Addis Ababa University
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Experimental Investigation of the Engineering Properties of Railway Bituminous Blanket Modified with Waste Steel Slag

By

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DECLARATION AND APPROVAL

I, **Mugula Julius**, do declare that this thesis is my own work except where due acknowledgement is made in the text and that it has never, to the best of my knowledge, been submitted for any prior academic award or qualification.

Signed: Date: 24th July 2020

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This Thesis is hereby submitted with the approval of my Advisor and Examiners;

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DEDICATION

To God, the enabler of all undertakings, this study being not an exception, I ascribe my thanks to You most.

To my dear mother, **Nagawa Cissy**: All that I am or ever hope to be, I owe to you.

To my family, you gave me all the moral support and encouragement needed to see this study through.

Thank you all.

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ABSTRACT

Increasing the axle load and speed on existing railway lines is one of the railway industry's approach that has been taken to improve the rail transport system. In this regard, improvement in stability of railway embankments, in terms of blanket layer inclusion, as an important part of each railway infrastructure is necessary more than ever. This study investigated the feasibility of using waste steel slag in enhancing the performance of bituminous railroad blanket layers. Waste steel slag is extensively and continuously being produced as waste from many industrial processes during the manufacture of steel products. According to Mame Steel Factory, a renown, steel processing plant in Addis Ababa, on average, about 7,000-8,000 tons of steel slag is produced as waste annually by a single steel factory in Ethiopia. However, it is left piled on sites of manufacture and later deposited in landfills.

Well-graded natural basalt rock aggregate was blended with well-graded proportions of 25%, 50%, and 75% of waste steel slag aggregate by dry weight, adopted from previous studies. Control samples of purely natural rock aggregates and purely waste steel slag were also prepared. Marshall Mix design analysis (ASTM D1559), Indirect Tensile Strength and Moisture Susceptibility (AASHTO T283) were used to evaluate the laboratory performance of modified blanket layer mixtures.

The minimum Marshall Stability value for modified asphalt mixtures was 34.4% above the 8000N recommended for heavy traffic load category by AREMA specifications for concrete structures and foundations (2010). Modified mixtures of 25%, 50% and 75% Waste Steel Slag Aggregate yielded higher unconditioned Indirect Tensile Strength than the unmodified mixes. Voids in Total Mix values obtained for all modified and unmodified mixtures were within AREMA (2010) requirement of 3%-5%. On average, the Tensile Strength Ratio values of both modified and unmodified mixtures were greater than the minimum 75% recommended by AREMA (2010) specifications for good performance with 25% WSSA modified mixture emerging with the highest Tensile Strength Ratio value. Although up to 100% replacement of the basalt aggregate by Waste Steel Slag Aggregate is effective, the optimal replacement percentage is 25%. Therefore, it is possible to utilize waste steel slag to enhance the performance of bituminous railroad blankets.

Key Words: Aggregate, Bitumen, Blanket, Waste Steel Slag, Marshall mix design.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highways and Transportation Officials
ACQ	Acceptance Quality Characteristics
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
AREMA	American Railway Engineering and Maintenance-of-way Association
ASTM	American Society for Testing and Materials
BS	British Standards
CKE	Centrifuge Kerosene Equivalent
DGM	Dense Graded Mixes
EAF	Electric Arc Furnace
ERC	Ethiopia Railways Corporation
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
LAAV	Los Angeles Abrasion Value
MEPLDG	Mechanistic-Empirical Pavement Layer Design Guide
NCHRP	National Cooperative Highway Research Program
NOC	National Oil Corporation
NSA	National Slag Association
OBC	Optimum Bitumen Contents
PMB	Polymer Modified Bitumen
SBS	Styrene-Butadiene-Styrene
SMA	Stone Mastic Asphalt
TFV	Ten Percent Fines Value
TRB	Transportation Research Board
TSR	Tensile Strength Ratio
VFB	Voids Filled with Binder
VMA	Voids in Mineral Aggregate
VTM	Voids in Total Mix
WSSA	Waste Steel Slag Aggregates

CHAPTER ONE: INTRODUCTION

1.1 Background

Railways are a vital and effective means of mass conveyance. They have played a key role in modern transportation and social development. This is because railway transportation has a high capacity, high efficiency, and low pollution compared to other transportation modes. Today, railways are experiencing higher demands, which will, in turn, impose greater demands on railway track performability, [32]. Among the criteria for a good railway transportation system is having high-quality track formation. To achieve this, substantial quantities of natural rock aggregates are being utilized annually for the construction of railway embankments. The demand for large volumes of natural aggregates poses numerous environmental problems and is partially responsible for the sharp increase in project costs because of scarcity of such aggregates. Therefore, to meet the great demand for aggregates, many mountains or hills and rivers have been exhaustingly exploited, which has resulted in environmental pollution and eventual destruction of the environment.

Reuse of waste steel slag as an aggregate in bituminous mixtures has been used for many years in many countries [6], [69], [72]. The inherent physical properties of waste steel slag produce hot mix asphalt (HMA) with high stability and good stripping resistance (moisture damage resistance) [27]. Moisture damage in hot mix asphalt layers is a serious problem especially in zones of high precipitation. Many developing countries are spending large sums of donor funds on railway construction materials, yet the return on investment is overwhelmed by short service lives due to moisture damage.

Despite the fact that over the years an increase in traffic and speeds have placed a greater structural demand on conventional track constructed initially to cater for much lighter traffic, gradual improvement to track support system has remained confined to track superstructure, that is, rails, sleepers, fastening system and so on. The substructure below sleeper level remained practically unchanged. Many methods were exploited in the past to rehabilitate the weak formation. Among these, the provision of the blanket is the most effective technique of formation rehabilitation and formation strengthening; however, it comes with unfavorable financial aspects. These can be overcome by the provision of a cheaper blanket achieved by replacement of the costly crushed natural aggregates by cheap and freely available waste steel slag.

The use of waste steel slag can alleviate environmental pollution by reducing the accumulation of waste materials, which invariably will also reduce construction costs. Electric arc furnace (EAF) steel slag is among the more common waste materials used in construction, [56], [68], [77], [78]. The use of steel slag has tremendously contributed to green technology as its use has preserved the natural ecosystem through a reduction in the amount of dumped wastes and consumption of conventional aggregates in asphalt mix production, [38], [49], [56]. Need therefore arises to determine aggregate blends to substitute conventional ones (natural rock aggregates) and the use of waste steel slag can be a good option.

1.2 Problem Statement

With increasing train axle loads and speeds on existing railway lines over the years, a greater structural demand has been set on conventional track initially constructed to cater for much lighter traffic at slower speeds. The provision of a blanket layer on top of formation has however been sought as an essential option to construct a stable embankment suitable for running heavier axle loads at higher speeds. The existing blankets such as bituminous blankets, geogrids and geomembranes have provided unsatisfactory embankment stability as axle loads and speeds increase. Therefore, there is need to enhance the engineering properties of such blankets through utilization of stronger and readily available substitute materials like, replacement of natural aggregate in the bituminous blanket by waste steel slag aggregate. Steel slag is extensively and continuously being produced as waste from many industrial processes during the manufacture of steel products. However, in emerging economies like Ethiopia, it is left piled on sites of manufacture and later deposited in landfills. Very limited research has been conducted in Ethiopia about the use of waste steel slag. Therefore, a study that focuses on improving the engineering properties of the railway blanket and general performance of the embankment, is very necessary.

1.3 Objectives of the Study

1.3.1 Main Objective

The primary objective was to investigate the feasibility of using waste steel slag in enhancing the performance of the bituminous railroad blanket layer.

1.3.2 Specific Objectives

i) To assess the conformity of the physical and mechanical properties of the aggregates, bitumen used, and bitumen-aggregate mixture characteristics, with specifications,
ii) To determine the optimum waste steel slag content to be used and,
iii) To assess the influence of waste steel slag on the resistance of bituminous mixtures to moisture damage.

1.4 Significance of the study

As train speeds and axle loads increase on existing railway lines, there is a need to improve the stability quality of railway embankments by devising solutions that will lengthen their service lives to reduce investment on the line maintenance activities. The use of waste steel slag for railway natural rock aggregate replacement is justifiable for technical, economic and ecological reasons, [56]. The technical evaluations consist of the definition of the physical, chemical and mechanical properties which the material must possess to be suitable for use in railway construction. The economic evaluations take into account the global cost of the natural aggregate in relation to the cost of the alternative material. The ecological evaluations include; risk of groundwater pollution and space scarcity for waste steel slag storage. The Federal Republic of Ethiopia has invested large sums of donor funds through the Ethiopia Railway Corporation (ERC) in the development and maintenance of the existing Addis Ababa Light Rail Transit and the other railway projects. While the lifespan of a railway line may be increased, the maintenance cost for the railway line may also reduce, thus saving large funds for other development projects. Griffith et al, [30] provided evidence that research and development are statistically and economically important in stimulating innovation. The use of waste steel slag is an innovative and sustainable way of averting the environmental risks and improving the quality of the bituminous blanket layer which in turn reduces on the thickness of the ballast and sub-ballast layers to be constructed resulting in reduced aggregate volume on the constructed line.

1.5 Hypothesis

If waste steel slag is used in modifying the bituminous railway blanket layer by replacing the natural rock aggregate, there will be an improvement in the mixture's properties and general performance of the blanket layer. Improper disposal of waste steel slag will substantially decrease.

1.6 Scope of the Study

The scope of the research work described herein was limited to laboratory investigations of the feasibility of using waste steel slag in the modification of the bituminous railway blanket layer. Natural aggregates (basalt rock aggregates) were used in this study and these were obtained from the Hana Mariam stone quarry site in Addis Ababa, Ethiopia. Waste steel slag aggregates were also used. These were obtained from Mame Steel Mill plant, also located in Addis Ababa, Ethiopia. 80/100 bitumen penetration grade was used in this research and it was obtained from National Oil Corporation (NOC) in Addis Ababa.

Laboratory tests such as Marshall Mix design analysis, Indirect Tensile Strength and Moisture Susceptibility were conducted on prepared bituminous mixtures. Well-graded natural basalt rock aggregate was blended with well-graded proportions of 25%, 50%, and 75% of waste steel slag aggregate by dry weight. Control samples of purely natural rock aggregates and purely waste steel slag were also prepared and tested.

1.7 Material Characterization

Laboratory experiments as per recommended test standards and specifications were conducted to simulate field conditions. Research materials sampling was conducted as per ASTM C143/C143M guideline. These materials were then tested for mechanical and physical properties to assess their conformity with relevant standards and specifications. Waste steel slag and natural basalt aggregate samples were tested for Particle Size Distribution/Sieve Analysis, Los Angeles Abrasion Value, Aggregate Impact Value, Aggregate Crushing Value, Water Absorption and Specific Gravity, Bulk density, Stripping and Coating, Flakiness Index and others. Penetration at 25^0c and Softening Point tests were conducted on the bitumen sample used.

Mixtures were prepared to determine the Optimum Bitumen Content of the natural basalt aggregates using the Marshall mix design method as per ASTM D1559. At Optimum Bitumen Content, Marshall specimens were prepared with varying waste steel slag aggregate content after which the optimum waste steel slag aggregate content was obtained guided by the mixture volumetric properties. Moisture susceptibility tests such as Indirect Tensile Strength and Tensile Strength Ratio were also conducted as guided by AASHTO T283 to evaluate the modified mixture's resistance to moisture damage. It is upon this background that an optimum bituminous blanket mixture was proposed to improve railway embankment functionality.

1.8 Conceptual Framework

The purpose of the conceptual framework was to summarize the relationship between literature, methods and the results of the study. The use of waste steel slag in the modification of bituminous blanket mixtures was based on the fact that bitumen-aggregate adhesion is fundamental to the performance of these mixtures. Adhesion between two different surfaces is defined as the process in which dissimilar particles/surfaces are held together by valence and/or interlocking forces, [82]. Adhesion determines the tendency of two materials with dissimilar molecules to cling to one other, [55]. It can be measured directly with contact angle approaches (i.e., wetting potential), [58] or with practical approaches, such as a suitable tensile test (e.g., Bitumen Bond Strength Test).

Traditionally, Hot Mix Asphalt (HMA) production and construction specifications require measurement of volumetric properties of the HMA such as air voids, bitumen content, and aggregate gradation that are assumed to be related to an arbitrary level of performance. Specifications for materials and construction (M&C) variables also known as Acceptance Quality Characteristics (AQCs) are used to control quality and primarily tie the AQCs to performance through intuition, engineering judgment, or both. Minimum in-situ density is an AQC used in specifications where the relationship to better performance is intuitive, i.e., higher in-situ densities generally means better performance, [73].

The conceptual framework of this study presented in Figure 1-1 focused on blending of well-graded natural basalt rock aggregates with well-graded waste steel slag aggregates. The aggregate mix proportions were therefore regarded as independent variables. The type of asphalt binder determines the quality of the hot mix asphalt which were controlled by the predetermined type of asphalt binder (80/100 Penetration grade). Besides, the properties of the aggregate and binder mixtures are influenced by aggregate characteristics (size, shape, surface area, chemical constituents, acidity/alkalinity, adsorption surface density, pore-volume, and surface charge) and asphalt binder characteristics (viscosity, film thickness, chemistry of asphalt and surface energy) , [74], [83]. These were considered to be independent variables and were kept constant in the study. Processing hot mix asphalt techniques can affect the quality of the mix. This was considered an external factor that could affect the results of the study. This factor was controlled by following standard procedures described in the specifications used in the study. Samples were then prepared and tested by following standard specification procedures and test methods respectively processes were evaluated. Marshall Mix design properties and resistance to moisture damage were observed as the dependent variables.

