ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

By:

Getachew Adibaru Ewnetie

A Thesis submitted to the School of Graduate Studies in partial fulfillment of

the Requirements for the Degree of

Master of Science

in

Road and Transport Engineering

Advisor:

Robeam Solomon (PhD)

March 2025

Addis Ababa, Ethiopia

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UNDERTAKING

I, the undersigned, certify that, this thesis work titled **“Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt Mixtures**” is my original work performed under the supervision of my thesis advisor **Dr. Robeam Solomon** and has not been presented elsewhere for assessment and for degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

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Abstract

Warm mix asphalt (WMA) technology is recently developed and includes organic and chemical additives as well as water-based process (foaming effect), known for its environmental benefits, allows asphalt materials to be produced, placed and compacted at a relatively lower temperature than hot mix asphalt (HMA). This study evaluates the moisture sensitivity of water-based foamed warm mix asphalt (WBFWMA) by utilizing the hydrated lime additives as anti-stripping agent. The performance test was conducted with modified Lottman test for two nominal sizes of aggregate (20mm and 14mm). Statistical analysis using two-tailed t-test was also conducted to check the significance of the test result. The test result indicates that WBFWMA is more sensitive to moisture induced damage than HMA. However, the ITS value for lime-modified WBFWMA is comparable to HMA, revealing that it provides similar performance along with added environmental and cost benefits. The result recommended the use of lime-modified WBFWMA for its environmental and safety advantages.

Key words: Anti-Stripping, Foamed Bitumen, Hydrated Lime, Hot Mix Asphalt, Indirect Tensile Strength, Marshall Mix Design, Moisture Susceptibility, Tensile Strength Ratio, Warm Mix Asphalt.

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List of Abbreviations

AASHTO	–	American Association of State Highway and Transport Officials
AC14	–	Asphalt concrete with nominal maximum aggregate size of 14mm
AC20	–	Asphalt concrete with nominal maximum aggregate size of 20mm
ASTM	–	American Society for Testing and Materials
BS	–	British Standard
WBFWMA	–	Water-Based Foamed Warm Mix Asphalt
Gmb	–	Bulk Specific Gravity
Gmm	–	Theoretical Maximum Specific Gravity
HMA	–	Hot Mix Asphalt
ITS	–	Indirect Tensile Strength
NAPA	–	National Asphalt Pavement Association
OBC	–	Optimum Bitumen Content
PG	–	Performance Grade
SHRP	–	Strategic Highway Research Program
TSR	–	Tensile Strength Ratio
Va	–	Air Voids
VFB	–	Voids filled with bitumen
VMA	–	Voids in Mineral aggregate
WA	–	Water Absorption
WMA	–	Warm Mix asphalt

CHAPTER ONE

1. INTRODUCTION

1.1 General Background

In recent years, warm mix asphalt technology is chosen as an alternative sustainable and environmentally friendly paving material because of the concern about environmental issues, like global warming, environmental pollution and energy depletion [35]. Several warm-mix asphalt (WMA) technologies are used to reduce the temperature at which the asphalt materials are produced, placed and compacted, apparently without compromising the performance of the pavement. The interest in the use of warm-mix asphalt (WMA) for road pavement construction in the world is growing rapidly [63].

Warm mix asphalt (WMA) technology has developed in Europe and is gaining popularity worldwide mainly due to its environmental benefits and ability to improve engineering properties of asphalt binders with added advantages for reduction in emission and fuel consumption when compared with conventional HMA [51]. There are several types of technology used in warm mix asphalt, including water-based (foaming effect) technology, organic and chemical additives [44]. Even though these technologies are quite different, they all target the same goals of lower bitumen viscosity, better workability, and reduced emission. Foamed warm mix asphalt (FWMA) has several advantages in terms of reduction production temperature that results energy savings, reduction in emission during production and construction, along with low production cost, extending paving season, providing safety for workers, and more others.

In the case of WMA production, concerns arise about the possibility of lower production temperatures that may not completely dry the aggregates, and consequently increase the potential for moisture-induced damage. It is also believed that WMA produced with water-based technologies may lead to water entrapment within the asphalt mixture which could, in the long term, trigger moisture susceptibility problems [38]. The use of foamed bituminous asphalt mixtures is not widespread in the world because of the reason that include the limited number of related international literature, not too high strength, increased sensitivity to moisture and rutting [11].

Despite several benefits that foamed warm mix asphalt (FWMA) offers, the concern arises regarding the potential moisture-induced damage that can be produced within it because of production process. Injection of water to the hot bitumen to produce the foam warm mix asphalt (WBFWMA) has been proved to be an environmentally friendly technology, which could achieve the same performance as other warm mixing asphalt techniques. However, as the production process of WBFWMA mixture is short and the mixing temperature is low (130–140 °C), residual water from foaming or the moisture trapped in the asphalt mixture from incomplete evaporation may be retained in asphalt mixtures, even after compaction, that might generate failure during the service life, which manifests as a loss of adhesion between the binder and stripping of stone aggregate [58].

1.2 Statement of the problem

Warm mix asphalt technology has gained popularity and known for its environmental and cost benefits, allows asphalt materials to be produced, placed and compacted at a relatively lower temperatures compared to HMA without compromising quality or performance. WMA has gained popularity recently for use in construction of roads in cold climates, tunnels, and locations requiring long hauling distances due to its low temperature that permits to travel long distances without experiencing a significant drop in temperature during compaction.

When the proper method and procedure are used during preparation, other performance characteristics of the WMA mixtures will be improved or comparable to HMA mixtures of the same mix proportion. However, the main drawback of WMA is still moisture-induced damage because of its lower production temperature, which makes the asphalt mixture more susceptible to moisture. This is the reason why; it necessitates a separate investigation of moisture sensitivity evaluation of foamed warm asphalt mixtures among others.

In light of the aforementioned, a laboratory test was carried out to evaluate the effectiveness of hydrated lime additive on the ability of water-based foamed warm asphalt (WBFWMA) mixtures to withstand moisture damage.

1.3 Objectives

The objective of the study are as follows:

- Assess the impact of moisture on mechanical strength of WBFWMA.
- Assess the influence of hydrated lime additive on moisture damage resistance of WBFWMA.

1.4 Research Questions

- What is the impact of moisture on mechanical strength of WBFWMA compared to HMA?
- What is the degree of effectiveness of using hydrated lime additives on moisture damage resistance potential of foamed warm mix asphalt?
- What possible challenges can the asphalt industry encounter when applying water-based foamed warm mix asphalt?

