
	68.0	88%	12%		1236.0	703.1	1239.3	536.2	2.305	4.83	15.82	69.49	9.98	0.93	9.58	2.34
	67.0	88%	12%		1238.6	705.8	1243.5	537.7	2.304	4.89	15.88	69.18	10.78	0.93	10.0	2.74
Average	**67.5**			**2.422**	**1238.2**	**705.8**	**1242.7**	**536.83**	**2.307**	**4.77**	**15.76**	**69.77**	**9.87**		**9.37**	**2.54**
5.0	67.5	88%	12%		1240.4	711.9	1245.3	533.4	2.325	4.07	15.52	73.80	10.89	0.96	10.5	3.38
	68.0	88%	12%		1241.7	713.1	1246.1	533	2.330	3.89	15.37	74.20	10.96	0.96	10.5	2.64
	68.0	88%	12%		1244.1	714.6	1249.5	534.9	2.326	4.05	15.50	73.89	11.05	0.96	10.61	2.89
Average	**67.8**			**2.424**	**1242.1**	**713.2**	**1247.0**	**533.77**	**2.327**	**4.00**	**15.46**	**73.96**	**10.97**		**10.53**	**2.97**
5.5	67.5	88%	12%		1244.3	715.4	1246.9	531.5	2.341	3.58	15.40	76.76	9.57	0.96	9.2	3.14
	68.0	88%	12%		1242.4	714.2	1247.8	533.6	2.328	4.10	15.86	74.12	8.68	0.96	8.3	2.87
	69.5	88%	12%		1246.2	716.9	1252.4	535.5	2.327	4.15	15.90	73.88	8.96	0.96	8.6	3.28
Average	**68.3**			**2.428**	**1244.3**	**715.5**	**1249.0**	**533.53**	**2.332**	**3.95**	**15.72**	**74.92**	**9.07**		**8.71**	**3.10**
6.0	68.5	88%	12%		1248.3	717.1	1250.7	533.6	2.339	2.93	15.91	81.58	7.16	0.96	6.9	3.58
	70.0	88%	12%		1250.7	718.8	1252.0	533.2	2.346	2.67	15.68	74.20	7.21	0.96	6.9	3.17
	68.0	88%	12%		1247.5	716.6	1249.5	532.9	2.341	2.86	15.85	81.93	6.94	0.96	6.66	3.37
Average	**68.8**			**2.410**	**1248.8**	**717.5**	**1250.7**	**533.23**	**2.342**	**2.82**	**15.81**	**79.24**	**7.10**		**6.82**	**3.37**