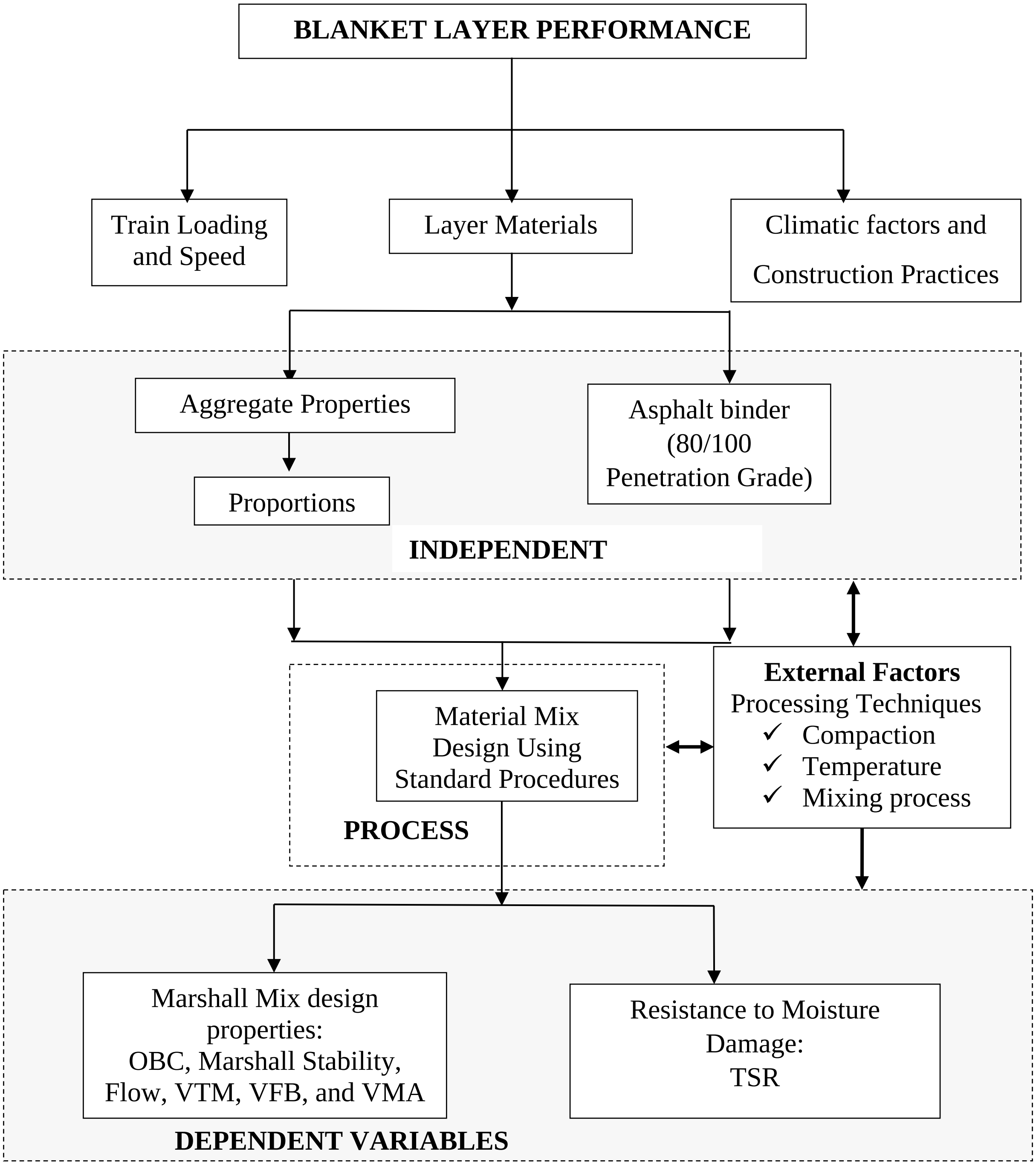

Figure 1-1: Research conceptual framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The objective of this chapter was to present a brief overview of the bituminous blanket layer and its material specifications, a review of the concept of bituminous mixtures, the fundamental theories and associated mechanisms of bitumen-aggregate adhesion, the previous studies that have utilized waste steel slag in bituminous layer construction, and to identify literature gaps on the use of waste steel slag in modification of bituminous mixtures. These are presented herein in that order.

2.2 Overview of the Blanket layer

Ordinarily, a blanket is a layer of specified coarse, granular material of designed thickness provided over the full width of formation between subgrade and ballast. Provision of a blanket layer is essential to prevent failure of track formation because of deficient bearing capacity and to defend against swelling and shrinkage, sufficient blanket thickness must be provided in all cases at the time of construction of new lines, permanent diversions, raising of formation, in cuttings and so on, or while rehabilitating a failing track formation, [42].

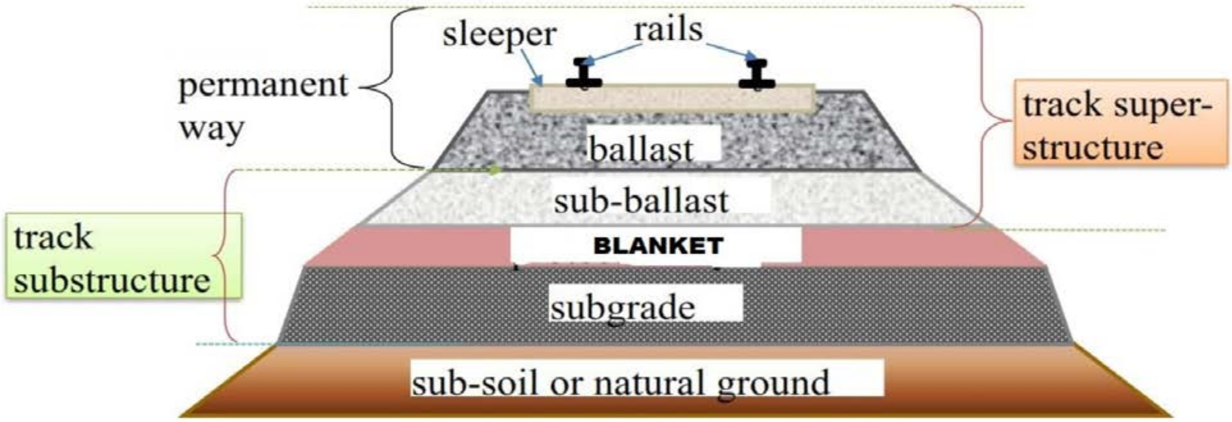

Figure 2-1: A typical Railway Embankment with a Bituminous Blanket, [42]

According to the Indian Ministry of Railways - Geotechnical Engineering Directorate Manual [42], a blanket layer plays out the accompanying capacities; It diminishes traffic-induced stresses to a fair limit on the top of subgrade, in this manner, forestalls subgrade failures under antagonistic basic states of precipitation, seepage, track support, and traffic loadings. It forestalls penetration of ballast into the subgrade and keeps upward relocation of fine particles from subgrade into the ballast under adverse critical conditions during service. It encourages seepage of surface water and reduces moisture variations in the subgrade, in this manner decreasing track maintenance issues. It forestalls mud pumping by isolating the ballast and subgrade soil. Accordingly, aggregation of negative pore water pressure in the soil mass is prevented which is liable for mud pumping.

2.3 Blanket layer material specifications

To guarantee that the blanket layer is of acceptable quality and ready to satisfy the capacities talked about in the section above, blanket layer materials must fit within specific attributes, for example, particle size distribution/gradation, shape, surface roughness, particle density, bulk density, strength, hardness, toughness, resistance to attrition and weathering, [33]. AREMA (2010), specifies limiting values for most materials to be used in railway construction and maintenance.

2.4 Concept of Bituminous Mixtures

A bituminous mix is any mixture of mineral aggregates bound together using a bituminous binder. In some cases, other materials such as mineral, natural fibers, crumb rubber, and anti-strip additives are added in small quantities to improve some of the mix properties, [69]. Aggregate typically makes up about 95% of Hot Mix Asphalt (HMA) by weight, whereas asphalt/bituminous binder makes up the remaining 5% by volume. A typical HMA is about 85% aggregate, 10% asphalt binder, and 5% air voids, [73].

At high temperatures, asphalt binder is a liquid with a consistency like that of engine oil. At room temperature, most asphalt binders will have the consistency of clay or delicate elastic. At negative temperatures, asphalt binder can turn out to be fragile – asphalt samples put away in a cooler will break like glass whenever dropped on a hard surface. Many asphalt binders contain little rates of polymer to improve their physical properties; these materials are called polymer modified binders. Generally speaking, the asphalt binder that has a higher viscosity, a higher softening point, better temperature stability, or a more sufficient viscosity at a high temperature can result in a mix that will maintain a certain level of strength and stiffness without a significant shear deformation at high temperature. A great part of the present asphalt binder specifications was intended to control changes in consistency with temperature, [63].

Hot mix asphalt mixtures are mostly made of aggregate; aggregates used in HMA must be of good quality to ensure the resulting layer will perform as expected. Aggregates used in HMA mixtures may be either crushed stone or crushed gravel/sand. In either case, the material must be thoroughly crushed, and the subsequent particles ought to be cubical instead of flaky or elongated. Aggregates should be free of dust, dirt, clay, and other toxic constituents. Aggregate particles carry most of the load in HMA layers, thus aggregates should be tough and abrasion-resistant, [73].

Entirely, HMA blends contain small amounts of air voids. In the laboratory, HMA blends are usually designed to contain about 4% air voids, with a range of about 3 to 5%, depending on the type of blend being designed and the design procedure being used. When air voids are high, the aging of asphalt film and entry of water to the mix is possible, [63]. Properly constructed HMA layers will usually contain about 6 to 8% air voids immediately after placement and compaction. After construction, as traffic passes over a layer, the HMA will normally gradually compact to air void levels approaching the design value of 3 to 5%. However, if the layer is not compacted adequately during construction, compaction under traffic may fail to reduce the air voids content to the design value and, as a result, the layer will be permeable to both air and water, potentially leading to moisture damage and excessive age hardening, [73].

Mixing of asphalt and aggregate is accomplished in one of the several ways: concrete, warm mix asphalt concrete, cold mix asphalt concrete, cut back asphalt concrete, mastic asphalt concrete, natural asphalt concrete, and hot mix asphalt. This study concentrates on hot mix asphalt design for blanket layer.

2.5 Hot Mix Asphalt

Hot mix asphalt concrete (regularly contracted as HMA/HMAC) is delivered by warming the asphalt binder to decrease its viscosity and drying the aggregate to expel moisture from it before blending. Blending is by and largely performed with the aggregate at around 300 °F (approximately 150 °C) for virgin asphalt and 330 °F (166 °C) for polymer modified asphalt, and the asphalt cement at 200 °F (95 °C). Clearing and compaction must be performed while the asphalt is adequately hot. HMAC is the form of asphalt concrete most commonly used on highly trafficked layers such as those on major highways, racetracks, and airfields. HMA is typically applied in layers, with the lower layers supporting the top layer but also applied for blanket layer in railway embankments. There are Dense Graded Mixes (DGM), Stone Mastic Asphalt (SMA) and various Open-graded HMA, [73].

2.5.1 Mix Design Methods for Hot Mix Asphalt

A few mix design methods are used for the preparation of HMA. These include; Marshall Mix design, Superpave (Superior performing pavement) method, and Hveem technique for mix design. These strategies are briefly described in the following paragraphs.

The Marshall Mix design relies upon compacting tests using a standard drop hammer over the extent of asphalt binder contents. The binder content is selected to deliver required air void content and voids in the mineral aggregate (VMA). A fundamental piece of the Marshall Mix Design technique is the stability and flow test, which is an empirical procedure used to assess the quality/strength and flexibility of the HMA, [37]. Marshall blend configuration is utilized in this research because of the accessibility of the equipment (Marshall mechanical assembly) and the relative straightforwardness to lead the tests when contrasted with Hveem and Superpave blend structure strategies.

The Hveem strategy for blend configuration is one of a kind in its utilization of the Centrifuge Kerosene Equivalent (CKE) test to decide an underlying appraisal of the asphalt binder content for a given aggregate. Laboratory samples are prepared using a kneading compactor and afterward assessed using a stabilometer test and a swell test. A cohesiometer test may likewise be used to assess HMA properties in the Hveem method. Likewise, with the Marshall Mix design method, the assessment of blend volumetrics is a significant piece of the Hveem method, [37].

Superpave technique is like the Marshall framework in its utilization of blend volumetrics, however, laboratory specimens are prepared using a gyratory compactor instead of a drop hammer. Superpave likewise incorporates a thorough arrangement of prerequisites for aggregate gradations and property requirements. The Superpave method of mix design was intended to incorporate blend test techniques and a related computer program that would foresee the performance of HMA layers, as a guide in the structure and investigation of blends. However, this computer program never delivered dependably precise predictions of rutting and fatigue cracking, and this aspect of Superpave was rarely actualized, even though the Mechanistic-Empirical Layer Design Guide (MEPDG) is from numerous points of view a continuation of the Strategic Highway Research Program (SHRP) endeavors for flexible layers, [37].

2.6 Aggregates

For purposes of this thesis, aggregate is defined as crushed stone, sand and/or gravel. Crushed stone is the product resulting from the artificial crushing of rock, boulders, or large cobblestones, substantially all faces of which have resulted from the crushing operation, [84].

According to Roberts et al, [63]., about 95% of the volume of HMA is made up of aggregates, HMA pavement performance is greatly influenced by the characteristics of the aggregates (Size, shape, surface area, porosity, chemical constituents, acidity/alkalinity, and surface charge). Aggregates in HMA are divided into three types according to their size: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36mm sieve. Fine aggregates are those that go through the 2.36mm sieve and are held on the 0.075mm sieve. Mineral filler is defined as that part of the aggregate passing the 0.075mm sieve. Mineral filler is a very fine material with the consistency of flour and is additionally alluded to as mineral residue or rock dust.

2.6.1 Natural Aggregates

Naturally-occurring aggregate deposits, whether sand and gravel or un-weathered rock for crushed stone, are formed by a variety of geologic processes. Volcanoes, earthquakes, glaciers, rivers and streams, and marine processes have each contributed to the formation of the materials often used as aggregate.

The physical and chemical properties of aggregate result from the geologic origin and mineralogy of the potential source and its subsequent weathering or alteration. Many of the properties of aggregates relate to grain size, texture, mineralogy, pore space, and weathering products. These are all characteristics that can be observed and described by traditional geologic methods. Knowledge of which physical or chemical qualities determine the suitability of aggregate enables geologists to characterize potential aggregate sources, [36].

According to Roberts et al, [63]., the largest single use of natural aggregates is in construction, and much of that aggregate is used in Portland-cement concrete or bituminous mixes. The specifications for natural aggregate in Portland-cement concrete or bituminous mixes are generally more rigorous and specific than for other construction-related uses. If aggregate can meet the specifications for these uses, it will satisfy almost any other use. Therefore, the specifications required for Portland cement concrete and bituminous mixes, and the geologic observations that help describe them, are emphasized in this thesis.

Major physical properties that affect the use of aggregate in bituminous mixtures are gradation of particle sizes; particle shape; particle-surface texture; porosity; pore structure; specific gravity; thermal properties; and susceptibility to volume changes. Chemical properties of aggregate that unfavorably influence the quality and strength of bituminous blends incorporate oxidation of specific minerals, transient responses, for example, blossoming, and longer-term responses, for example, the salt silica response. The presence of certain contaminants can prevent the cement from hydrating or bitumen from adhering to the aggregate, thus it is extremely important to ensure that aggregates are clean and free from deleterious materials, [36].

To help ensure that aggregates satisfactorily meet engineering specifications, they are often subjected to standard tests. Common tests and measurements (geologic observations) can be made in the field or laboratory by an experienced geologist to help evaluate the quality of potential aggregate sources. These include resonance when struck with a hammer, friability or pulverulence when squeezed between the fingers, ease of fracturing, nature of fracture surfaces and fracture fillings, odor on fresh fracture, color and variations in color, internal structure such as porosity, granularity, seams, and vein-lets, reaction to water, such as absorption of droplets on fresh fractures, expulsion of air or slaking, softening, or swelling potential when immersed, and capillary suction against the tongue; and reaction to acid, [48]. These rather simple and inexpensive tests (observations) can be used to estimate more specific physical and chemical properties important to determining the aggregate quality and determining if deleterious contaminants are present.

There is a variety of reasons to conduct more extensive engineering tests such as petrographic analysis, including to determine compliance with specification requirements, to ensure thorough quality controls and to obtain measurements of the physical properties used by the engineer in the design of pavements, foundations, bituminous mixes, etc., [44]. These tests expose aggregate to conditions that simulate the conditions under which the aggregate will be used. The tests are expensive and time-consuming and are generally only used for detailed resource appraisals and in exploration.

The most common guidelines that outline testing procedures and specifications for natural aggregates are those described by the American Society for Testing and Materials (ASTM). The construction industry often relies on the results of previous BS and ASTM tests of materials and the service records of these materials in actual use to estimate the quality of similar materials, [84].