1.5 Scope and limitation of the study

The scope of the study covers carrying out a laboratory test to evaluate the performance of water-based foamed warm mix asphalt in the presence of moisture compared to hot mix asphalt. It started from preparation of foamed warm mix asphalt mixtures by utilizing free water system technology in WMA and carry out indirect tensile strength tests that simulate the field performance of the mixture using hydrated lime additives as anti-stripping agent to find out its effect on the moisture induced damage resistance of water-based foamed warm mix asphalt mixtures. In addition, conventional hot mix asphalt mixtures of the same mix proportions that have not been treated will also be assessed to determine the treatment's level of effectiveness.

The limitation for the study was that, since warm mix asphalt is not common in use of it in Ethiopia and in East Africa’s pavement industry, it was difficult to find specialized laboratory setup to produce the foamed asphalt binder. The methodology used to produce the foamed binder by injecting cold water to hot bitumen using a syringe and thorough mixing with a mechanical mixer has also a limitation that might affect the test results of asphalt mixtures. The unavailability of organic and chemical additives in the local market to prepare the warm mix asphalt mixtures was also one of the challenges and limitations. Hence, water-based foamed warm mix asphalt mixtures were prepared for the study using a free water system of foaming effect technology.

1.6 Significance of the study

To address similar issues with the next generation of asphalt industry, warm mix asphalt technology, which offers numerous advantages over traditional hot mix asphalt in terms of cost, environment, health, and safety, the study will have benefits for assessing the efficacy of hydrated lime additives used as adhesion agent on the moisture-induced damage resistance potential of water-based warm mix asphalt mixtures. The study's conclusion will also be helpful for future research on the topic and its importance in the design and construction of asphalt pavement for various road projects using warm mix asphalt.

1.7 Thesis Organization

This study is basically divided into five main chapters. Chapter one intends to introduce the background, problem statement to the topic, the scope and purposes in doing the study. The second chapter contains the summary of theoretical and empirical literature reviews for related works of the previous studies similar to the thesis subject. The third chapter presents a detailed description of material selection and research methodology followed in the study. The fourth chapter presents laboratory test results, such as volumetric properties and mix design results of all types of mixes, followed by the analysis and evaluation of the effect of production temperature and technologies used in warm mix asphalt along with the effectiveness of hydrated lime additives on moisture induced damage resistance of asphalt mixtures. It was done with quantitative evaluation of the stripping potential through numerical simulation. Lastly, the fifth chapter provides a summary of the findings with conclusions and recommendations.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Warm Mix Asphalt Technology

The current practice of asphalt industry shifts towards warm mix asphalt of a relatively advanced new technology of asphalt pavement industry due to its lower production temperature of saving energy consumption and reduced emission. Warm mix asphalt is a relatively new technology that originated and first introduced in Europe in the late 1990s as a measure to reduce greenhouse gas emissions, but the technique was first created by a Professor Csanyi at Iowa State University in 1956. Warm mix asphalt is the designation given to asphalt mixtures that are heated and poured at temperatures between 200 ^{0}F and 250 ^{0}F [15].

Warm mix asphalt is the generic term for a variety of technologies that enable hot mix asphalt pavement material to be produced, placed, and compacted at lower temperatures without compromising quality or performance. The lower production and placement temperature make warm mix asphalt a greener alternative reducing both fuel consumption and production of greenhouse gases, which the reduction for fuel consumption can be from 35 up to 50 %.

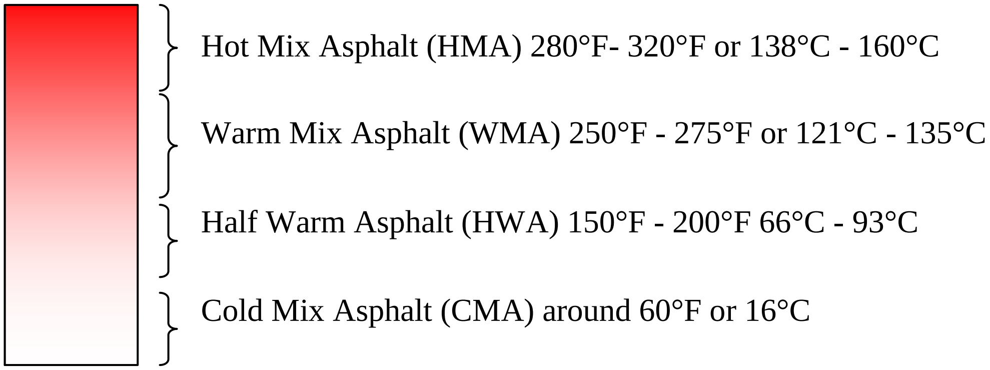

FIGURE 1. TYPICAL MIXING TEMPERATURE RANGE OF ASPHALT MIXTURES

One of the most important advantages of warm mix asphalt technology is that it needs less energy when mixing, hence energy consumption at the point of mixing can be reduced by up to 30% and as a result, less fuel is needed. The design of warm mix asphalt mixtures is like the conventional hot mix asphalt design of using the same practices with materials selection, proportions, volumetric characteristics, mechanical properties, and performance tests of asphalt mixes among others. WMA is less costly to produce than traditional HMA, because warm mix asphalt is manufactured and shipped at lower temperatures, it does not cool as fast as its hotter counterpart. Due to this property of WMA, it can be shipped over longer distances without compromising the quality of the produced mix and used outside of the normal paving and road construction seasons. WMA technology can deliver temporary changes to bitumen behavior to ensure full coating using less heat energy required compaction at lower temperature [21].

Lowering mixing and compaction temperatures has various advantages, particularly in terms of environmental and energy savings, which improves performance and safety as well as the environment [1].

Environmental benefits: -

- ✓ Less usage of carbon fuels
- ✓ Reduced greenhouse gas emissions during production
- ✓ Minimizes the production of fumes (around 50% at 10 ^{0}C).

Performance benefits:

- ✓ Comparable or better performance than hot mix asphalt
- ✓ Reduced binder hardening at low temperature

Health and safety benefits:

- ✓ Lower temperature provides cooler working conditions
- ✓ During winter and nighttime operation allows improved vision by reducing steam

Provide delivery cost savings:

- ✓ Shorter work schedules
- ✓ Lower costs for labor, plant, and traffic management
- ✓ Less disturbance for road users since the carriageway reopened more quickly

Since warm mix asphalt is mixed, poured, and laid at lower temperatures than hot mix asphalt, which results in more smoke, fumes, and dust that can cause respiratory problems, it is also healthier for the environment and the health of asphalt workers. Because WMA technologies have minimal gas emissions and enhance working conditions while minimizing worker exposure to gases and fumes created during asphalt paving, it can be used safely in tunnels and on days with poor air quality [39].

The basic principle of warm mix asphalt technology is that by adding certain additives in the mix, the coating of the aggregates by the binder is greatly enhanced and can be achieved at a considerably less temperature (typically 30 ^{0}C less) compared to the hot mix process. From these, free water system, water-bearing additives, chemical additives and organic additives or a combination of additives might be required to produce the warm mix asphalt mixtures [16].