Appendix G: Moisture Susceptibility of Asphalt Mixes

G.1. Moisture Susceptibility for Dry Sample

Test Method: ASTMD4867

Dry Sample											
Mix (%)	OBC	Sample No.	Gmm	Thickness (mm)	Mass of Specimen in [g]			Volume of Specimen [Cm^3]	Gmb	Air Void (%)	Indirect Tensile Strength (KPa)
					Air Dry	Water	SSD	E	F	Pa	
			A	t	B	C	D	D-C	B/E	(A-F)*100/A	ITS
0.0	5.0	A	2.452	68.0	1239.3	701.8	1245.8	544	2.278	6.9	854.6
		B		69.0	1241.6	703.2	1247.0	543.8	2.283	6.7	877.6
		C		67.5	1237.9	697.1	1243.3	546.2	2.266	7.3	836.5
Average				**68.2**	**1239.6**	**700.7**	**1245.4**	**544.7**	**2.276**	**7.0**	**856.2**
3.0	5.0	A	2.446	67.0	1240.5	700.7	1246.6	545.9	2.272	6.9	874.3
		B		68.5	1242.3	702.4	1249.7	547.3	2.270	7.0	899.1
		C		69.0	1244.8	704.6	1250.5	545.9	2.280	6.6	858.5
Average				**68.2**	**1242.5**	**702.6**	**1248.9**	**546.4**	**2.274**	**6.9**	**877.3**
6.0	5.0	A	2.438	69.0	1241.3	700.4	1248.6	548.2	2.264	7.1	867.7
		B		68.0	1245.6	702.5	1249.2	546.7	2.278	6.5	914.1
		C		69.5	1248.6	705.1	1254.6	549.5	2.272	6.8	894.6
Average				**68.8**	**1245.2**	**702.7**	**1250.8**	**548.1**	**2.272**	**6.8**	**892.1**
9.0	5.0	A	2.441	68.5	1242.6	700.5	1249.4	548.9	2.264	7.3	892.6
		B		67.5	1238.8	697.6	1244.7	547.1	2.264	7.2	932.3
		C		70.0	1244.2	703.2	1250.5	547.3	2.273	6.9	910.5
Average				**68.7**	**1241.9**	**700.4**	**1248.2**	**547.8**	**2.267**	**7.1**	**911.8**
12.0	5.0	A	2.443	67.5	1239.5	701.1	1245.5	544.4	2.277	6.8	908.4
		B		68.5	1241.7	702	1248.8	546.8	2.271	7.0	938.8
		C		67.0	1237.4	699.3	1243.4	544.1	2.274	6.9	954.4
Average				**67.7**	**1239.5**	**700.8**	**1245.9**	**545.1**	**2.274**	**6.9**	**933.9**

G.2. Moisture Susceptibility for Wet Sample

Test Method: ASTMD4867

Wet Sample															
Mix (%)	OBC (%)	Sample No.	Gmm	Thickness (mm)	Mass of Specimen in [g] Air Dry	Water	SSD	Volume of Specimen $[Cm^3]$	Gmb	Air Void (%)	volume of air voids	SSD Mass,(g)	Vol. of absorbed water, cm^3	Saturation (%)	Tensile Strength (Kpa)
			A	t	B	C	D	E D-C	F B/E	Pa (A-F)*100/A	Va Pa*E/100	D'	J' D'-B	S' 100*J'/Va	ITS
0.0	5.0	A	2.446	67.5	1240.3	701.5	1248.3	546.8	2.268	7.3	39.7	1267.3	27.0	67.91	658.0
		B		68.5	1242.6	704.1	1249.6	545.5	2.278	6.9	37.5	1265.6	23.0	61.35	674.6
		C		67.0	1239.8	697.7	1245.4	547.7	2.264	7.5	40.8	1269.7	29.9	73.23	649.4
Average				**67.7**	**1240.9**	**701.1**	**1247.8**	**546.7**	**2.270**	**7.2**	**39.3**	**1267.5**	**26.6**	**67.5**	**660.7**
3.0	5.0	A	2.442	68.5	1243.6	702.6	1248.6	546	2.278	6.7	36.7	1270.1	26.5	72.12	684.5
		B		69.0	1245.8	705.1	1251.7	546.6	2.279	6.7	36.4	1274.3	28.5	78.20	722.1
		C		67.5	1240.1	700.3	1247.5	547.2	2.266	7.2	39.4	1268.8	28.7	72.88	705.2
Average				**68.3**	**1243.2**	**702.7**	**1249.3**	**546.6**	**2.274**	**6.9**	**37.5**	**1271.1**	**27.9**	**74.4**	**703.9**
6.0	5.0	A	2.438	67.5	1240.3	701.4	1247.6	546.2	2.271	6.9	37.5	1264.7	24.4	65.1	737.5
		B		68.0	1242.6	704.1	1249.9	545.8	2.277	6.6	36.1	1268.6	26.0	72.0	701.6
		C		69.0	1245.6	706.1	1252.6	546.5	2.279	6.5	35.6	1267.4	21.8	61.3	761.0
Average				**68.2**	**1242.8**	**703.9**	**1250**	**546.2**	**2.276**	**6.7**	**36.4**	**1266.9**	**24.1**	**66.1**	**733.4**
9.0	5.0	A	2.441	68.5	1244.9	703.5	1251.6	548.1	2.271	7.0	38.1	1269.5	24.6	64.6	777.6
		B		68.0	1239.7	698.6	1245.3	546.7	2.268	7.1	38.8	1266.3	26.6	68.5	804.5
		C		69.5	1247.8	705.2	1254.5	549.3	2.272	6.9	38.1	1272.8	25.0	65.6	750.5
Average				**68.7**	**1244.1**	**702.4**	**1250.5**	**548.0**	**2.270**	**7.0**	**38.4**	**1269.5**	**25.4**	**66.2**	**777.5**
12.0	5.0	A	2.443	67.0	1238.9	697.4	1245.4	548	2.261	7.5	40.9	1267.5	28.6	70.0	784.6
		B		68.0	1242.2	703.1	1249.5	546.4	2.273	6.9	37.9	1269.3	27.1	71.5	818.5
		C		67.5	1239.8	698.7	1245.0	546.3	2.269	7.1	38.8	1266.8	27.0	69.6	824.2
Average				**67.5**	**1240.3**	**699.7**	**1246.6**	**546.9**	**2.268**	**7.2**	**39.2**	**1267.9**	**27.6**	**70.3**	**809.1**