2.6.2 Waste Steel Slag Aggregates

Environmental, economic and technical issues have prompted expanding consideration being paid to the subject of reusing minimal materials in the development of street and railroad foundations, [31]. Impact heater slag is characterized by the American Society for Testing and Materials, [13] as the non-metallic item comprising basically of silicates and alumino-silicates of calcium and different bases that are created in a liquid condition all the while with iron in an impact heater. The impact heater is the essential method for diminishing iron oxides to liquid, metallic iron. It is persistently accused of iron oxide sources (metals, pellets, sinter, and so on.), motion stone (limestone and dolomite), and fuel (coke). Liquid iron gathers in the base of the heater and the fluid slag glide on it. Both are occasionally tapped from the heater. The slag comprises fundamentally of the contaminations from the iron mineral (mainly silica and alumina) joined with calcium and magnesium oxides from the transition stone. Sulfur and debris that may originate from the coke will likewise be contained in the slag, which originates from the heater as a fluid at temperatures about 1500°C. It is a man-made liquid stone, comparative in numerous regards to volcanic magmas, [66].

2.7 Factors that Influence Adhesive Bond between Asphalt and Aggregate

The factors affecting bitumen-aggregate bonds are elaborated under this section of the literature review. These include; effect of asphalt binder characteristics and aggregate characteristics.

2.7.1 Effect of Asphalt Binder Characteristics

The asphalt binder characteristics can impact both the adhesion of the asphalt-aggregate system and the cohesion of the mastic. The properties of the asphalt binder that can influence the asphalt-aggregate bond relate to the chemistry of the asphalt (e.g., polarity and constitution), viscosity, film thickness, and surface energy, [74], [83]. The cohesive strength of the asphalt matrix in the presence of moisture is also influenced by the chemical nature of the binder and processing techniques.

The chemical interaction between the asphalt binder and the aggregate is basic in understanding the ability of compacted bituminous blends to resist moisture damage. Robertson, [65] describes that the carboxylic acids in asphalt binders are quite polar and adhere strongly to dry aggregate. However, this chemical group tends to be removed easily from aggregate in the presence of water. One reason behind this conduct is the way that sodium and potassium salts of carboxylic acids in asphalt are basically surfactants or soaps, which are debonded under the action of traffic in the presence of water, [59]. Note that calcium salts from hydrated lime are much more unaffected by the action of water. Robertson, [65] also suggested that aged asphalts are more prone to moisture damage than un-aged asphalts, due to the presence of strongly acidic material in oxidized binders. Petersen et al., [81] observed that asphalt binders containing ketones and nitrogen are the least susceptible to moisture damage. The viscosity of the asphalt binder does play a role in the inclination of the asphalt mixture to strip. It has been reported that asphalts with high viscosity resist displacement by moisture better than those that have low viscosity. Asphalts with high viscosity usually carry a high concentration of polar functionalities that provide more resistance to stripping, [83].

It has also been reported that the bond strength is directly related to film thickness. Samples with thicker asphalt film tend to have cohesive failure after moisture conditioning. On the other hand, specimens with thinner asphalt film have an adhesive failure, [34]. Concerning surface energy, according to the thermodynamic theory of asphalt- adhesion, low values of asphalt film for the asphalt is preferable to provide better wetting.

2.7.2 Effect of Aggregate Characteristics

Aggregate properties have a greater effect on adhesion than some of the binder properties. Size and shape of the aggregate, pore volume and size, surface area, chemical constituents at the surface, acidity and alkalinity, adsorption size surface density, and surface charge or polarity are some of the widely cited aggregate characteristics that can influence moisture damage, [80].

The chemistry of aggregate affects the asphalt-aggregate adhesion substantially; various mineral components of the aggregates show a different affinity for asphaltic material. When an aggregate is coated with asphalt, the aggregate selectively adsorbs some components of the asphalt. The general trend is that sulfoxides and carboxylic acids have the highest affinity for aggregates. It is also apparent that aromatic hydrocarbons have much less affinity for aggregate surfaces than the polar groups. Therefore, the type and quantities of the adsorbed components affect the degree of adhesion and various aggregates develop bonds of different strengths, [65].

Aggregates are commonly classified as either hydrophilic (i.e., a greater natural affinity for water than for asphalt binder) or hydrophobic (i.e., a greater natural affinity for asphalt than for water), [21], [34], [80]. It is commonly known that acidic aggregates are hydrophobic while basic aggregates are hydrophilic. However, there are notable exceptions and the general conclusion is that few if any aggregates can completely resist the stripping action of water, [80]. For example, limestone is classified as hydrophobic aggregate and granite is considered as hydrophilic, however, the level of basic or acidic conditions of the limestone and granite aggregates may vary according to their chemical composition.

Rough surfaces and therefore larger contact areas are preferred for a better adhesive bond. Porosity is another vital characteristic of the aggregate that can affect asphalt adsorption. For example, when the asphalt binder coats a rough aggregate surface with fine pores, the air is trapped and the asphalt has difficulty penetrating the fine pores, [65]. However, the diffusion of asphalt binder into pores is also reliant on the viscosity of the asphalt binder at mixing temperatures.

Moisture and dust can also significantly decrease the bond strength of aggregate-asphalt framework. The presence of dust particles on the aggregate inhibits the complete wetting of the aggregate by the asphalt binder since the asphalt is adhered to the dust particles and not to the aggregate itself, [46].

2.8 Moisture damage in asphalt layers

Stripping is the phenomenon in which loss of adhesion between asphalt cement and aggregate surface occurs in bituminous mixtures. This typically begins at the bottom of the hot mix asphalt (HMA) layer and progresses upward. Stripping usually causes distresses in pavements, which leads to poor pavement performance and an increase in the maintenance cost, [2].

Özen, [54] states that moisture damage and permanent deformation (rutting) are the primary modes of distresses in hot-mix asphalt (HMA) pavements. The performance of HMA pavements is related to cohesive and adhesive bonding within the asphalt–aggregate system. The stripping of asphalt from the aggregates results in the reduction of the strength of asphalt concrete mixture. The reduction in strength may contribute to the development of various forms of pavement deterioration such as rutting, raveling, and cracking, [3].

Moisture damage is an important cause of failure of asphalt concrete pavements. Existence of moisture in the pavement can manifest itself in the loss of cohesion within the bituminous binder itself or the loss of adhesion between the binder and the aggregates, the latter results in the stripping phenomenon. This observed phenomenon is the de-bonding of bitumen films from aggregate surfaces due to the greater affinity of the aggregate for water than for bitumen. Furthermore, stripping can be caused by hydraulic scouring resulting from the repeated generation of excess pore water pressure arising from traffic loading. Hence, stripping leads to a weakened pavement that is susceptible to pore pressure damage and premature cracking, [60].

Water damage in asphalt concrete mixtures in general and in porous asphalt concrete, specifically, is dependent on many factors including however not constrained to aggregate structure and type as well as binder type and amount. Quantifying water damage in mixtures is an entangled task and the subject of research around the world, [22], [24], [41].

Significant economic benefits derive from understanding the fundamental mechanisms of failure and moisture effects in porous asphalt to prolong the service life of this environmentally friendly pavement material. According to Xingwei and Huang, [75], Moisture damage is also one of the most difficult distresses to recognize in hot mix asphalt (HMA) layers because the surface appearance can take various forms such as rutting, shoving, raveling, or cracking.

2.9 Previous studies

A survey through international literature reveals that waste steel slag has already been considered for use in both building and highway road construction, however, only the coarse portion of waste steel slag was utilized in replacement of the coarse portion of natural aggregate, [10], [31]. Pasetto and Baldo, [56] conducted a mix design and performance analysis of asphalt concretes with Electric Arc Furnace slag. The Electric Arc Furnace (EAF) steel slags in their study possessed physical and mechanical properties which are comparable with the characteristics of natural aggregates usually used in transport infrastructure, full chemical suitability with the bitumen used in pavements and complete environmental compatibility. The results were acceptable for all the mix designs with the slag, with good estimations of Marshall Stability and Marshall Quotient, without penalization as far as densification and workability of the mixes. The satisfaction of the severe Superpave volumetric requisites relating to the compaction tests with the gyratory technique and the limited axial deformation developed during the RLAT tests led to the conclusion that the

EAF steel slag asphalts for wearing courses have less probability of developing excessive permanent deformations. The dynamic analysis at low frequency, representative of conditions with slow channeled traffic, further confirmed an extremely positive overall performance of the mixtures, in terms of both stiffness and fatigue resistance. The mixes with EAF slag had been characterized by low water damage so demonstrating good durability. The results of the 90% steel slag content (3/SS) stand out, which was also the one with the highest EAF slag content, its skeleton is composed of 90% of this material; 2/SS, 1/SS and LS mixes (respectively with 60%, 30% and 0% of EAF slag) are characterized by progressively decreasing properties. All in all, the trials had confirmed that the utilization of waste material from steel production in the lithic skeleton of asphalts is technically satisfactory option that satisfies the spirit of the "Zero Waste" target, that the iron and steel industry has been focusing on in the most recent decade.

Huang et al., [31], noted that the angular shape, hardness, and roughly textured surface give steel slag the ability to substitute coarse aggregates in the asphalt where mix stability (resistance to rutting) and skid-resistance are concerned. Collaborative research was carried out by the Strategic Highway Research Program (SHRP) and the University of Petroleum and Minerals in Saudi Arabia to optimize the use of steel slag as a mineral filler. It was discovered that blend durability (resistance to moisture, fatigue) was improved when coarse slag aggregates were enhanced with limestone filler and fine aggregates, and the bitumen prepared using polymer modification, [18].

A comparison of steel slag and crushed limestone aggregate was done by Maslehuddin et al., [45]. They examined the mechanical properties and durability qualities of steel slag aggregate concrete in comparison with limestone aggregates. Their outcomes indicated that the durability and physical properties of concrete with steel slag aggregates were better than limestone aggregates. They proposed that the utilization of steel slag aggregates in concrete was beneficial, especially in areas where good quality aggregates are not accessible or must be hauled from far off distances. Abrasion resistance, specific gravity, water absorption, chemical soundness, alkalinity, the concentration of chloride and sulfates were tested and compared with limestone aggregates. Shrinkage and expansion attributes of steel slag and sand cement mortar specimens were assessed and the length was measured at periodic intervals. Their outcomes indicated that the compressive strength of steel slag aggregates increased with the proportion of coarse aggregates from 4550 psi (31.4 MPa) with 45% coarse aggregates to 6190 psi (42.7 MPa) with 65% coarse aggregates. The flexural strength and split tensile strength also increased while the water absorption capacity was reduced. They expressed that the shrinkage of steel slag exposed to a dry environment was similar to limestone aggregate with no major expansion for example less than 0.05% as specified by ASTM C 33. The time of initiation of reinforcement corrosion and time of cracking of concrete specimens was observed to be longer than with limestone aggregates.

Airey et al., [5] reported that the use of basic secondary aggregates such as oxygen steel and blast furnace slag significantly increases the mixture density and stiffness modulus compared to primary aggregate mixtures. The moisture susceptibility of these secondary aggregate mixtures was similar to that of the control mixes of conventional aggregates although there was an increased susceptibility to age hardening. They further observed that the overall permanent deformation resistance and fatigue performance of the slag mixtures tended to be similar to that of control mixes.

Ahmedzade and Sengoz, [4] evaluated the use of steel slag coarse aggregate in hot mix asphalt concrete. Four different asphalt mixtures containing two types of asphalt cement (AC-5; AC-10) and coarse aggregate (limestone; steel slag) were used to prepare Marshall specimens and to determine optimum bitumen content. Mechanical characteristics of all mixtures were evaluated by Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength tests. The electrical sensitivity of the specimens was also investigated following ASTM D257-91. It was observed that steel slag used as a coarse aggregate improved the mechanical properties of asphalt mixtures. Moreover, volume resistivity values demonstrated that the electrical conductivity of steel slag mixtures was better than that of limestone mixtures.

The influence of load channelization on stripping was investigated using cores and block samples from a heavily loaded highway in Uganda by Bagampadde and Kigundu, [16]. The original 80/100 asphalt (virgin and RTFOT aged) was characterized using conventional methods. Stripping of mixtures was measured using ASTM D1664 and that of cores using visual diametrical plane rating and loss in indirect tensile strength due to soaking. The pore saturation and air voids were found to be influenced by groundwater level and wheel track location across traffic lanes. Stripping was rated higher in the wheel paths than between wheel paths, especially in shallow water table areas where it was observed to be 82% higher, implying possible dependency of stripping on channelization.

Gorkem and Sengoz, [29] predicted stripping and moisture-induced damage of asphalt concrete prepared with polymer-modified bitumen and hydrated lime. The results indicated that hydrated lime addition and polymer modification increased the resistance of asphalt mixtures to the detrimental effect of water. Moreover, it was found out that samples prepared with SBS (styrene-butadiene-styrene) PMB (polymer modified bitumen) exhibited more resistance to water damage compared to samples prepared with EVA (ethylene vinyl acetate). The results indicated that lime addition and compound modification increased the resistance of asphalt mixtures to the harmful result of water. Moreover, it had been recognized that samples ready with SBS (styrene-butadiene-styrene) PMB (polymer changed bitumen) exhibited a lot of resistance to moisture damage compared to samples prepared with EVA (ethylene vinyl acetate).

Finally, industrial by-products like steel slag require an in-depth study of its potential toxicity. There are several dangerous heavy metals and salts present in the steel slag. A leaching test is required before using the EAF slag as a filling material. Manso et al., [43] conducted the leaching test for determining the possible attack of concrete in the environment. Analysis of leached water from crushed slag aggregates was used to detect the sulfates, fluorides and total chromium present in it. The results showed that a smaller size of crushed slag produces a higher concentration of dangerous substances in leached water. The cloistering effect was found to be greater in larger sizes of crushed slag. It was concluded that the use of EAF slag aggregate in concrete will help to reduce its potential toxicity and the results confirmed an important cloistering effect of the cementitious matrix on the contaminant elements. Also, some previous research was carried out at the Cleveland State University by Obratil et al., [52] who examined the effect of replacing various percentages of natural aggregates with steel slag in a standard concrete pavement mixture which showed satisfactory results.

2.10 Literature gaps and challenges

Numerous investigations have been conducted on alternative earth-amicable materials that are perfect with common aggregates in terms of performance, [7], [9], [47], [61]. The significant constituent as far as volume and weight of a typical asphalt mixture is aggregate; along these lines, modern waste and reused aggregates are basic in developing and maintaining works for thruways. However, of all the literature reviewed, the detailed mechanisms of waste steel slag interaction with the natural or conventional aggregates are not clarified.

Ultimately, hesitance to utilize other than normal materials in construction will not be settled by innovations for the utilization of waste materials alone. Reluctantly it is proposed that enactment may have to be considered to authorize the controlled utilization of these wastes. This would decrease the danger of environmental contamination and diminish the burden of recovering natural aggregate.

From the literature reviewed, the durability of asphalt mixtures (and hence the service life of railway embarkments with bituminous blanket layers) depends, at least in part, on the bond between the bitumen and the mineral aggregates. In practice, the selection of the bitumen binder and aggregate during layer construction is governed largely by development financial aspects: the cost of transporting the heavy aggregates any significant distance (haulage) is prohibitive so the aggregates are sourced locally to the construction site. Thus, the aggregates used on railway lines reflect the local geology. Consequently, there are wide variations in the durability/toughness of asphalt blends and different techniques have been utilized to improve them.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

This chapter provides an overview of the materials and methods used for this research. The research design philosophy used in the study is discussed. The chapter also deliberates on the methods adopted to achieve the objectives of the study.