- Free water system: - In warm mix asphalt (WMA), a free-water system is a foaming technique that lowers the viscosity of the asphalt by directly applying cold water to the hot bitumen, in which the water turns into steam and diffuses throughout the asphalt, lowering production temperatures.
- Water-bearing additive: - Warm mix asphalt (WMA) water-bearing additives are materials that lower the mixing and compaction temperature while maintaining or enhancing the performance characteristics of asphalt mixtures by assimilating moisture into the asphalt mixture, these additives lower the requirements for high temperature, which has environmental and cost benefits.
- Organic additives: - In production of Warm mix asphalt mixtures, organic additives are materials derived from natural or synthetic organic compounds those include waxes and bio-based additives used to enhance the workability and improving the adhesion and coating of aggregates with asphalt binder at lower temperature.

- Chemical additives: - In warm mix asphalt, the chemical additives that include surfactants and amine-based additives used to enhance the adhesion and coating of aggregate and asphalt binder at lower mixing and compaction temperature, results better workability and overall performance of asphalt mixture.

Warm mix asphalt technology has numerous advantages such as energy and resources saving due to lower mixing temperatures, improve working conditions for lower emissions of fumes, aerosols and odour at both plant and work site, quicker reopening of new traffic surfaces and lower production and laying temperatures reduce thermal aging of the bitumen and extending its service life.

There are three major types of warm mix asphalt technology identified, such as foaming effect, organic additives, and chemical packages. The foaming effect as its name indicates creates the foaming during the mixing process to increase the workability of asphalt mixture. It can be achieved by production process modification or introduce little amount of water to the asphalt mixture during the production using a hydrophilic material, which results a volume expansion of the binder that creates in asphalt foam to reduce viscosity and hence allows increased workability and aggregate coating during production of asphalt mixtures at lower temperature. The organic additives of warm mix asphalt technology often referred to as wax, which reduces the viscosity of asphalt binder at certain temperatures that allows the asphalt mixtures to be mixed and placed at lower temperatures. The chemical packages include anti-stripping additives and compaction aids that are designed to enhance adhesion, coating, and workability of the asphalt mixture at lower temperatures [16].

The WMA technologies are classified by type as organic additives, chemical additives and those technologies that introduce water into the mix through a water-bearing additive or through a modification into the production process creating the foamed phenomenon.

Table 1. Examples of Warm Mix Asphalt Technologies

Foaming Effect		**Organic Additives**		**Chemical Additives**	
Warm Mix Asphalt Technology	**Recommended Additive/Usage**	**Warm Mix Asphalt Technology**	**Recommended Additive/Usage**	**Warm Mix Asphalt Technology**	**Recommended Additive/Usage**
Aspha-min®	0.3% by total weight of bitumen	Sasobit®	0.8-3.0% by weight of bitumen	CECABASE RT®	0.2-0.4% by weight of bitumen
ADVERA® WMA	0.25% by total weight of bitumen	Asphaltan-B®	2.5% by weight of bitumen	Rediset WMX®	2% by weight of bitumen

Foaming Effect		**Organic Additives**		**Chemical Additives**	
WAM-Foam®	No additive. It is a two-component binder system that introduces a soft and hard foamed binder at different stages during plant production	Licomont BS 100	3% by weight of bitumen	Evotherm®	Generally pumped directly off a tanker truck to the asphalt line using a single pair of heated valves and check valves to allows for circulation
LEA®	1.0-2.0% by weight of bitumen	-	-	-	-
LEAB®	0.1% by weight of bitumen	-	-	-	-

2.1.1 Foaming Effect

The foaming effect is one of the most used WMA technologies in the world due to its cost-effectiveness, which is no extra additives are required and the water is easier to handle and obtain. The concept behind the foamed WMA is that the water turns to steam dispersed throughout the asphalt, and then the steam expands the volume of the binder providing a corresponding temporary reduction in viscosity. This foaming effect plays a vital role in reducing the surface tension and improves the coating of aggregates with bitumen, which enhances the adhesion properties that leads a more durable and reliable asphalt pavements. There are two commonly known techniques of producing foamed WMA such as free water system and foaming admixture [28].

1) **Free Water System**

Free water systems were developed by those manufactures for asphalt plants to produce large scale warm mix asphalt and used either a single nozzle or a series of nozzles to inject a small amount of water to produce the required foamed asphalt. The foaming effect by the free water system is that water expands when it turns to steam, where in this expansion of water inside the asphalt will result in a reduction of viscosity, allowing a lower temperature for aggregate coating and mixture compaction [43].

2) **Foaming Admixture**

There are different types of warm mix asphalt technologies that use foaming admixture techniques to produce WMA. There are two types of foaming admixture techniques, i.e., hydrophilic materials and damp aggregates which are discussed in the section below.

a) **Hydrophilic Materials:** Warm mix asphalt technologies using hydrophilic materials such as synthetic zeolite are framework silicates that have large vacant spaces in their structure that allow space for large cations like calcium, barium, potassium and sodium, and even relatively large molecules and cation groups such as water. Technologies that use hydrophilic materials as foaming technique include Asphamin® and ADVERA® WMA [3].

b) **Damp Aggregate:** Warm mix asphalt using damp aggregate as a foaming method have been used for construction of asphalt pavements especially in Europe. Low Energy Asphalt (LEA) is one of the well-known technologies that used damp aggregate as a foaming admixture to produce warm mix asphalt at about as 95°C. In the LEA WMA process, there are five phases shown below to produce warm mix asphalt [24].

Phase 1:	Heat the coarse aggregate to about or more than 266 ^{0}F (130 ^{0}C), and then mix and coat with hot asphalt at approximately 338 ^{0}F (170 ^{0}C) based on asphalt binder grade.
Phase 2:	All the coarse aggregate should be fully coated by all the asphalt and have a thick film of asphalt.
Phase 3:	Wet and cold fine aggregate was added, and moisture from fine aggregate should trigger asphalt foaming.
Phase 4:	Foamed asphalt encapsulates fine aggregates.
Phase 5:	Thermal equilibrium reached; all aggregates should be coated uniformly.

The foaming caused by water-bearing additives includes inorganic synthetic crystals like zeolites, which deliver its water at contact with heated asphalt binder producing the foaming effect. The general mechanical process is based on introducing small amounts of cold water that are injected into a stream of the heated binder at temperatures ranging from 130 to 150 ^{0}C. The process of mixing cold water with hot binder results in a volumetric expansion, hence the viscosity of the binder is reduced which favors the coating of the aggregates at lower temperature and improves the workability of asphalt mixture [3].