Appendix H: Stability Correlation Ratios

Volume of Specimen cm^3	Approximate Thickness of Specimen		Correlation Ratio
	mm	in.	
302 to 316	38.1	1 1/2	2.78
317 to 328	39.7	1 9/16	2.50
329 to 340	41.3	1 5/8	2.27
341 to 353	42.9	1 11/16	2.08
354 to 367	44.4	1 3/4	1.92
368 to 379	46.0	1 13/16	1.79
380 to 392	47.6	1 7/8	1.67
393 to 405	49.2	1 15/16	1.56
406 to 420	50.8	2	1.47
421 to 431	52.4	2 1/6	1.39
432 to 443	54.0	2 1/8	1.32
444 to 456	55.6	2 3/16	1.25
457 to 470	57.2	2 1/4	1.19
471 to 482	58.7	2 5/16	1.14
483 to 495	60.3	2 3/8	1.09
496 to 508	61.9	2 7/16	1.04
509 to 522	63.5	2 1/2	1.00
523 to 535	65.1	2 9/16	0.96
536 to 546	66.7	2 5/8	0.93
547 to 559	68.3	2 11/16	0.89
560 to 573	69.8	2 3/4	0.86
574 to 585	71.4	2 13/16	0.83
586 to 598	73.0	2 7/8	0.81
599 to 610	74.6	2 15/16	0.78
611 to 625	76.2	3	0.76

Source: Asphalt Institute Manual Series No.2 (Ms-2), Sixth Edition.

Appendix I: Photo during Laboratory Work

Source: Bilisumma Lemi

Softening Point of Bitumen

Source: Bilisumma Lemi

Penetration of Bitumen

Source: Bilisumma Lemi

Flash Point

Source: Bilisumma Lemi

Washing of Aggregate

Source: Bilisumma Lemi

Specimen on oven in separate dish

Source: Bilisumma Lemi

weighting of material using proposed gradation

Source: Bilisumma Lemi

Filter Paper Preparation

Source: Bilisumma Lemi

Placing Bitumen on Heater

Source: Asebew Almaw

Sample Compacted Specimen

Source: Dejene Dereje

Placing Hammer on Compaction Machine

Source: Muluken Geremew

Recording Weight of Specimen (SSD)

Source: Bilisumma Lemi

Marshall Stability Machine

Source: Dejene Dereje

Specimen for Indirect Tensile Strength test

Source: Bilisumma Lemi

Waste Tire Powder

Date: 22/10/2020 G.C

Date: 23/10/2020 G.C

Source: Bilisumma Lemi

Theoretical maximum specific gravity of Un-compacted Specimen (Gmm)

Date: 14/09/2020 G.C

Pictured by Asebew Almaw

Oven-dried aggregate on separate containers

Date: 15/09/2020 G.C

Pictured by Asebew Almaw

weighted specimen on oven