3.2 Research Design

The research design was conducted using mixed methods (triangulation). It involved philosophical assumptions that guided the direction of collecting, analysing, and mixing qualitative and quantitative approaches in many phases in the research process. Laboratory experiments as per required test standards and specifications were conducted to simulate field conditions. The study was conducted following the methodological flow chart shown in Figure 3-1.

3.3 Materials

3.3.1 Asphalt cement

80/100 penetration grade asphalt, was used in this study. This is the only grade of asphalt recommended by the AREMA (2010) general specifications, [9] for use in relatively cold climates like Ethiopia. The asphalt was obtained from the National Oil Corporation (NOC) in Addis Ababa, who are the known suppliers of asphalt for local construction works in Ethiopia. ASTM D449-89 physical requirements were used to confirm the suitability of the asphalt used, as recommended by AREMA (2010) Standard. The laboratory results of penetration and softening points are presented in Table 3-1.

Table 3-1: Properties of bitumen used in the study

Asphalt Binder	Test	Units	Values	AREMA Specifications (2010)
80/100	Penetration	0.1mm	92.5	80-100
	Softening Point	^{o}C	46.5	42-51

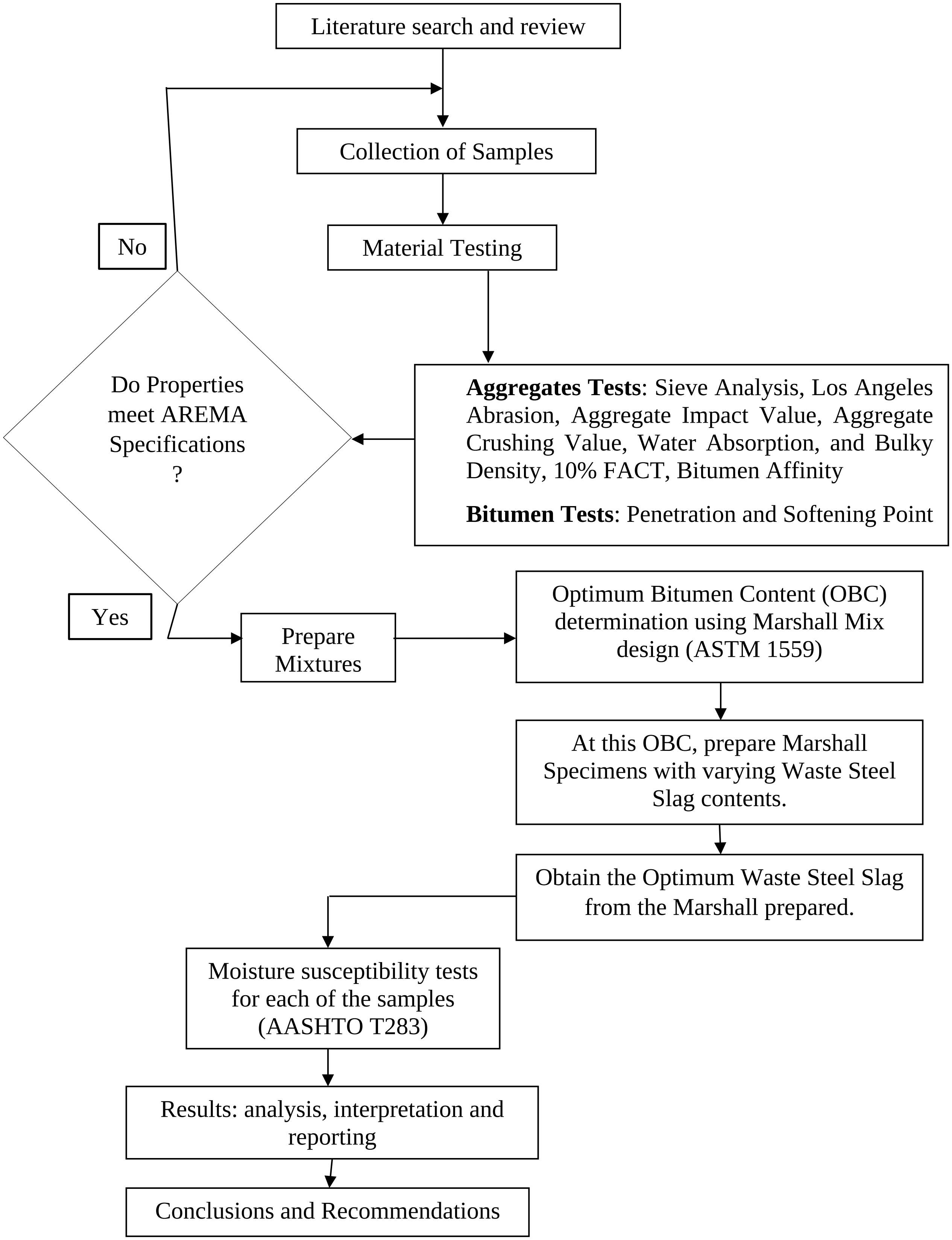

Figure 3-1: Research Steps

3.3.2 Waste steel slag aggregates

A preliminary visit to Mame steel Mill Plc. was conducted before actual steel slag sampling in order to gather decisive information about the samples regarding the study. After interacting with the Quality Assurance Managers and laboratory technicians at the factory, information about the consistency and storage of the waste steel slag produced was obtained. The waste steel slag was sampled from the stockpiles at Mame Steel Mill plant using the quartering method (ASTM D75), [14]. To mitigate the expansion problem of steel slag, the materials sampled were immediately washed to accelerate the hydration process of any available free lime and magnesia. In addition, the samples were obtained from stockpiles that were deposited approximately two years ago in the factory yard as suggested by Kneller et al, [35]. Laboratory technicians at the factory provided information on the age of the waste steel slag dumped. However, this information was crosschecked by independently interviewing the Quality Assurance Manager. Samples of waste steel slag were taken to the laboratory for chemical analysis. Lumps of waste steel slag were crushed to form different sizes as shown in Figure 3-2. Table 3-2 shows the chemical analysis results of the used waste steel slag.

Table 3-2: Chemical Characterization of Waste Steel Slag (Mame Steel Mill Plant)

Compounds	Steel Slag General Composition* (%)	Waste Steel Slag Composition (%)
Calcium Oxide CaO	47-55	31.2
Iron III Oxide Fe_2O_3	20-26	28.8
Silicon Oxide SiO_2	7.5-15	10.02
Magnesium Oxide MgO	1.3-3.7	3.09
Aluminium Oxide Al_2O_3	1.2-1.7	16
Manganese Oxide MnO	3.5-5.3	6.07
Sodium Oxide NaO	-	0.02
Potassium Oxide K_2O	-	0.06
Sulphide	-	0.08
Chloride Content	-	0.02
Residue Insoluble in HCl and Na_2CO_3	-	4.04
Insoluble residue in HCl and KOH	**-**	0.6

*__(Ahmedzade & Sengoz, [4])__

Figure 3-2: Waste steel slag aggregates crushed to different sizes

Natural Basalt rock aggregates were used in the study. The rationale for the choice of the natural rock aggregates lies in the fact that they exist in larger quantities as compared to other rock types and according to the Ethiopian Railways Corporation, about 90% of railway construction projects in Ethiopia use crushed basalt rock aggregates. The aggregates were sampled from Hana Mariam Quarry located in the outskirts of Ethiopia's capital, Addis Ababa. The question arises on how one would know beforehand that this source of natural aggregates had the specified mineral. It was fortunate that this being under exploitation the proprietors had the requisite information. Prior to quarrying of materials, an assessment of natural aggregate potential was conducted by the quarry proprietors. This included the location, quality, and the volume of the potential aggregate. A discussion with the management staff of the quarry, therefore, provided the relevant geologic information about the quarry.

3.4 Methods

3.4.1 Materials testing

All materials used in the study were tested using standard procedures recommended by the relevant test standards to ascertain whether they meet the requirement of AREMA (2010). All the sampled natural rock aggregates and waste steel slag were subjected to the following tests listed in Table 3-3.

Table 3-3: Laboratory tests conducted on materials

Material	Properties	Test Method
Aggregates	Aggregate gradation/Sieve analysis	BS 812-103.1: 1985
	Aggregate Impact Value (AIV)	BS 812 Part 112:1990
	Aggregate Crushing Value (ACV)	BS 812 Part 110:1990
	Los Angeles Abrasion Value (LAAV)	ASTM C131-89
	Water Absorption	BS 812 Part 2:1975
	Bulk Density	BS 1377 Part 2:1990
	Flakiness Index (FI)	BS 812-105: 1990
	Bitumen Affinity	BS EN 12697-11:2005
	Ten Percent Fines Value (TFV)	BS 812 Part 111:1990
	Bulk Specific gravity	BS 1377 Part 2:1990
Bitumen	Penetration at 25^{o}C	ASTM D5-86
	Softening point	ASTM D36-70

3.4.2 Optimum Bitumen Content (OBC)

This was determined using the popular Marshall Mix design method in accordance with ASTM D1559. The Marshall Specimens of neat bitumen were prepared following the Asphalt Institute Method, [63]. Seven (7) binder contents were considered i.e.3.5,4.0, 4.5, 5.0, 5.5, 6.0 and 6.5%. Three specimens were prepared for each binder content and the average values of three specimens for the unit weight, Marshall Stability and flow properties were determined. Twenty-one (21) specimens were therefore prepared for Optimum Bitumen Content determination as shown in Table 3-4. The coarse aggregates of each specimen were heated to a temperature of 180 ^{o}C as per the ASTM D1559 standard. These were then mixed with the binder to have a uniform coating of aggregates.

All the asphalt concrete mixtures were prepared in accordance with the standard 75-blows Marshall Design method for designing Hot Asphalt Mixtures. The asphalt contents at maximum stability, maximum density, 3mm flow and at 4% air voids were obtained from Marshall curves and the four asphalt contents averaged to come up with the optimum binder content for a given material. From the plotted curves, stability, flow, air voids and voids in mineral aggregates (VMA) were determined and compared with the specifications set out in the AREMA (2010) general specifications for concrete structures and foundations.

Table 3-4: Binder Contents for the natural rock aggregates

Aggregate Type	Binder Content						
	3.5%	4.0%	4.5%	5.0%	5.5%	6.0%	6.5%
Basalt	A1	A2	A3	A4	A5	A6	A7
	B1	B2	B3	B4	B5	B6	B7
	C1	C2	C3	C4	C5	C6	C7

3.4.3 Sample Preparation of Modified Bituminous Mixtures

The basalt rock aggregates were blended with the coarse proportions of 25%, 50%, and 75% of waste steel slag aggregates by dry weight. Control samples containing purely natural rock aggregates and purely waste steel slag were also prepared as indicated in Table 3-5.

At the optimum binder content and varying percentages of waste steel slag content, three (03) Marshall specimens were prepared using the Marshall procedure described in subsection 3.4.2 of this report. Waste steel slag content was varied from 0%, 25%, 50%, 75% and 100% by dry weight of the well-graded basalt aggregates. A total of Twelve (12) Marshall specimens were prepared as described in the test program in Table 3-5.

Table 3-5: Test program for sample preparation

Bitumen Type	Rock Aggregates	Waste Steel Slag Aggregate in well-graded proportions				
		0%	25%	50%	75%	100%
80/100	Basalt	A0	A25	A50	A75	A100
		B0	B25	B50	B75	B100
		C0	C25	C50	C75	C100

All samples were designated by their respective percentage of waste steel slag. A sample labelled A25, B25 or C25 implied that it was made of 75% of Basalt and 25% of waste steel slag by dry weight.

3.4.4 Evaluation of Marshall properties for modified bituminous mixtures

The Marshall properties of the modified Hot Mix Asphalt (from natural rock aggregates and waste steel slag) were evaluated in accordance with ASTM D1559. The Marshall parameters considered were as follows;

3.4.4.1 Bulk density

The bulk density was determined in accordance with the standard method described in ASTM D2726-96 (ASTM, 1996). The weight of the specimen was measured in air and then in water at 25ºC and then in saturated surface dry conditions. Bulk density was calculated using equation 3-1.

$$\rho_{bd} = \frac{\rho_w m_1}{m_3 - m_2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3-1)$$

where;

ρ_{bd}= Bulk density of specimen (gcm^{-3})

ρ_w= Density of water at 25ºC = 0.997gcm^{-3} (CML, 2000)

m_1= Mass in air (dry specimen) (g)

m_2= Mass submerged in water (g)

m_3= Mass of saturated surface dry specimen (g)

3.4.4.2 Maximum Theoretical Density

The maximum theoretical density (voids-free density of asphalt mixes) was determined in accordance with the standard method (Rice's method) described in ASTM D2041-95 and AASHTO T209-94 (ASTM, 1995, AASHTO, 1994). The maximum theoretical density was used to calculate voids content of bituminous mixtures. This method was also used to determine the amount of binder absorbed by the aggregates in an asphalt mix. The maximum theoretical density was computed using equation 3-2.

$$\rho_{d\,max} = \frac{A}{\frac{A-(B-C)}{\rho_w}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .3-2$$

where;

A = Mass of dry sample in air (or surface dry in denominator only), g

B = Mass of container and sample immersed in water, g

C = Mass of container immersed in water, g

ρ_w = Density of water at 25°C set to be 0.997gcm-3 (CML, 2000)

3.4.4.3 Voids Content, Voids in Mineral Aggregate and Voids filled with Binder

The voids content was defined as the volumetric percentage of a sample that is not filled by aggregate and binder at 25°C. The voids in mineral aggregate (VMA) was defined as the difference in bulk volume of the mix and mineral aggregates in the mix, expressed as percentage of bulk volume of the mix. The voids filled with binder were defined as the volume of effective binder in the mix, expressed as a percentage of volume of voids in the aggregates. The computations were performed in accordance with the procedures described in ASTM D3203 and AASHTO Designation PP19-93. The voids content, voids in mineral aggregate and voids filled with binder were calculated using the equations 3-3, 3-4 and 3-5 respectively.

$$V_0 = \frac{\rho_{d\,max} - \rho_{bd\,mix}}{\rho_{d\,max}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3-3$$

where;

V_0 = Void content in %

$\rho_{d\,max}$ = Maximum theoretical density of sample (gcm^{-3})

$\rho_{bd\,mix}$ = Bulk density of asphalt mix sample (gcm^{-3})

$$VMA = 100 - V_{agg}$$

$$VMA = 100 - \frac{(100 - p) \times \rho_{bd\,mix}}{\rho_{bd\,agg}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3-4$$

VMA = Voids in mineral aggregate (%)

V = Volume of aggregate, cm^{-3}

p = binder content in %

$\rho_{bd\,mix}$ = Bulk density of asphalt mix sample, (gcm^{-3})

$\rho_{bd\,agg}$ = Average bulk density of total aggregates, (gcm^{-3})

$$V_{fb} = \frac{V_{bit}}{VMA} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3-5$$

V_{fb} = Voids filled with binder, %

V_{bit} = Volume of effective binder, cm^{-3}

VMA = Voids in mineral aggregate (%)

3.4.4.4 Marshall Stability and Flow

The Marshall Stability and flow tests were performed on each specimen in accordance with the procedure described by ASTM D1559-89. The resistance to plastic flow of the bituminous mixture was measured using the Marshall apparatus with a dial gauge recording system. The specimens were first placed in a water bath at 60ºC for a period of 40 minutes for conditioning purposes before being crushed. The maximum load in Newton (N) at which failure occurred (Marshall Stability) and flow (total movement or strain occurring in the specimen between zero load and maximum load during the stability test) were then recorded.