For foamed admixture, Aspha-min® and ADVERA® WMA were selected; and for free water system, WMA foamed by injecting a small amount of water was produced under a laboratory setup. In this, various laboratory tests were performed to verify the overall performance of warm mix asphalt mixtures produced with foaming method. Some of the foaming admixtures used to produce warm mix asphalt mixtures are discussed hereunder [24].

Aspha-Min®: Aspha-Min® is a synthetic inorganic foaming additive to manufacture warm mix asphalt mixture. Its development dates back more than 10 years to when the European Union set industry targets to reduce CO2 emissions by 15% and has been used in Europe for quite a long time, while in U.S it has been used in road paving projects as well as a paving demonstration at the 2004 World of Asphalt [26].

ADVERA® WMA: ADVERA® WMA is a synthetic mineral foaming additive of inorganic chemical powder, which is also an aluminosilicate or hydrated zeolite powder. For manufacturing of WMA using ADVERA® WMA additive, it is recommended to add a rate of 0.25% by weight of the asphalt mixture [23].

2.1.2 Organic Additives

This technology introduces commonly used organic additives like waxes and fatty acid amide to produce warm asphalt mixtures. In general, the organic additive reduced binder viscosity when heated above their melting point. Examples of WMA technologies use organic additives include Sasobit® and Licomont BS-100 [9].

Sasobit®: Sasobit® is a synthetic hard wax of fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from coal gasification using the Fischer-Tropsch (FT) process [7]. In the Fischer-Tropsch synthesis, coal, or natural gas (methane) is partially oxidized to carbon monoxide which is subsequently reacted with hydrogen (H2) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of carbon (C5) to C100 plus carbon atoms.

2.1.3 Chemical Additives

Chemical additives in warm mix asphalt are materials that improve the adhesion properties that results to enhancing the bond between the aggregate and asphalt binder by; lowering the surface tension, creating stronger adhesion with forming the molecular links that resist moisture infiltration, modifying the physical properties of asphalt binder to make flexible and improving its ability to maintain adhesion, displacing moisture from aggregate surface that allows asphalt binder to make better contact with aggregate, creating micro-molecular changes in the asphalt binder facilitating better bonding with aggregate, all enhances the adhesion and makes the bond between asphalt binder and aggregate more stronger to withstand the damage with moisture [30, 54]

This type of additive is composed of a combination of emulsifier agents, surfactants, polymers, and additives to improve the coating, workability, and mechanical characteristics of the asphalt mixtures [52]. The chemical additive that used surfactant acted as “lubricant” to reduce the internal friction during mixing and compaction of asphalt mixtures and work at the microscopic interface of aggregate and the asphalt. This “lubricant” is effective at a certain temperature ranging from 85°C to 140°C typically. Cecabase RT®, Evotherm® and Rediset^{TM} WMX are representative chemical additives to produce warm mix asphalt mixtures.

Cecabase RT®: Cecabase RT® is a patented chemical additive that is made up of 50% renewable raw materials to increase workability to produce the warm asphalt mixture at a lower temperature. The Cecabase RT® is available in liquid form and can be injected directly into the asphalt [60].

Evotherm®: Evotherm® uses a non-proprietary technology that is based on a chemical additive that includes surfactants i.e., additives to improve aggregate coating, mixture workability, and compaction as well as adhesion promoters or anti-stripping agents to produce warm asphalt mixtures [27].

Rediset TM: Rediset™ is a chemical additive-based warm mix asphalt technology that is a combination of cationic surfactants and organic additive-based rheology modifier, in which the surfactants improve the wetting of aggregate surfaces with binder by “active adhesion,” and the other components that the additive reduce the viscosity of the binder results coating and workability of asphalt mixtures at lower temperature [36].

2.2 Moisture Susceptibility of Asphalt Mixtures

Almost a few decades ago, one of the primary concerns in pavement construction was moisture-induced damage or moisture susceptibility in asphalt pavements [46]. The cohesive failure within the asphalt bitumen and the adhesive failure between the bitumen and aggregates are the two main characteristics of moisture-induced degradation to asphalt pavement. The detrimental effects of moisture on the adhesive and cohesive properties, both of which affect the performance of asphalt mixtures, must be taken into consideration. Recent research has demonstrated that moisture damage is undoubtedly not limited to adhesive failure, but that weakening of the cohesive strength of the mastic due to moisture infiltration is equally important [30].

The performance of asphalt mixture towards moisture induced damage dominantly influenced by aggregate mineralogy, bitumen characteristics and anti-stripping additives alongside construction methods, climate, and traffic loading [40, 46]. Moisture susceptibility test simulates the effect of moisture on the field performance of asphalt mixtures conditioning in the laboratory. Implementation of any laboratory test for moisture susceptibility or stripping will always require calibration of the results that the test generates with observed field performance.

2.2.1 Laboratory Testing Methods For evaluating Moisture Susceptibility

Tests to determine the moisture-resistant of asphalt–aggregate mixtures are categorized into two main categories i.e., qualitative and quantitative tests. While quantitative tests provide a value for a specific parameter of the asphalt mixtures, such as strength gain and/or loss before and after moisture conditioning of the specimen, qualitative tests, which are to be conducted for moisture susceptibility of asphalt mixtures, provide a subjective evaluation of the stripping potential of asphalt mixtures.

- Qualitative assessments of asphalt mixes' susceptibility to moisture:
  a) **Freeze-thaw test: -** It is a widely used type of laboratory test used to characterize to moisture sensitivity of asphalt mixtures by simulation the environmental condition pavement moisture damage with assess the durability and resistance of asphalt mixtures against freezing and thawing cycles, which simulates the environmental conditions that lead to deterioration due to moisture with prepared asphalt mixtures performed freeze-thaw cycles with the maximum of cycles being ten times [42].

b) **Rolling bottle test: -** It is a stripping test conducted on aggregate and bitumen mixture, which is placed in a jar filled with water, wherein the jar rotated and the contents are agitated that helps to evaluate the affinity between aggregate and bitumen with visual observation [30].

c) **The boiling water test:** - This test is a quick laboratory test to evaluate the stripping of asphalt mixtures by visual observation which can be conducted on loose mixtures under the effect of boiling water for a pre-determined period of 10min [30].

- Quantitative evaluations of asphalt mixes' susceptibility to moisture:
  a) **Indirect tensile strength test: -** This test can be used to evaluate the resistance of moisture damage conducted with samples subjected to applied load with a loading rate of 5.08 cm/min until the sample is fractured, wherein, the maximum load value is recorded at the time of fracture [6].
  b) **Marshall immersion test:** This test method measures the loss of Marshall Stability caused by water action on compacted asphalt paving mixtures that comprise asphalt cement of penetration grade [12].
  c) **Immersion-compression test:** This test determines how much cohesiveness is lost when water interacts with compacted bituminous mixtures that contain penetration-grade asphalts with a numerical index containing reduced cohesiveness by comparing the compressive strengths of newly molded and cured specimens with those of duplicate specimens that have been submerged in water under specific conditions [25].