3.4.5 Moisture Susceptibility test

The moisture susceptibility of asphalt mixtures was evaluated in accordance with the procedure described in AASHTO T283 Test, [1]. This test measures water susceptibility (stripping resistance) of mixtures in form of the Indirect Tensile Strength (ITS) of cylindrical specimen. The test is conducted on dry and wet conditioned specimens measuring 4 inches (100 mm) in diameter and 2.56 inches (65.0 mm) in height. The specimens were loaded until failure at a rate of 2 inches per minute (50.8 mm per minute) in compression by using the Marshall apparatus as shown in Figure 3-3. Two types of data were obtained from this test. The first was the indirect tensile strength (ITS) of the dry and wet conditioned specimens. The second was the tensile strength ratio (TSR), calculated by dividing the average ITS values of the wet conditioned specimens by the average ITS values of the dry conditioned specimens. The ITS value is a measure of the tensile characteristics and durability of the asphalt mixture, whereas the TSR is a measure of its resistance to moisture damage.

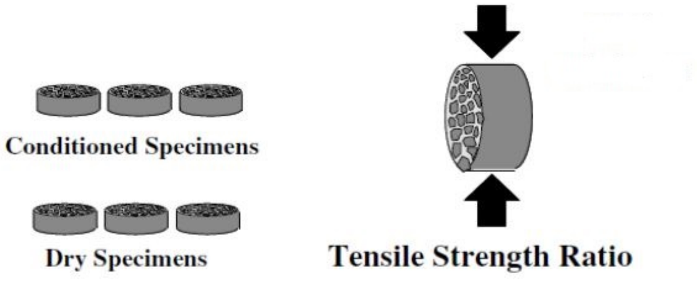

Figure 3-3: Indirect Tensile Test used for Dry and Conditioned Specimens for AASHTO T283, [70]

The loads were applied parallel and loading the vertical diametrical plane to the specimen as shown in Figure 3-4. In order to compute the ITS, equation 3-6 was used.

$$S_t = \frac{636.62 \times P_{max}}{t \times D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3-6$$

where;

S_t = Indirect tensile strength ($KNmm^{-2}$)

P_{max} = maximum load at failure (N)

t = height of specimen

D = diameter of specimen

Using the optimum bitumen content obtained in as described subsection 3.4.2 of this report, six (6) Marshall specimens were prepared for each of the modified samples as shown in Table 3-6.

Table 3-6: Specimen labels for ITS samples

0% WSSA		25% WSSA		50% WSSA		75% WSSA		100% WSSA	
Wet	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**
A0W	A0D	A25W	A25D	A50W	A50D	A75W	A75D	A100W	A100D
B0W	B0D	B25W	B25D	B50W	B50D	B75W	B75D	B100W	B100D
C0W	C0D	C25W	C25D	C50W	C50D	C75W	C75D	C100W	C100D

A sample labelled A25W implied that it was made of 75% of basalt and 25% of waste steel slag by dry weight conditioned in a water bath (Wet) before testing and A25D was not conditioned before testing (Dry). Hence a total of thirty (30) samples for the tests were prepared. Of the six modified specimens for a particular waste steel slag content, three (03) were conditioned in a water bath maintained at 60^{o}C for a period of 24 hours (label W) as shown in Figure 3-6. They were then removed and tested in the indirect tensile machine and the maximum load at which failure in form of a crack in the middle of the specimen was recorded as shown in Figure 3-4.

Figure 3-4: Diametric loading of Marshall Specimen under Indirect Tensile Strength test

The remaining three samples were not conditioned. They were tested after 24 hours of their preparation at room temperature. The moisture susceptibility or stripping potential was determined by calculating the Tensile Strength Ratio (TSR) using equation 3-7. TSR is a ratio of Indirect Tensile Strength after and before water conditioning. Prior to moisture sensitivity evaluation, air voids were calculated using equation 3-3 and checked to ensure saturation was achieved during the 24-hour conditioning period.

$$TSR = \frac{S_{t,wet}}{S_{t,dry}} \quad \ldots\ldots (3-7)$$

Where;

TSR = tensile strength ratio,

$S_{t,dry}$ = average tensile strength of un-conditioned samples ($kNmm^{-2}$), and

$S_{t,wet}$ = average tensile strength of conditioned samples ($kNmm^{-2}$).

Figure 3-5: Water bath conditioning for 24hours

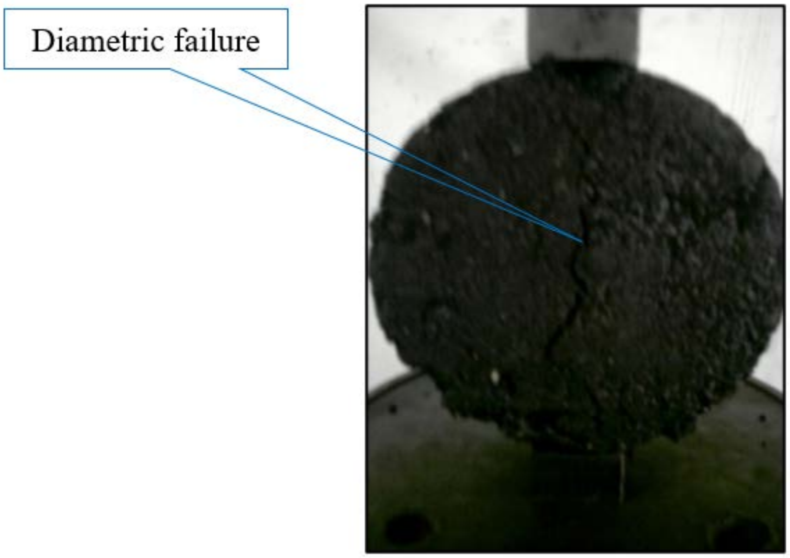

Figure 3-6: Diametric Marshall Specimen failure

3.4.6 Validity

Validity determines whether the research truly measures that which it was intended to measure or how truthful the research results are, [28]. In order to test validity of the study, hypothesis testing technique was adopted. Evidence that the research hypothesis formulated about the relationship between the dependant variable (Tensile strength ratio, TSR) and independent variables (Aggregate and bitumen properties) derived from a theory, was supported. To check whether the TSR of the modified mixtures is above the 75% required level (AREMA specifications, 2010), and whether waste steel slag added improved the TSR, the following hypotheses were formulated in line with the specific objectives of the study.

Hypothesis 1	H_o: The TSR of modified mixtures is less than 75%
	H_1: The TSR of modified mixtures is greater than 75%
Hypothesis 2	H_o: Waste steel slag aggregates added do not influence the TSR
	H_1: Waste steel slag aggregates added do influence the TSR

3.4.7 Reliability

Reliability is defined as the extent to which results are consistent over time and the extent to which the tested samples accurately represent the total population under study, as well as the extent to which the results of a study can be reproduced under a similar methodology (Golafshani, 2003). The approach adopted in this report to evaluate the reliability of the data generated in the study was to examine the relative absence of random measurement error in the measurements recorded during the experiments. Random measurement errors were indexed by a measure of variability of individual item scores around the mean index score. Repeatability and reproducibility of data recorded were in accordance with the precisions stated in all test standards used (BS, AASHTO and ASTM). Pursuant to evaluation of reliability of the results recorded, the laboratory results were recorded indexing the average of several tests conducted. As indicated in Table 3-7, the average value of two data points was recorded (46.5°C) as the softening point for bitumen. The proceeding figures were number of data points used for computing average (2) and the range (0.8) respectively.

Table 3-7: Reliability demonstration for bitumen properties used in the study

Asphalt Binder	Test	Units	Values	AREMA Specifications
80/100	Penetration	0.1mm	92.5 (2,1.0)	80-100
	Softening Point	°C	46.5 (2,0.8)	42-51

3.4.8 Data analysis

Data analysis was done to identify the factors which might contribute significantly to the TSR of the mixtures used in this study. The data generated was coded into Statistical Analysis Software (SAS) in order to test the hypotheses formulated in section 3.4.6. The factor considered was the Tensile Strength Ratio (TSR) generated from the moisture susceptibility tests at a 0.05 significance level or 95% confidence interval.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter consists of presentation, analysis and interpretation of results of tests carried out to achieve the objectives of the study. This chapter discusses the results obtained from the experiments conducted in comparison with results obtained by previous scholars. The hypotheses stated in chapter three were evaluated. This chapter also compares the findings of the study to literature reviewed in chapter two and limits specified by the AREMA (2010) specifications.

4.2 Material Properties

4.2.1 Asphalt Cement

Softening point test was used to measure and specify temperature at which asphalt binders begin to show fluidity. It is also useful in evaluating uniformity of batches supplied to sites. Penetration is a critical parameter used in grading of asphalt binders. The laboratory results of penetration and softening points are presented earlier (Table 3-1). The results were compared with the AREMA (2010) general specifications for concrete structures and foundations. The bitumen had an average penetration with in the required range (80mm-100mm). The softening point was also with in the specified temperature range (42ºC - 51ºC).

4.2.2 Aggregate Properties

Material gradation/particle size distribution is one of the most important aggregate properties because it affects stability and durability of mixtures. Consequently, it is a primary consideration in asphalt mix design. The mean gradation data of the natural aggregates and waste steel slag used in the study are presented in Appendix 1. The gradation curves presented in Figure 4-1 indicate that the gradation curve of the blended waste steel slag aggregates lies within the limits provided by AREMA (2010) specifications for AC20. AC20 means that the maximum size of aggregates required for continuously graded asphalt concrete surfacing was 20mm. The results of natural basalt rock aggregate and WSSA indicate that the material gradation was within specification limits.

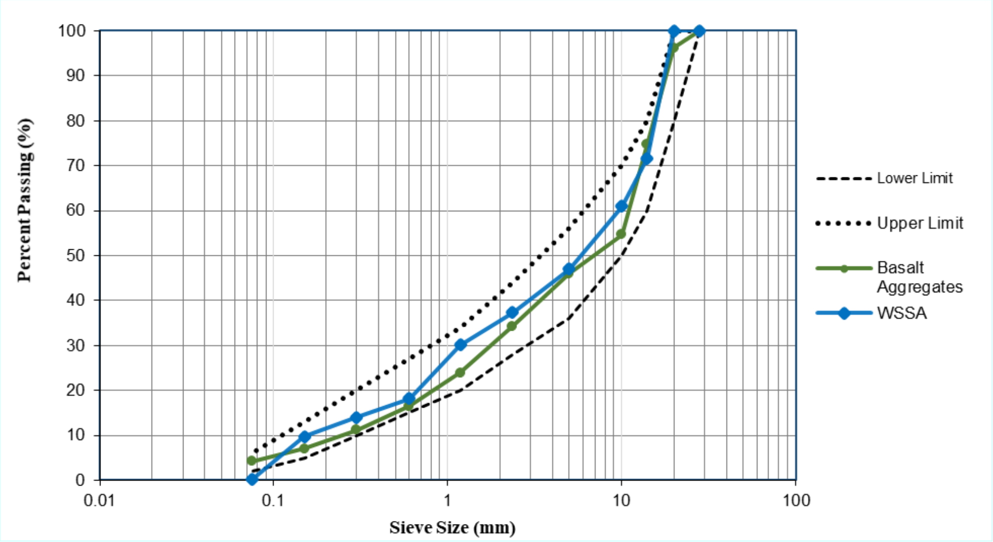

Figure 4-1: Aggregate gradation curves and specification limits

Aggregates used in railway construction should be strong enough to resist crushing under loading. If the utilized aggregates are weak, the integrity of the embankment structure is likely to be adversely affected. In order to ensure that only aggregates that meet the minimum strength requirements are used, Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), Ten Percent Fines Value (TFV), Flakiness Index and Los Angeles Abrasion Value (LAAV) tests are often performed. In this study, therefore, mechanical or physical characterisation of the aggregates was based on AIV, ACV, LAAV, TFV, FI, bulky density and water absorption. The results of some important properties of all the aggregates used in the study are summarised in Table 4-1. Aggregate Impact Value (AIV) gives a relative measure of the resistance of an aggregate to sudden shock or impact whereas Aggregate Crushing Value (ACV) and TFV gives the relative measure of resistance to crushing under gradually applied loads. The resistance to hardness was assessed using Los Angeles Abrasion (LAAV) test. The AIV and ACV for the basalt aggregates were observed to be higher than those for Waste Steel Slag Aggregates (WSSA). However, the LAAV and TFV of basalt aggregates were less than those for WSSA but all aggregate properties were within specified BS 882:1992 limits. The bulky specific gravity of waste steel slag aggregates (3.214gcm^{-3}) indicated that waste steel slag aggregates were heavier than the conventional natural basalt aggregates. The water absorption of the waste steel slag aggregates (0.83%) is approximately three times that of the basalt aggregates (0.26%). The low absorption of both aggregates should contribute to an impermeable asphalt concrete blanket desirable for railway embankments.

Table 4-1: Aggregate test results

Sample Description	Sample Source	W. Abs. %	AIV %	TFV kN	FI %	ACV %	Bitumen Affinity %	LAA %	G_{sb} Wet	G_{sa}	ρ_{loose} kg/m^3	% Passing Given Sieve Size (mm)											Remarks
												28.00	20.00	14.00	10.00	5.00	2.36	1.18	0.60	0.30	0.15	0.75	
Natural Basalt Rock Aggregates	Hana Mariam Quarry	0.26	12.3	235.9	18.3	16.5	96.70	15.1	2.617	2.628	1.618	100.0	96.2	74.8	54.7	46.0	34.3	23.9	16.5	11.2	7.0	4.2	*Dry condition*
			11.1	237.7		16.0	60.30																*Wet condition*
Average		**0.26**	**11.7**	**236.8**	**18.3**	**16.3**	**78.5**	**15.1**	**2.617**	**2.628**	**1.618**	**100.0**	**96.2**	**74.8**	**54.7**	**46.0**	**34.3**	**23.9**	**16.5**	**11.2**	**7.0**	**4.2**	*Compliant*
Specification; BS 882: 1992	**Min**	**-**	**-**	**150**	**-**	**-**	**40**	**-**	**2.600**	**2.600**	**-**	**100**	**80**	**60**	**50**	**36**	**28**	**20**	**15**	**10**	**5**	**2**	*Satisfactory results*
	Max	**-**	**25**	**-**	**40**	**25**	**100**	**30**	**-**	**-**	**-**	**100**	**100**	**80**	**70**	**56**	**44**	**34**	**27**	**20**	**13**	**6**	

Sample Description	Sample Source	W. Abs. %	AIV %	TFV kN	FI %	ACV %	Bitumen Affinity %	LAA %	G_{sb} Wet	G_{sa}	ρ_{loose} kg/m^3	% Passing Given Sieve Size (mm)											Remarks
												28.00	20.00	14.00	10.00	5.00	2.36	1.18	0.60	0.30	0.15	0.75	
Waste Steel Slag Aggregates	Mame Steel Factory	0.83	11.2	258.6	20.9	15.4	96.30	19.3	3.156	3.214	1.803	100.0	100.0	71.6	60.9	46.9	37.2	30.0	18.0	13.8	9.8	0.2	*Dry condition*
				_		_	53.30																*Wet condition*
Average		**0.83**	**11.2**	**258.6**	**20.9**	**15.4**	**74.8**	**19.3**	**3.156**	**3.214**	**1.803**	**100.0**	**100.0**	**71.6**	**60.9**	**46.9**	**37.2**	**30.0**	**18.0**	**13.8**	**9.8**	**0.2**	*Compliant*
Specification; BS 882: 1992	**Min**	**-**	**-**	**150**	**-**	**-**	**40**	**-**	**2.600**	**2.600**	**-**	**100**	**80**	**60**	**50**	**36**	**28**	**20**	**15**	**10**	**5**	**2**	*Satisfactory results*
	Max	**-**	**25**	**-**	**40**	**25**	**100**	**30**	**-**	**-**	**-**	**100**	**100**	**80**	**70**	**56**	**44**	**34**	**27**	**20**	**13**	**6**	

Legend:

W. Abs.	Water Absorption	FI	Flakiness Index	G_{sb}	Bulk Specific Gravity
AIV	Aggregate Impact Value	LAAV	Los Angeles Abrasion Value	G_{sa}	Apparent Specific Gravity
TFV	Ten Percent Fine Value			ρ_{loose}	Loose Density

4.3 Marshall Mix Design Analysis

4.3.1 Bulk Density

The density of the compacted mix is the unit weight of the mixture or the weight of a specific volume of asphalt mixture. Density is important because proper density in the finished product is essential for lasting blanket performance. Mix properties are required to be measured in volumetric terms as well as weight. Density allows converting units of weight to volume. It was observed in Figure 4-2 that the bulk density of the laboratory compacted asphalt mixture was increasing as bitumen content increased and reached a peak and then decreased. This trend was expected because bulk density initially increased due to the fact that the hot asphalt binder lubricates the particles allowing the compaction effort to force them closer. After reaching the peak, bulk density decreased because the additional bitumen added produces thicker films around the individual aggregates particles, thereby pushing the particles further apart thus resulting in lower bulk density, [63].

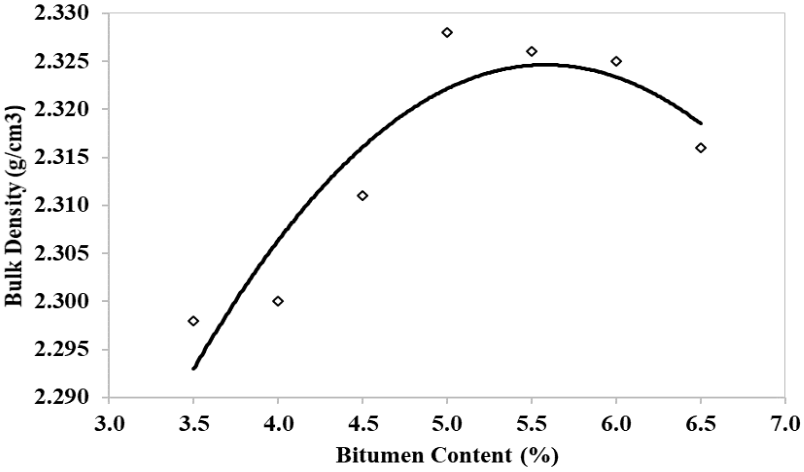

Figure 4-2: Bulk density variation bitumen content

The bulk density at 5% bitumen content was observed to abnormally outlie the trend. This is attributed to the fact that among the three specimens tested at 5% bitumen content, one specimen showed an abnormally high bulk density probably due to testing inaccuracies.

4.3.2 Marshall Stability and Flow

Marshall Stability measures mass viscosity of asphalt/aggregate mixtures and may determine resistance to permanent deformation, [63]. Generally, Marshall Stability values increased with increasing asphalt content reached a peak and then decreased as shown in Figure 4-3**.** This can be explained by the fact that all the voids are filled with bitumen at optimum bitumen content. More bitumen into the mix causes one to one contact of aggregate particles, become loose and the load is mainly transmitted by hydrostatic pressure through bitumen thus the strength of mix reduces as bitumen content increases. Figure 4-3 shows typical variation of Marshall Stability values giving an optimum bitumen content of 4% by weight of mix as indicated in the summary of results attached as Appendix 2.

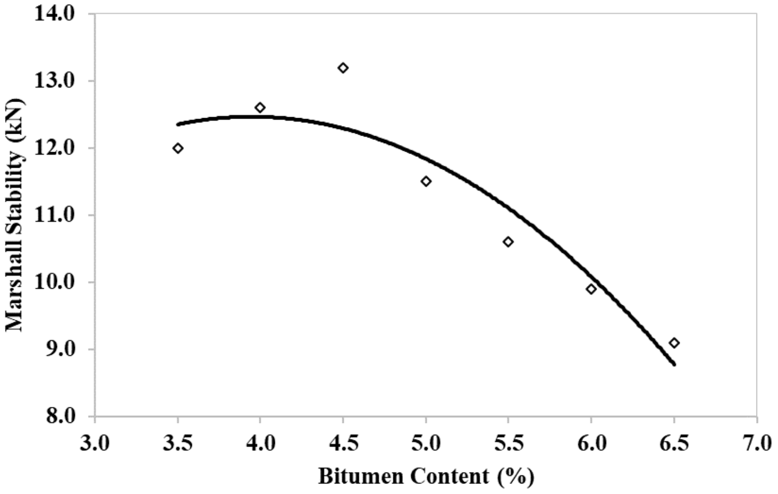

Figure 4-3: Marshall Stability variation with bitumen content

It was noted that all stability values were above the minimum value of 8kN recommended for heavy load category by AREMA (2010) specifications. A bituminous mixture with a minimum stability value of 8kN produces negligible deformation for a given bituminous layer under train loading conditions of upto 30 tons, [50]. The stability of a mixture depends on internal friction and cohesion. Internal friction among the aggregate particles is related to aggregate characteristics such as shape and surface texture while cohesion results from the binding ability of bitumen. The stability at 4.5% bitumen content was also observed to abnormally outlie the trend. This could also be a result of testing errors.

Table 4-2: Summary of Marshall Mix design properties

Binder Content (%)	Marshall Stability (kN)	Marshall Flow (mm)	Voids in Total Mix, VTM (%)	Bulk Density (gcm^{-3})	Voids Filled with Binder, VFB (%)	Voids in Mineral Aggregate, VMA (%)
3.5	12.0	2.9	8.2	2.298	50.56	15.60
4.0	12.6	3.2	7.3	2.300	56.38	16.00
4.5	13.2	3.9	6.1	2.311	63.70	16.01
5.0	11.5	4.1	4.3	2.328	71.99	15.85
5.5	10.6	4.5	3.8	2.326	76.70	16.35
6.0	9.9	4.8	2.8	2.325	81.18	16.80
6.5	9.1	5.2	2.0	2.316	83.87	17.60

Marshall Flow variation with bitumen content was also plotted as shown Figure 4-4. It shows that Marshall flow increased as bitumen content was increased.

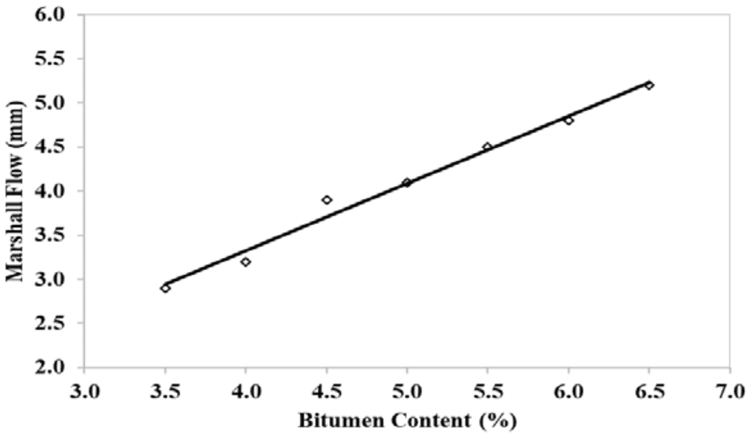

Figure 4-4: Marshall Flow variation with Bitumen content

4.3.3 Voids in Total Mix (VTM)

Voids in total mix is defined as the total volume of the small pockets of air between the coated aggregate particles throughout the compacted bituminous mixture, expressed as a percentage of the bulk volume of the compacted bituminous mixture. Figure 4-5 shows typical VTM variation with bitumen content for the basalt aggregates used in the study. Generally, the graph illustrates that VTM values decreased with increasing bitumen content. This trend was expected because as the bitumen content increases, bitumen fills the voids.

Research has shown that the amount of air voids in an HMA mixture affects the stability and durability. When the in-place air voids decrease to less than 3%, rutting of asphalt mixture is likely to occur, in case of paving mixtures, due to plastic flow, [86]. However, when the air voids are above approximately 8%, the mix is permeable to air and water, and the rate of oxidation of the asphalt binder is significantly increased resulting in premature cracking and/ or ravelling, [23]. The rate of oxidation is a function of the air voids as well as the asphalt film thickness.

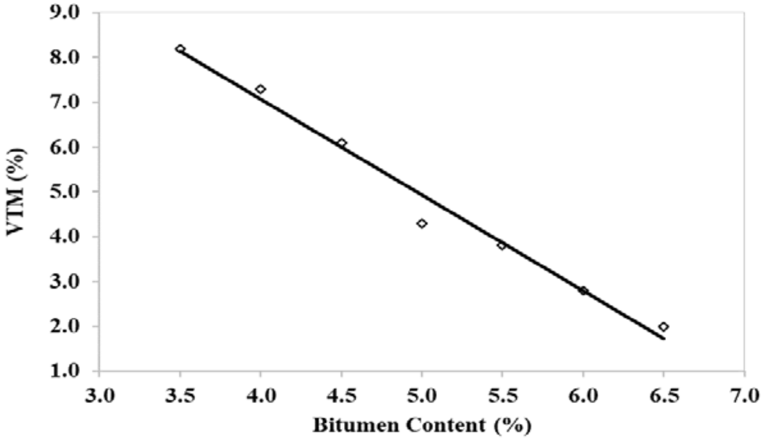

Figure 4-5: VTM variation with Bitumen content

4.3.4 Voids in the Mineral Aggregate (VMA)

Voids in the mineral aggregate (VMA) are the void spaces that exist between the aggregate particles in the compacted asphalt mixture, including the space filled with the binder. Figure 4-6 generally showed that VMA values increased with increasing bitumen content.

VMA represented the space that was available to accommodate the effective volume of binder (i.e., all of the binder except the portion lost by absorption into the aggregate) and the volume of air voids necessary in the asphalt mixture. The more the VMA in the dry aggregate, the more space is available for the binder. Since a thick binder film on the aggregate particles results in a more durable asphalt mixture, specific minimum requirements for VMA of 14% for AC20 asphalt mix is recommended by AREMA (2010) specification. The obtained VMA value was above the minimum 14% recommended.

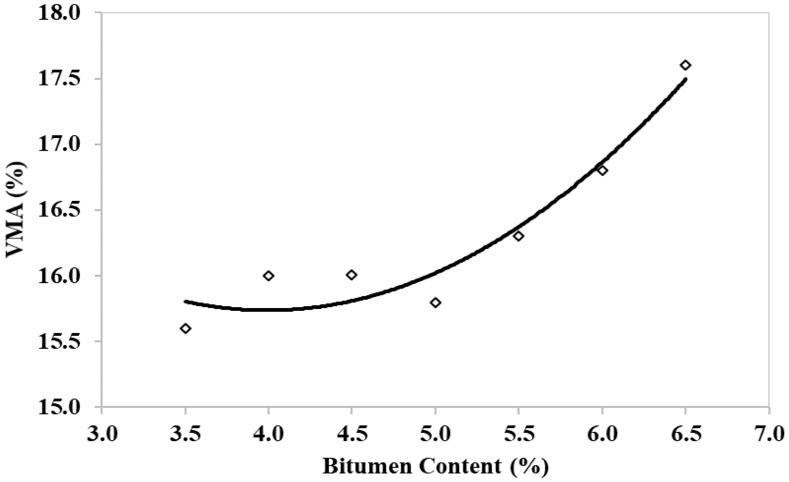

Figure 4-6: VMA variation with Binder Content

Minimum VMA values are required so that a durable binder film thickness may be achieved. Increasing the density of the asphalt mixture by changing the gradation of the aggregate may result in minimum VMA values with thin films of binder and a dry looking, low durability asphalt mixture. Therefore, economizing in binder content by lowering VMA is actually counter-productive and detrimental to the blanket layer quality. Low VMA mixes are also very sensitive to slight changes in binder. If binder content varies even slightly during production, the air voids may fill with binder resulting in flushing of a layer, [63].

VMA is most affected by the fine aggregate fractions which pass the No. 200 sieve. The reason for this is that these particles tend to be absorbed by the binder film. Because they take up volume, there is a tendency to bulk (extend) the binder resulting in a lower VMA. Other factors that affect VMA are compaction effort (number of gyrations), gradation, particle shape and particle texture. When the VMA is too low, sufficient asphalt cement cannot be added to the mixture to provide a satisfactory film thickness without overfilling the voids, [63].

4.3.5 Voids Filled with Bitumen (VFB)

Voids filled with Bitumen (VFB) are the void spaces that exist between the aggregate particles in the compacted asphalt mixture that are filled with binder. VFB was expressed as a percentage of the VMA that contains binder. Figure 4-7 shows that VFB values increased with increasing bitumen content. It was noted from Table 4-3 that the VFB values were in the range of 60% to 75% as recommended in the AREMA (2010) specification for concrete structures and foundations.

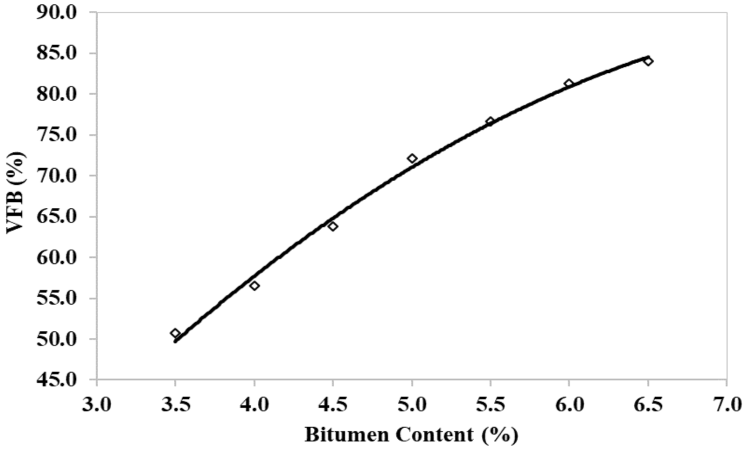

Figure 4-7: VFB variation Bitumen Content

Including the VFB requirement in a mix design helps prevent the design of asphalt mixture with marginally acceptable VMA. The main effect of the VFB is to limit maximum levels of VMA and subsequently maximum levels of binder content. VFB also restricts the allowable air void content for asphalt mixtures that are near to the minimum VMA criteria.

Asphalt mixtures designed for lower loading conditions may not pass the VFB requirement with a relatively high percentage of air voids in the field even though the air void requirement range is met. The purpose for the VFB is therefore to avoid less durable asphalt mixtures resulting from thin films of binder on the aggregate particles in heavy load situations. The voids filled with asphalt cement are inversely related to the air voids. As the percentage of air voids approaches zero, the percentage of voids filled with asphalt cement approaches 100%, [63].

In summary, the Optimum Bitumen Content was determined from four mixture volumetric properties as guided by the ASTM D1559 procedure. It is the average of the bitumen contents at maximum bulk density (5.6%), maximum Marshall Stability (4.0%), Marshall flow at 3mm (3.6%) and Voids in Total Mix at 4% (5.4%), and was obtained as 4.7%.