There are two ways that moisture damage can occur, either the bitumen weakens due to cohesion failures in the presence of moisture, or the bitumen and aggregate lose their adhesion [13].

2.3 Mechanism of Stripping

Stripping of asphalt pavement is disbanding of bitumen film from the surface of the aggregate, causes a loss of bond between aggregates and asphalt binder in the presence of moisture. There are different mechanisms by which stripping of asphalt binder from an aggregate surface may occur [8]. These mechanisms include detachment, displacement, spontaneous emulsification, pore pressure, film rupture, hydraulic scouring, PH instability, environmental effects, adhesion and cohesion and these mechanisms may act individually or together to cause adhesion failure in bituminous mixtures.

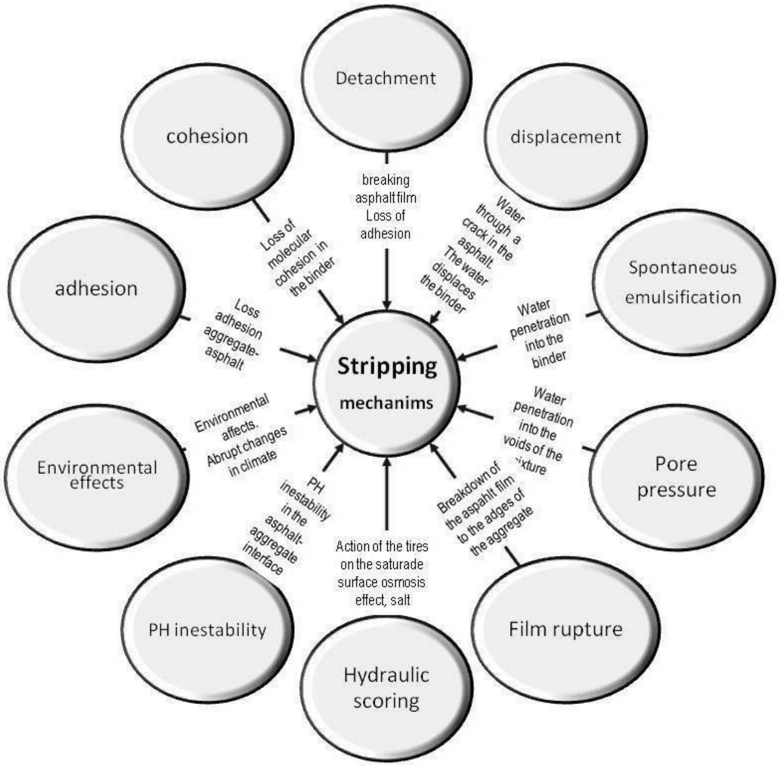

FIGURE 2. MECHANISMS OF STRIPPING

From the above different stripping mechanisms, some of them are discussed in the section hereunder.

a) **Detachment:** Detachment is the separation of an asphalt film from an aggregate surface by a thin layer of water, with no obvious break in the asphalt film [40]. Where stripping by detachment has occurred, the asphalt film can be peeled cleanly from the aggregate, indicating a complete loss of adhesion.
b) **Displacement:** Stripping or displacement results from the penetration of water to the aggregate surface through a break in the asphalt film, which is caused by incomplete coating of the aggregate or by film rupture [31].
c) **Spontaneous Emulsification:** In spontaneous emulsification, water and asphalt combine to form an inverted emulsion, where asphalt represents the continuous phase and water represents the discontinuous phase.
d) **Pore Pressure:** Pore pressure has been suggested as a mechanism of stripping in high void mixes where water may circulate freely through interconnected voids. When densification of the mix from traffic loading occurs, water might be trapped in impermeable voids that previously permitted water circulation.
e) **Hydraulic Scouring:** Hydraulic scour occurs at the pavement surface, here stripping results from the action of vehicle tires on a saturated pavement surface [30]. Water is sucked under the tire into the pavement by the tire action.

2.4 Factors Causing Stripping

Stripping is the loss or breakdown of the adhesive bond between the aggregate and the asphalt binder in the presence of moisture caused by conditions under which the aggregate is more likely wetted by water than asphalt bitumen. It is a quite complex problem which depends on many variables including the type and use of mix, asphalt binder characteristics, aggregate properties, construction methods, imposed traffic loads and environmental effects [30].

TABLE 2. FACTORS INFLUENCING STRIPPING

Factors	Determining Characteristics	Favorable Properties
Aggregate Properties	Surface texture, mineralogy, porosity, surface moisture, surface chemical composition and surface coating	Rough surface texture, carbonaceous aggregate, low silica content, optimum amount of porosity, surface dry aggregate, no coating
Bitumen Characteristics	Asphalt film thickness, viscosity, physical and chemical structure	High asphalt film thickness, High viscosity, existence of phenol and nitrogen
Construction Method	Compaction method, drainage system, air void mechanism,	Adequate compaction, proper drainage system, low air void percentages, adapt water resistance additives on each layer of pavement
Environmental Condition	Climates, Environmental temperature	Warm climates, mild temperature (low rate of changing in temperature), no freeze-thaw cycles
Imposed traffic load	Traffic load	Low traffic

The loss of the bond between the aggregate and the binder due to moisture damage is known as stripping, which causes many surface manifestations such as rutting, corrugations, shoving, raveling, and cracking Stripping of asphalt pavements has been a significant problem for many transportation agencies, which is recognized as a cause of premature pavement damage. The development of test procedures for evaluating stripping potential appears to be progressing towards the measure of strength or modulus loss i.e., loss of adhesion or cohesion of asphalt mixtures that have been compacted and conditioned under moisture [33].

2.5 Methods to Prevent Stripping

To prevent or at least minimize the moisture damage of asphalt mixtures, varies measures can be taken that ranges from material selection to construction practices, pavement design and using anti-stripping additives. Asphalt mixtures are mainly comprised of asphalt, filler, and skeleton aggregate, in which the skeleton aggregate mass accounts for about 95% of the total mass of the asphalt mixture [8]. Since stripping is the loss of adhesive bonds between asphalt and aggregate in the presence of moisture, there are different methods to reduce stripping effect such as drying of aggregates before mixing and washing of aggregates to remove dusts from the aggregate surface, pretreat aggregates to modify aggregate surface properties to replace ions that are likely contribute to poor asphalt binder-aggregate adhesion and use of anti-stripping additives. In the pavement industry, a commonly used method to prevent moisture damage is using anti-stripping additives on asphalt mixtures.