4.4 Performance Analysis of Modified Mixtures

Based on previous researches by Asi et al. (2007) and Magdi et al (2015), steel slag contents of 25%, 50%, 75%, and 100% were adopted in this study. These mixtures were conducted at constant bitumen content of 4.7%, optimum for the neat basalt aggregate, so as to clearly determine the effect of steel slag replacement. The Marshall properties of the modified Hot Mix Asphalt (from natural rock aggregates and waste steel slag) were evaluated in accordance with ASTM D1559. A summary of the test results is presented Table 4-3. In the remaining part of this report, a "modified mixture" means the coherent body made of bitumen binder, natural aggregate and waste steel slag uniformly blended as per test procedure described in section 3.4.3.

Table 4-3: Summary Marshall Test results for Modified Mixes

WSSA Content (%)	OBC (%)	Marshall Stability (N)	Marshall Flow (mm)	Bulk Density (gcm^3)	VFB (%)	VMA (%)	VTM (%)	Marshall Quotient (N/mm)
0	4.7	12432	4.64	2.324	68.05	15.73	4.80	2679.3
25		16221	4.48	2.401	65.46	16.90	4.31	3620.8
50		18222	6.22	2.447	58.26	19.35	3.80	2929.6
75		16608	5.73	2.505	53.47	21.59	3.62	2898.4
100		12196	5.26	2.615	53.67	22.45	3.46	2317.3

4.4.1 Bulk density of modified mixtures

The bulk density of modified mixtures increased with increasing percentage of Waste Steel Slag Aggregate (WSSA) as indicated in Figure 4-8. This was possibly due to the bulk specific gravity of the waste steel slag being higher than that of basalt aggregate. It was further observed that un-modified mixtures (0% and 100% WSSA) had the lowest and highest bulk densities respectively.

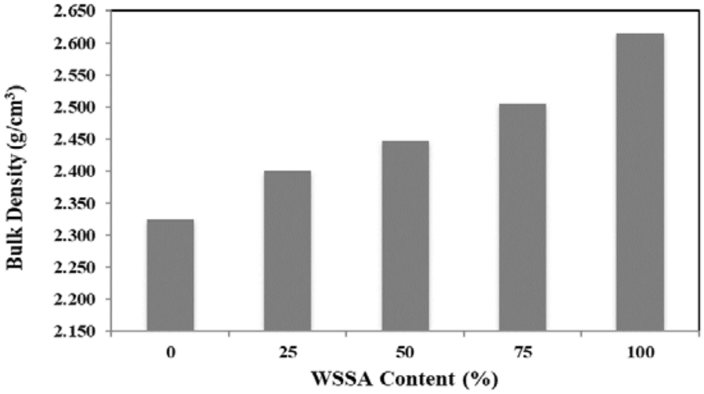

Figure 4-8: Bulk density of modified asphalt mixtures

4.4.2 Marshall Stability and Quotient

The Marshall stability values plotted against different Waste Steel Slag Aggregate (WSSA) Contents is shown in Figure 4-9. It was noticed that the Marshall Stability values for modified asphalt mixtures were above the 8000N (as indicated by dashed line in Figure 4-9) recommended for the heavy train load category. It was also observed from Figure 4-9 that the modified asphalt mixtures (25%, 50% and 75%) exhibited better Marshall stability than the unmodified asphalt mixtures (0% and 100%). The higher stability and lower flow are important criteria for Marshall Mix design analysis. The Marshall stability of asphalt concrete reflects its ability to resist shoving and rutting under traffic if it is used as a paving material. The Marshall flow is the ability of asphalt concrete to resist the gradual settlements and movements in the sub-grade without cracking, [76].

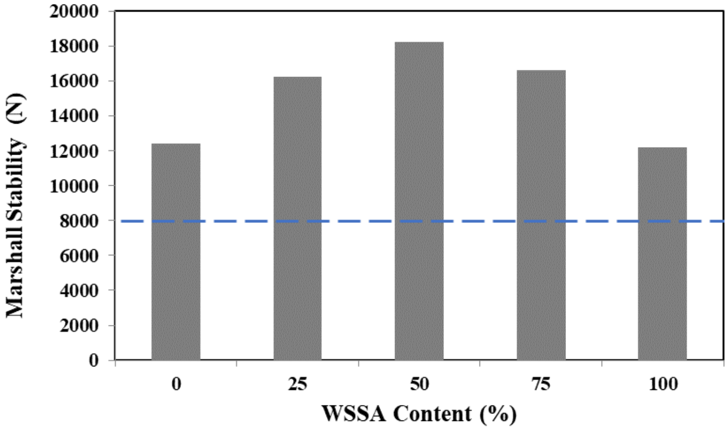

Figure 4-9: Marshall Stability of modified asphalt mixtures

It was also observed that all the Marshall stability values for the modified and unmodified asphalt mixtures were above the recommended minimum 8000N (as indicated by dashed line in Figure 4-9) for heavy loading category. It is believed that the reason for this is possibly due to the lower crushing a value of the waste steel slag when compared to Basalt aggregates as indicated in Table 4.1, [67]. This could also be possibly due to the optimum bitumen content of waste steel slag being lower or higher than the optimum bitumen utilized in the study.

Marshall Quotient (MQ) also known as rigidity ratio is defined as the ratio of Marshall Stability to flow of the mixture, [63]. The MQ values for modified asphalt mixtures (25%, 50% and 75%) were higher than that of unmodified asphalt mixtures (0% and 100%) as shown in Figure 4-10. These values were also higher than the recommended minimum 2000 N/mm by the Malaysian standard specifications for flexible pavements, Table 4.3.5, [85]. This trend could possibly be explained by the fact that waste steel slag aggregate possesses higher angle of internal friction, angularity and higher bulk specific gravity as compared to basalt aggregate, [7]. This property enhances better aggregate interlock and qualifies waste steel slag as suitable asphalt paving material, [53]. Therefore, modified asphalt mixes are likely to show higher resistance to permanent deformations and shear stress.

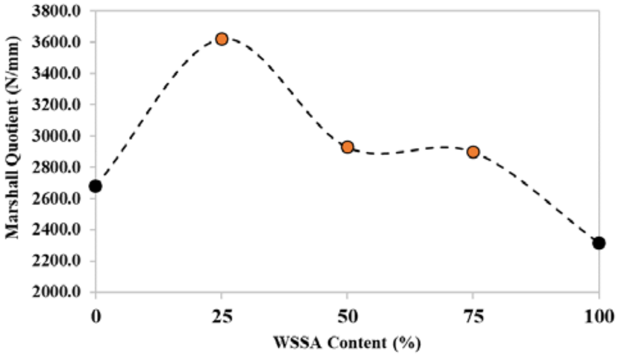

Figure 4-10: Marshall Quotient for modified mixtures

4.4.3 Voids in Total Mix and Voids in Mineral Aggregate

The Percentage of air voids in total mix (VTM) decreased while VMA increased for specimens prepared with WSSA when compared to the values of the basalt aggregate specimens as shown in Figures 4-11 and 4-12, respectively. It seems that the particle shape, grading and maximum nominal size for the aggregate used play the major role in the determination of these values. It was observed from the summary of results attached in Appendix 3 that the VTM values obtained for all mixtures meet the AREMA (2010) specification requirement of 3%-5%. The VMA values were above the minimum 14% recommended for AC20 asphalt mix by the same specification.

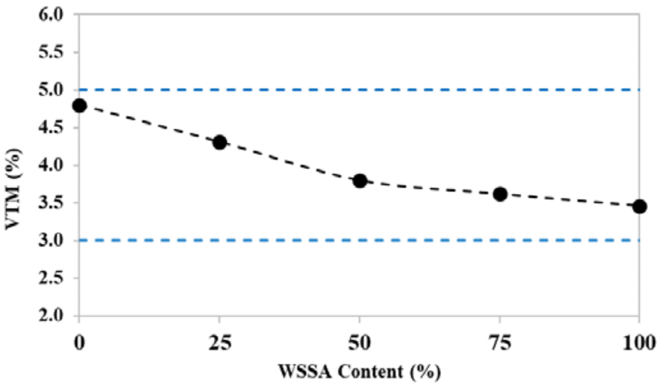

Figure 4-11: Voids in Total Mix for modified mixtures

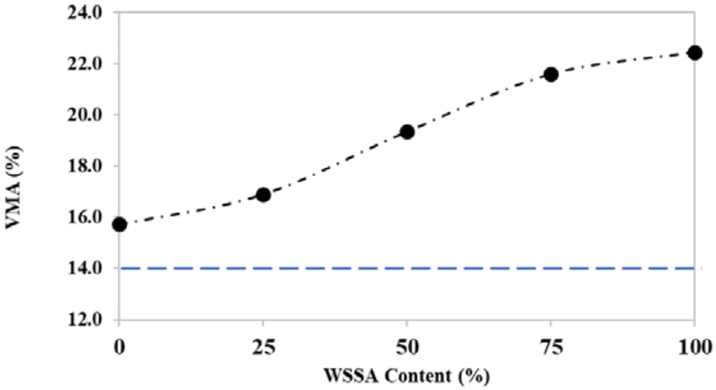

Figure 4-12: Voids in Mineral Aggregate for the modified mixes

4.4.4 Voids Filled with Bitumen

It was observed that the Voids Filled with Bitumen (VFB) values obtained for 0% and 25% waste steel slag mixtures were within the AREMA (2010) specification recommended range of 60% to 75% whereas those for 50%, 75% and 100% waste steel slag mixtures had their VFB values below 60% as shown in Figure 4-13. This is attributed to the change in the gradation of the samples as the waste steel slag aggregate content is increased, from 25% resulting in reduction in the available void spaces between aggregate particles.

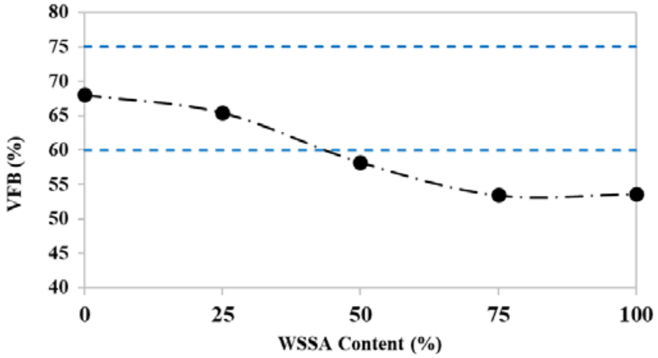

Figure 4-13: Voids Filled with Bitumen for modified mixtures

4.4.5 Indirect Tensile Strength

The summary of Indirect Tensile Strength (ITS) results is attached as Appendix 4. The Indirect tensile strength and Tensile strength ratio (TSR) results were plotted against mixture types (WSSA Content) as shown in Figure 4-14. Generally, it was observed that the modified asphalt mixtures yielded better ITS than unmodified mixtures. It was further noted that the ITS of the modified mixtures dropped after moisture conditioning. As explained earlier in literature review, the stripping of bitumen from the aggregate results in the strength reduction of asphalt concrete mixture, [54].

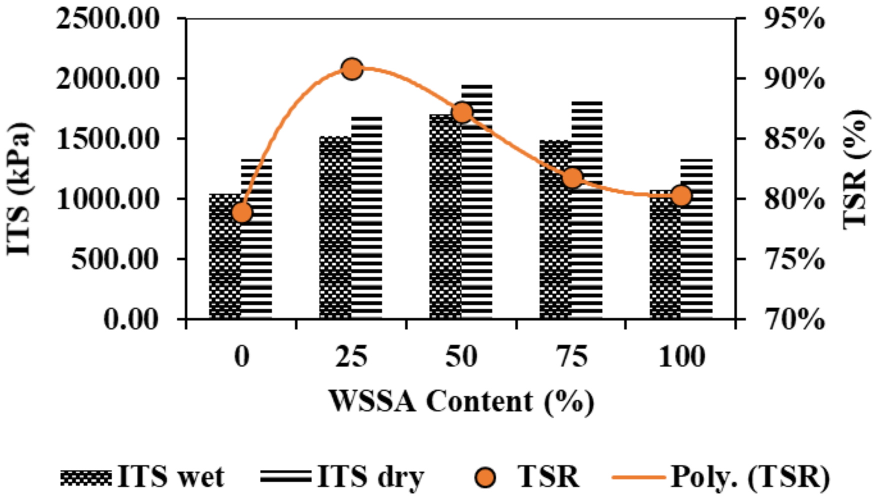

Figure 4-14: A plot of ITS and TSR against mixture types

In this study, the modified asphalt mixture with 50% WSSA exhibited the highest average Indirect tensile strength with 1701.33 kPa and 1948.79 kPa for conditioned and unconditioned specimens respectively compared to the other mixtures.

This was probably due to the low VTM (3.80%) of the 50% WSSA mixture as indicated in summary of results attached as Appendix 3. From other research findings, it was expected that a high VTM enables the mixture to have low strength and high deformation, [20], [71]. It was also observed that the modified mixture of 75% WSSA with 3.62% VTM provided second highest average ITS of 1498.72 kPa and 1830.76 kPa for conditioned and unconditioned specimens respectively as indicated Figure 4-14.

The addition of waste steel slag in the asphalt mixes increased the ITS of the modified mixtures. This was possibly attributed to the improved aggregate structure of the waste steel slag. The test results plotted in Figure 4-14 were in conformity with the findings of Asi et al., [10] and Oluwasola et al., [53]. In the literature reviewed, it was also noted that aggregate properties have a greater impact on adhesion than some of the binder properties, [80].

4.4.6 Moisture Susceptibility

The summary of moisture susceptibility results is attached as Appendix 4. It was observed in Figure 4-15 that the obtained Tensile Strength Ratio (TSR) values for most of modified mixtures were well above the limit value 75% (0.75), since it has been generally considered suitable by many agencies for good performance, [17]. Size and shape of the aggregate, pore volume and size, surface area, chemical constituents at the surface, acidity and alkalinity, adsorption size surface density, and surface charge or polarity are some of the widely cited aggregate characteristics that can influence moisture damage, [80]. Waste steel slag aggregates bear some of these characteristics. However, the question would be how significant were these values above the threshold of 75%. The proceeding parts of this report address this question.

The summary of moisture susceptibility results attached as Appendix 4 indicate that the 25%WSSA modified mixture had highest moisture resistance with TSR value of 91% whereas the lowest moisture resistance was attained by the neat (0% WSSA) mixture with TSR value of 79%. It was also observed that modified mixtures (25%,50% and 75% WSSA) showed better moisture damage resistance than unmodified mixtures (0% and 100% WSSA) as indicated in Figure 4-15. Basalt is generally considered a hydrophilic aggregate and its level of basicity or acidity condition may vary according to its chemical composition. It was expected that basalt aggregates have higher possibility of stripping due to the fact that they have higher moisture damage propensity because they have low affinity for water as compared to WSSA.