2.6 Anti-Stripping Additives

There are different types of anti-stripping additives used to improve the adhesion properties of aggregate and asphalt binder includes but not limited to hydrated lime, liquid anti-stripping additives of amine products, polymer additives, bio-based additives and nanomaterials. Hydrated lime is the most effective, affordable and superior adhesion agent to minimize the stripping potential of asphalt mixtures in the presence of water, which can be applied either in dry or slurry states. Liquid anti-stripping additives are chemical surfactants that reduce the aggregate's surface tension promoting better surface coverage. Polymers are chemical additives that enhance the adhesion properties of asphalt binder and aggregates that improve the moisture sensitivity resistance and includes, styrene-butadiene-styrene (SBS), Ethylene Vinyl Acetate (EVA) and Polypropylene [49]. Bio-based additives are natural polymer and synthetic organic materials that used to enhance the adhesion of aggregate-bitumen for better coating and improve the moisture resistance of asphalt mixture, and includes Lignin, starch and vegetable oils [37]. Nanomaterials are chemical additives used to improve the mechanical strength of asphalt mixture with better adhesion and coating properties of aggregate with asphalt binder and results increased resistance of moisture induced damage, which includes Nanoclays, Carbon Nanotubes and Silica Nanoparticles [56].

2.6.1 Hydrated Lime

Hydrated lime works by replacing negative ions on an aggregate surface with positive calcium ions, results improved binder–aggregate adhesion by interacting with carboxylic acids in the asphalt and forming insoluble salts that are readily adsorbed at the aggregate surface [34]. One of the important components often used in asphalt mixes is hydrated lime, which serves as a combination of anti-stripping agent, filler, and modifier. Besides reducing moisture sensitivity, it also increases initial stiffening thereby helping minimize rutting and reduces long-term oxidative hardening of the asphalt.

The effectiveness of hydrated lime additives as an adhesion agent in mitigating moisture induced damage of asphalt mixtures is highly dependent on its physicochemical interaction with both asphalt binder and aggregate particles. The finer the hydrated lime particle, the larger the surface area and the higher the number of hydrated lime particles for the same weight, hence, the effectiveness of hydrated lime will be increased with the increase in fineness. However, using too fine of hydrated lime particles can have negative consequences on the performance of asphalt mixture. For example, excessively fine particles can increase the viscosity of the asphalt mixture, making it more difficult to mix and spread that affects workability of the mixture.

The use of lime in asphalt paving began in the early 1900s, of the various molded distresses, raveling, rutting, cracks. Perhaps the seriousness of all distress is due to loss of adhesion and cohesion between asphalt and aggregates, causing the asphalt to be stripped away. Hydrated lime, because it leads to more prominent bonding between asphalt and aggregate has become an important additive in asphalt paving. For reducing moisture damage in asphalt concrete pre-treatment aggregates with lime, typically 1-1.5% is the most effective method.

There are various theories regarding the adhesion of asphalt to aggregates. One is related to surface chemistry and helps to explain why lime is so effective. Most stripping occurs with silica or silica bearing aggregates having negative charges and with clay coated aggregates also having negative charges largely due to the clay.

Since asphalt cement contains acidic components, for example carbocyclic acid, the bond is weakened due to negative charges repelling each other. When hydrated lime is added, it persists positive charges enhances the bonding due to opposite charges attracts each other. One of the common silicas bearing rocks used in asphalt paving is granite, which contains more than 50% coats of silica. Other siliceous rocks include sandstone, quartzite, Rhyolite, basalt, and siliceous limestone. Clay gravel is another aggregate known to strip. With this type of aggregate, lime reduces the plasticity of the clay and increases the strength of the mix.

There are numerous advantages of adding lime in to asphalt paving mixes including the following.

- ✓ Improved resistance to moisture
- ✓ Increased strength and stability
- ✓ Increased initial stiffness
- ✓ Reduce long-term viscosity and age hardening
- ✓ Increased ductile flow at low temperature
- ✓ Increased pavement durability

Generally, hydrated lime improves durability by reducing stripping, improving tensile strength and reducing age hardening. The lime typically used in asphalt mixes is dry hydrated lime. However, lime slurry made from hydrate can also be specified, but increases cost because the water needed to make the slurry increases aggregate drying time and lowers the production rate. Thousands of kilometers of paved roads in Ethiopia more than 90% is surfaced with asphalt either hot mix asphalt or asphalt surface treatment. This extensive use of asphalt paving is based on product ability used in low cost of construction, durability and low life cycle cost inherent in this versatile paving system.

Due to its superior performance against moisture induced damage resistance and comfortable usage in comparison to other additives, hydrated lime is the most used adhesion agent in the asphalt pavement industry. A dry fine, free-flowing white powder with the chemical formula $Ca(OH)_2$ manufactured in state-of-the-art plants will be used for the study.

2.6.2 Performance of Hydrated Lime in WMA Mixtures

Hydrated lime increases the homogeneity of asphalt mixtures, preventing segregation and producing consistent and uniform asphalt mixtures, which can be used to produce the ideal mixture that balances moisture sensitivity, resistance to rutting, and workability [52].

a. **Moisture Susceptibility Resistance: -** Hydrated lime improves the binder-aggregate bond and reduces asphalt mixture peeling by increasing the adhesion between aggregate and binder, which lowers the effects of moisture-induced degradation [4, 52].
b. **Permanent Deformation (Rutting) Resistance: -** The addition of hydrated lime to the warm mix asphalt mixture increases the stiffness of the asphalt binder, which improves the asphalt's resistance to permanent deformation under heavy traffic loads [4].
c. **Reduction of Oxidation and Aging:** - Hydrated lime uses to slowdown the rate at which asphalt binder oxidizes and aging because of the chemical reaction between calcium hydroxide and the highly polar molecules in the bitumen [59].
d. **Reduction of Thermal Cracking:** - It increases the flexibility of asphalt binders, which reduces the possibility that asphalt binder may break due to factors other than aging, such as low-temperature wear and tear because of the reaction between the lime and the polar molecules in the asphalt binder, which increases the effective volume of the lime particles by encircling them with broad organic chains, it lowers cracking more than passive fillers [14].

2.6.3 Environmental and Economic Benefits of Hydrated Lime in WMA

Hydrated lime in warm mix asphalt mixtures has cost and environmental benefits in addition to mitigating moisture-induced damage and improving overall performance of asphalt mixtures.

Environmental benefits: - Hydrated lime is acknowledged as a sustainable and environmentally friendly adhesion agent, this is because it reduces the release of environmentally hazardous carbon emissions during the manufacturing of asphalt mixtures. For adhesion and anti-stripping, lime is a natural and abundant resource that is preferred over synthetic or chemical additives since its manufacture has less of an adverse environmental impact than other petroleum-based chemicals and synthetic materials [53].

Economic benefits: - Hydrated lime can save energy during production and paving by improving workability and stability, which can result in significant cost reductions during the warm mix asphalt manufacture and compaction process. Hydrated lime with recycled asphalt pavement is utilized more often in warm mix asphalt due to improved aggregate and asphalt binder adhesion. This improves RAP properties and reduces the amount of virgin material required for high-quality mixtures, results cost savings material procurement [65].

2.6.4 Comparative Studies on Antistripping Additives in Asphalt Mixtures

The use of liquid antistripping additives, hydrated lime, surfactants, biobased additives, and nanomaterials in asphalt mixtures for a number of reasons, including improving the asphalt mixture's workability, durability, and overall performance [57].

a) **Hydrated lime:** It is the most popular and efficient adhesion agent for improving the bond between the asphalt binder and aggregate, which reduces stripping and enhancing the asphalt mixture's overall performance under unfavorable environmental conditions, especially in areas with high moisture or freeze-thaw cycles [44].

b) **Liquid Anti-stripping additives:** The adhesion between the aggregate surface and the asphalt binder is enhanced by surface active compounds amine-based liquid anti-stripping additives, which reduce surface tension and increase aggregate wettability that is the most popular ways to mitigate the moisture sensitivity of asphalt mixtures [17].

c) **Polymer-based additives:** In recent years, the utilization of polymers to modify asphalt bitumen in production of asphalt mixture has grown significantly to enhance the durability and overall performance of asphalt mixtures under high traffic loads. From which styrene butadiene styrene (SBS), ethylene vinyl acetate, polyethylene, and styrene butadiene rubber are the most commonly used polymers for bitumen modification [58].

d) **Bio-based additives:** Introducing alternative asphalt binders made from green and renewable sources has become crucial due to the rising cost of energy and the urgent demand for petroleum-based products worldwide. Asphalt bitumen applied to bio-based materials, or bio-binders, found to be a good substitute for bituminous mixtures in order to promote environmental sustainability and the cost-effective alternative while maintaining the mixture's overall performance [35].

e) **Nanomaterials: -** The use of several nanomaterials in asphalt mixtures, including nano-silica, nano-CaCO3, nano-hydrated lime, and nano-bentonite, has been studied, and interest in doing so is growing rapidly. Nano-hydrated lime was made in a planetary ball mill. To create nano-hydrated lime, the optimal combinations of the main factors affecting the reduction of particle size during the milling process were found through a trial-and-error process [51, 53].

Effectiveness: The performance and durability of asphalt pavements can be greatly enhanced by anti-stripping additives, especially in wet environments or regions that experience frequent freeze-thaw cycles. In order to increase asphalt mixes' resistance to moisture damage, hydrated lime, amine-based liquid antistripping and other surfactants and polymer based-additives work to improve the adhesion between asphalt binder and aggregates. Most laboratory studies have evaluated the effectiveness of these additives on the basis of a short-period intensive moisture conditioning procedure, usually a freeze–thaw cycle [50].

Environmental Impact: Hydrated lime and bio-based additives have the least environmental impact, being derived from natural resources with relatively low toxicity and improve environmental sustainability, while amine-based liquid and polymer-based additives and nanomaterials, while effective, bring out environmental concerns related to production processes and decomposability, hence proper management of these additives is critical to minimizing their environmental impact [53].

Cost: While amine-based liquid anti-stripping additives, polymer-based, nanomaterials and bio-based additives can provide improved performance but at a higher cost, hydrated lime is one of the most popular and affordable alternatives.

2.7 Adhesion Theories

The stripping resistance potential of asphalt mixture is defined by the level of physical bond that is achieved between the aggregate and asphalt binder. The chemical bonding between asphalt and aggregate to optimize the adhesive bond and minimize moisture damage is dependent on asphalt rheology at mixing temperature and the nature of the aggregate surface, adsorbed cations on the aggregate surface, pore size, pore shape and aggregate mineralogy [48]. Interfacial activity between the aggregate surface and asphalt binder is fundamentally important in assessing stripping resistance potential of the asphalt mixture [66]. Aggregates with the presence of water are negatively charged, and as a result, a repulsive force develops between the negatively charged aggregate surface and the negatively charged asphalt binder at the interface. The intensity of the repulsion force develops between the aggregate and asphalt binder depends on the surface charge of both the aggregate and asphalt binder [32].

The adhesion work under presence of water conditions can also be referred to as the stripping work, which characterizes the internal structure of the asphalt mixture· The water pressure formed in the asphalt mixture under the action of external load will flush the asphalt binder, and the moisture will gradually replace the asphalt film wrapped around the aggregate surface, hence, the asphalt-aggregate system inside the mixture is dispersed into two systems of asphalt-water and water-aggregate [41].

2.8 Cohesion Theories

Stripping is controlled by cohesive failure within the bitumen/aggregate rather than at the bitumen–aggregate interface [34]. The mix design simulation of asphalt mixtures to be performed to study thermodynamic and cohesive properties of asphalt binder such as density, solubility parameter, cohesive energy density, and surface free energy. The Cohesion work in the asphalt mixture indicates that the amount of energy required for cohesive damage of the asphalt material itself under strain, and the larger the cohesion work value, the better the effect of its resistance to cohesive damage of the asphalt mixture and the more difficult it is for water molecules to diffuse in the asphalt binder film [67]. When the cohesion work of asphalt binder is negative in the presence of water, it indicates that the cohesive destruction of asphalt requires the process of absorbing energy from the outside world to be carried out, hence, the larger the value, the higher the adhesion and cohesion strength [18].

2.9 Performance Tests of Asphalt Mixtures

Asphalt mixture performance tests are used to correlate the laboratory prepared asphalt mixtures to the actual field performance of the pavement. Laboratory asphalt performance testing is that developing of physical tests that can satisfactorily characterize the key asphalt mixture performance parameters and how these parameters change throughout the service life of asphalt pavement under heavy traffic and adverse climate. These key parameters to the asphalt mixtures performance indicators are mentioned below.

a) **Deformation resistance**: - rutting or deformation resistance of asphalt pavement is one of a key performance parameter that can depend largely on asphalt mix design, in which the performance test efforts are concentrated on deformation resistance potential prediction of asphalt mixture.

b) **Fatigue life**: - fatigue cracking is a key performance parameter that depends more on structural design and subgrade support than mix design.

c) **Tensile strength**: - tensile strength can be related to asphalt mixture cracking – especially at low temperatures.

d) **Stiffness:** - stiffness in asphalt pavement is defined as the resistance of asphalt mixture to deformation within the elastic range. The stress-strain relationship characterized by elastic or resilient modulus is an important characteristic that high stiffness or high modulus of elasticity implies high resistance to elastic deformation and is desired where minimal deflection is preferred with temperature variations.

e) **Moisture susceptibility**: - certain combinations of aggregate and asphalt binder can be susceptible to moisture damage. Several deformation resistance and tensile strength tests can be used to evaluate the moisture susceptibility of asphalt mixture.