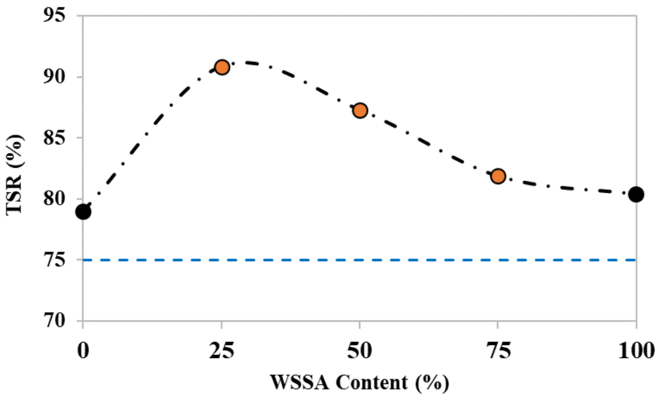

Figure 4-15: A plot of TSR values against types of mixtures

Integration of the waste steel slag asphalt mixture involved the need to optimise the mixes with the right binder content because the water damage resistance of the modified mixes with waste steel slag were higher than that of the unmodified mixtures, [56]. This can be justified by the fact that modified mixtures of 25%, 50% and 75% WSSA exhibited better moisture damage resistance (91%, 87%, and 82% respectively) whereas unmodified mixtures of 0% and 100% WSSA showed satisfactory moisture damage resistance (79% and 80% respectively) as they were all above the 75% threshold (dotted line) as indicated in Figure 4-15.

4.5 Statistical analysis

Data analysis was done to identify the factors which might contribute significantly to the TSR of the mixtures used in this study. The data generated was coded into Statistical Analysis Software (SAS) in order to test the hypotheses formulated in chapter 3. The factor considered was the Tensile Strength Ratio (TSR) generated from the moisture susceptibility tests at a 0.05 level of significance or 95% confidence interval.

4.5.1 Hypothesis One

The values of TSR for all modified mixtures in Appendix 4 were considered as a representative sample. Therefore, the objective was to test whether these values are on average less than 75%, the threshold value for good performance of the modified mixtures. The null hypothesis (H_o) was taken at the limiting TSR value of 75%. The hypothesis was modified as follows;

H_o: The TSR of modified mixtures is less than 75%

H_1: The TSR of modified mixtures is greater than 75%

$H_o: \mu_o < 75\%$, $H_1: \mu_o > 75\%$

The 95% confidence interval or 0.05% significance level for the mean TSR of modified mixtures obtained from MS-Excel outputs are shown in Table 4-4.

Table 4-4: Dependent Variable: TSR

t-Test: One-sample (TSR)	
Mean	83.872 (%)
Variance	25.152 (%)
Observations	5
Hypothesized Mean	75 (%)
df	4
$t_{\text{Statistic}}$	3.956
$P_{(T<=t)}$ one-tail	0.0084
t_{Critical} one-tail	2.132
$P_{(T<=t)}$ two-tail	0.0167
t_{Critical} two-tail	2.776

To reject or accept the null hypothesis, a comparison of the t_{critical} one-tail value and the $t_{\text{statistic}}$ value was made since this was a one-tailed test. From table 4-4, it was evident that $t_{\text{statistic}} = 3.956 > 2.132$, which calls for rejection of the null hypothesis. Therefore, basing on these results, it was logical to deduce that one is 95% confident that the average TSR value of modified mixtures was greater than 75%.

4.5.2 Hypothesis Two

The aim of this hypothesis was to test whether addition of waste steel slag significantly improved the TSR of the modified mixtures. The following hypothesis was formulated considering comparison of the mean TSR of unmodified samples (samples containing 0% and 100% WSSA) with the means of modified mixtures containing 25%, 50% and 75% WSSA separately.

H_0: Waste steel slag aggregates added does not influence the TSR.

H_1: Waste steel slag aggregates added influences the TSR.

H_o: $\mu_U - \mu_M = 0$, H_1: $\mu_U - \mu_M < 0$

Where μ_U is the mean of unmodified mixtures and μ_M is the mean of the modified mixtures. From the data shown in Table 4-4, $\mu_U = 79.5$ and $\mu_M = 86.7$.

This implies that; H_o: $\mu_U - \mu_M = -7.2$ ǂ 0 and H_1: $\mu_U - \mu_M = -7.2 < 0$. Therefore, the null hypothesis has to be rejected meaning that there is 95% confidence that the waste steel slag aggregates added influence the TSR value.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The feasibility of using waste steel slag in enhancing the performance of the bituminous railroad blanket layer has been investigated in this study. Natural basalt rock aggregate is replaced by Waste Steel Slag Aggregate (WSSA) in different asphalt concrete mixes. Marshall Mix design analysis, Indirect Tensile Strength and moisture susceptibility tests were conducted on prepared mixtures. The effectiveness of replacing natural basalt aggregate by WSSA was judged by the improvement in the physical and mechanical properties of the tested samples Based on the findings from this study, the following conclusions are drawn;

- The physical properties of natural basalt aggregates and WSSA basically satisfy the requirements of Marshall specification for the design of HMA. Based on laboratory test results, WSSA appears to be especially beneficial for use in Ethiopia and other developing countries to reduce the dependency on naturally occurring aggregate. Thus, it is recommended that the producers and the users of HMA in Ethiopia consider the use of WSSA.

- The minimum Marshall Stability value for modified asphalt mixtures is 34.4% above the recommended 8000N for heavy loading conditions by AREMA (2010) specifications for concrete structures and foundations. Asphalt mixtures modified with 25%, 50% and 75% WSSA yielded 26.7% more unconditioned Indirect Tensile Strength than the unmodified mixes (0% and 100% WSSA) and 32.6 % conditioned Indirect Tensile Strength more than unmodified mixtures. VTM values obtained for all modified and unmodified mixtures were within the AREMA (2010) requirement of 3%-5%. The lowest rigidity ratio/Marshall Quotient was 13.7% higher than the recommended minimum 2000 N/mm.

- The TSR values of both modified and unmodified mixtures were greater than the minimum 75% recommended by AREMA (2010) specifications for good performance with 25% WSSA modified mixture emerging with the highest TSR value. It is therefore logical for one to conclude that the resultant bituminous blanket layer will have satisfactory moisture damage resistance. Although up to 100% replacement of the basalt aggregates by WSSA is effective, the optimal WSSA replacement is 25%.

- Based on experimental findings, it can be concluded that it is possible to utilize waste steel slag to enhance the performance of the bituminous railroad blanket layer and reduce environmental degradation resulting from improper disposal of waste steel slag. From the economic point of view, the utilization of steel slag as a railway construction aggregate reduces the cost of extracting and processing naturally occurring aggregates. The steel producing industry also reduces the cost of treating and disposing of the large quantity of waste steel slag produced.

5.2 Recommendations

A similar research is recommended to be carried out on other aggregate types that may exist in large amounts and/or frequently used in railway construction and maintenance.

Regarding aggregate characteristics, petrographic analysis is recommended to further characterize the natural basalt rock aggregates. The detailed analysis of minerals by optical mineralogy in thin section, the micro-texture and structure are critical to understanding the origin of the rock. Petrographic analysis may further aid in explaining the mechanism of waste steel slag interaction in bituminous mixtures.

Other bitumen types such as the 60/70 penetration grade bitumen which is also more desirable for the few hot to warm climate regions in Ethiopia and other countries, should be evaluated for the same study so as to ascertain the cross effect of choice of asphalt binder to the modified bituminous mixture properties.

Field trials of the developed modified mixtures should be conducted to evaluate their field performance since this study was purely laboratory based.

Supplementary research is required to obtain new specifications for the use of waste steel slag aggregate in different fields of application. This is because the physical and mechanical properties of steel slag change with time as it is exposed to different weather conditions, hence need to regulate waste steel slag storage procedures.

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APPENDICES

7.1 Appendix 1

Mean Gradation data of aggregates used in the study

Sieve sizes (mm)	AVERAGE AGGREGATE SIZES (mm) % PASSING (HOT BINS)					AGGREGATE COMBINATION IN PERCENTAGE					COMBINED GRADING (BASALT AGGREGATES)	WSSA	SPEC. LIMITS	Upper Limit	Lower Limit
	20/14mm (A)	14/10mm (B)	10/6mm (C)	Stone Dust 6/0mm (D)	FILLER (CEMENT) (E)	A X 38%	B X 8%	C X 9%	D X 44%	E X 1%					
28	100.0	100.0	100.0	100.0	100.0	38.0	8.0	9.0	44.0	1	**100.0**	**100.0**	100	100	100
20	90.0	100.0	100.0	100.0	100.0	34.2	8.0	9.0	44.0	1	**96.2**	**100.0**	80-100	100	80
14	34.4	97.1	100.0	100.0	100.0	13.1	7.8	9.0	44.0	1	**74.8**	**71.7**	60-80	80	60
10	1.2	13.4	90.9	100.0	100.0	0.4	1.1	8.2	44.0	1	**54.7**	**61.0**	50-70	70	50
5	0.4	0.7	13.9	99.0	100.0	0.2	0.1	1.3	43.6	1	**46.0**	**47.0**	36-56	56	36
2.36	0.3	0.2	1.0	75.1	100.0	0.1	0.0	0.1	33.0	1	**34.3**	**37.3**	28-44	44	28
1.18	0.3	0.2	0.7	51.7	100.0	0.1	0.0	0.1	22.7	1	**23.9**	**30.1**	20-34	34	20
0.6	0.3	0.2	0.5	35.0	100.0	0.1	0.0	0.0	15.4	1	**16.5**	**18.2**	15-27	27	15
0.3	0.2	0.2	0.4	22.9	100.0	0.1	0.0	0.0	10.1	1	**11.2**	**14.0**	10-20	20	10
0.15	0.2	0.1	0.3	13.4	100.0	0.1	0.0	0.0	5.9	1	**7.0**	**9.8**	5-13	13	5
0.075	0.1	0.1	0.2	7.1	99.4	0.0	0.0	0.0	3.1	1	**4.2**	**0.2**	2-6	6	2

7.2 Appendix 2

Laboratory Marshall Mix Test Results for Basalt Aggregates

Binder Content (%)	Specimen No.	Marshall Stability (kN)	Average Stability (kN)	Marshall Flow (mm)	Average Flow (mm)	Voids in Total Mix, VTM (%)	Bulk Density (gcm^{-3})	Average Density (gcm^{-3})	Vois Filled with Binder, VFB (%)	Voids in Mineral Aggregate, VMA (%)
3.5	A1	11.8	12.0	2.91	2.9	8.2	2.294	2.298	50.56	15.60
	B1	12.1		2.93			2.309			
	C1	12.1		2.92			2.292			
4.0	A2	12.6	12.6	3.37	3.2	7.3	2.293	2.300	56.38	16.00
	B2	12.7		3.08			2.296			
	C2	12.5		3.14			2.310			
4.5	A3	13.3	13.2	3.87	3.9	6.1	2.308	2.311	63.70	16.01
	B3	12.9		3.98			2.308			
	C3	13.4		3.97			2.318			
5.0	A4	11.4	11.5	4.09	4.1	4.3	2.313	2.328	71.99	15.85
	B4	11.6		4.00			2.335			
	C4	11.5		4.07			2.335			
5.5	A5	10.5	10.6	4.48	4.5	3.8	2.326	2.326	76.70	16.35
	B5	10.7		4.56			2.326			
	C5	10.5		4.45			2.327			
6.0	A6	9.8	9.9	4.81	4.8	2.8	2.321	2.325	81.18	16.80
	B6	10.0		4.81			2.325			
	C6	9.9		4.68			2.328			
6.5	A7	9.0	9.1	5.22	5.2	2.0	2.314	2.316	83.87	17.60
	B7	9.0		5.22			2.317			
	C7	9.2		5.28			2.317			

7.3 Appendix 3

Results for Marshall Properties of Modified Mixtures

WSSA Content (%)	OBC (%)	Specimen No.	Marshall Stability (kN)	Average Stability (kN)	Marshall Flow (mm)	Average Flow (mm)	Bulk Density (gcm^{-3})	Average Density (gcm^{-3})	Vois Filled with Binder, VFB (%)	Voids in Mineral Aggregate, VMA (%)	Voids in Total Mix, VTM (%)	Marshall Quotient (kN/mm)
0	4.7	A0	12.342	12.430	4.77	4.64	2.329	2.324	68.05	15.73	4.80	2.681
		B0	12.399		4.50		2.321					
		C0	12.550		4.64		2.322					
25		A25	16.190	16.220	4.57	4.48	2.398	2.401	65.46	16.90	4.31	3.621
		B25	16.260		4.22		2.404					
		C25	16.210		4.65		2.401					
50		A50	18.340	18.223	6.18	6.22	2.450	2.447	58.26	19.35	3.80	2.930
		B50	18.200		6.22		2.446					
		C50	18.130		6.26		2.445					
75		A75	16.630	16.607	5.75	5.73	2.509	2.505	53.47	21.59	3.62	2.897
		B75	16.580		5.78		2.502					
		C75	16.610		5.67		2.504					
100		A100	12.210	12.197	5.31	5.26	2.614	2.615	53.67	22.45	3.46	2.317
		B100	12.240		5.25		2.616					
		C100	12.140		5.23		2.615					

7.4 Appendix 4

Indirect Tensile Strength and Moisture Susceptibility Tests Results

WSSA Content (%)	OBC (%)	Specimen No.	Specimen Height, t (mm)	Specimen Diameter, D (mm)	Measured Max. Load (N)	Indirect Tensile Strength (Wet) (kPa)	Indirect Tensile Strength (Dry) (kPa)	Average ITS (kPa)	TSR (%)	E-Modulus (MPa)	Average E-Modulus (MPa)
0	4.7	A0W	66.8	102.1	11285	1053.37		1051.59	79%	6525.54	7368.57
		B0W	66.9	101.9	11310	1056.19				6542.77	
		C0W	67.1	102.3	11270	1045.22				6475.82	
		A0D	66.4	102.2	14315		1342.93	1331.54		8291.86	
		B0D	66.7	101.9	14350		1344.10			8299.02	
		C0D	66.8	102.0	13995		1307.60			8076.39	
25	4.7	A25W	67.1	102.1	16615	1543.95		1528.67	91%	9518.08	9894.84
		B25W	66.7	102.1	16250	1519.08				9366.42	
		C25W	66.8	102.0	16300	1522.97				9390.11	
		A25D	66.5	102.0	17750		1665.93	1682.76		10262.17	
		B25D	66.8	101.9	18150		1697.49			10454.67	
		C25D	66.9	102.2	18095		1684.85			10377.60	
50	4.7	A50W	65.9	102.0	17810	1686.78		1701.33	87%	10389.36	11232.87
		B50W	66.3	102.1	18275	1718.69				10584.03	
		C50W	66.5	102.1	18115	1698.52				10460.99	
		A50D	66.8	102.0	20345		1900.91	1948.79		11695.55	
		B50D	66.4	101.9	20915		1967.87			12103.99	
		C50D	66.1	102.2	20985		1977.59			12163.32	
75	4.7	A75W	65.9	102.3	16125	1522.72		1498.72	82%	9388.57	10254.91
		B75W	65.9	102.1	15295	1447.17				8927.72	
		C75W	66.3	102.2	16245	1526.28				9410.34	
		A75D	66.6	102.0	19945		1869.13	1830.76		11501.70	
		B75D	65.9	102.1	19155		1812.39			11155.57	
		C75D	66.3	102.0	19235		1810.75			11145.58	
100	4.7	A100W	66.3	102.1	11335	1066.01		1074.38	80%	6602.68	7453.88
		B100W	66.3	102.0	11475	1080.24				6689.45	
		C100W	66.1	102.0	11405	1076.90				6669.07	
		A100D	66.0	102.0	14105		1333.86	1336.73		8236.53	
		B100D	65.9	101.9	14125		1339.09			8268.44	
		C100D	66.3	102.0	14205		1337.24			8257.14	