2.10 Previous Studies on Effects of Hydrated Lime Additives in Asphalt Mixtures

Several studies on the evaluation of asphalt mixtures' moisture sensitivity, with an emphasis on the impact of hydrated lime additives on the moisture sensitivity of asphalt mixtures, were carried out by various researchers at different times. The following are a few of these studies: The hydrated lime additive was successful in enhancing the asphalt mixtures' overall performance and stability, as well as their susceptibility to moisture [2]. The saturated surface dry (SSD) method of adding 1.5% of hydrated lime by the total weight of aggregate has significantly increased the tensile strength ratio, decreased the percentage of air voids, and enhanced the asphalt mixtures' resistance to moisture damage [5]. In both dry and slurry form, the addition of hydrated lime enhances the tensile strength and Marshall stability, results improved resistance to moisture sensitivity and permanent deformation, as well as improved overall performance of the hot mix asphalt mixture [10].

The addition of hydrated lime as an anti-stripping agent and ceramic fiber as reinforcement has improved the asphalt mixture's resistance to moisture sensitivity by raising the tensile strength values when compared to the control mixes [55]. By increasing the asphalt mixture's tensile strength and tensile strength ratio and decreasing the flow value and air voids, the addition of nano-hydrated lime has improved the asphalt pavement's overall performance by making it more resilient to distress in terms of moisture damage and permanent deformation. It has also improved the asphalt mixture's resistance to moisture sensitivity by increasing its Marshall stability [29]. The stiffness of the asphalt mixtures, which improves the durability and overall performance of asphalt pavement, was one of the basic material features and performance characteristics of asphalt mixtures treated with hydrated lime [22].

The surface free energy method results for warm mix asphalt indicate that hydrated lime increases the wettability of asphalt binder on the aggregate and improves the adhesion between the asphalt binder and aggregate. Furthermore, the difference between surface free energies of asphalt-aggregate and water-aggregate is higher in samples made with untreated aggregates, as using hydrated lime caused these values to decrease, which implies that more energy is needed for stripping phenomena to occur, and the rate of moisture damage decreases [54]. In comparison to other natural fillers, hydrated lime is an active filler that increases moisture damage resistance; nevertheless, the improvement is greatly reliant on aggregate mineralogy, according to the results of the rolling bottle test and surface free energy methods [64]. The performance of the mixtures against moisture damage was improved by the addition of hydrated lime and nano hydrated lime as mineral fillers. The modified mixtures showed the greatest increase in ITS value under dry conditions (20%) and under wet conditions (30%), which also led to an increase in the tensile strength ratio of more than 70% [45].

CHAPTER THREE

3.0 RESEARCH METHODS, MATERIALS AND PROCEDURE

3.1 Research Methodology

There are several similarities in the methods and approaches used to evaluate the moisture sensitivity of WBFWMA and HMA mixtures. The fundamental principles of sample preparation, which apply to both HMA and WBFWMA, include material selection, aggregate gradation, determining the amount of asphalt binder, and compaction. Both WBFWMA and HMA use the same fundamental principles for production and testing methods for determine the tensile strength and tensile strength ratio to assess how moisture-sensitive the asphalt mixes are.

3.2 Materials

The materials used for this study are divided mainly into four, i.e., aggregates, asphalt binder, hydrated lime additives and distilled water. Two types of aggregates with different nominal sizes, one type of binder and hydrated lime were used. The materials used are presented in the section below.

3.2.1 Aggregate

There are two types of natural aggregates that were sourced from different quarries used in this study, denoted as Aggregate A and Aggregate B. Aggregate type A with a nominal size of 20mm is obtained from China State Construction Engineering Corporation (CSCEC) and Aggregate type B with a nominal size of 14mm is from China Civil Engineering Construction Corporation (CCECC) were utilized in the asphalt mixtures, which were used for Kapchorwa – Swam and Busega – Mpigi road construction respectively. The physical properties of aggregates used in this study as received from site is presented in table 3 below.

TABLE 3. QUALITY TEST RESULTS OF AGGREGATES USED FOR ASPHALT MIXES

Test	Standard	Aggregate A – AC20	Aggregate B – AC14	Specifications
Bulk Specific Gravity (Dry)	AASHTO T 85	2.810	2.774	-
Bulk Specific Gravity (SSD)	AASHTO T 85	2.824	2.789	-
Apparent Specific Gravity	AASHTO T 85	2.850	2.815	-
LAA	ASTM C131 – 2020	18.6	19.1	30 maximum
ACV	BS 812 Part 110:1990	16.1	16.7	25 maximum
AIV	BS 812 Part 112:1990	11.0	11.4	25 maximum
Sodium Sulphate Soundness	AASHTO T 104 – 2020	0.01	0.01	12 maximum
TFV (dry)	BS 812 Part 111:1990	302	287	160 minimum
TFV (wet)	BS 812 Part 111:1990	275	258	-
Water Absorption	AASHTO T 85	0.49	0.52	2 maximum

The gradations of the fine and coarse aggregates shall be such that, when combined in proper proportions, the resultant mix will fall within the specified grading requirements for the required asphalt mixtures. The design aggregate blending proportions for both AC20 and AC14 mixes as per [61] is shown in table 4 below.

TABLE 4. DESIGN AGGREGATE BLENDING PROPORTION FOR AC20 AND AC14

Aggregate Size Range (mm)	Proportion in Blend (% by Mass)	
	AC20	AC14
10-20/14 mm	43	15
5-10 mm	11	40
3-5 mm	4	10
3 mm down	41	34
Filler (quarry dust)	1	1
Total	100	100

The laboratory mix gradation of AC20 and AC14 as [61] is shown below in tables 5 and 6 respectively.

TABLE 5. LABORATORY MIX GRADATION OF AC20

Sieve Size in mm	Filler	3-0 mm	5-3 mm	10-5 mm	20-10 mm	JMF	Lower	Upper	Average
28	100	100	100	100	100	100	100	100	100
20	100	100	100	100	88.7	95.1	80	100	90
14	100	100	100	99.3	29	69.4	60	80	70
10	100	100	99	90.2	4.7	57.9	50	70	60
5	100	98.1	78.3	3.6	3.7	46.3	36	56	46
2.36	100	76.9	1.3	2.3	2.7	34	28	44	36
1.18	100	55.3	1.1	2	2.2	24.9	20	34	27
0.6	100	40.6	1	1.7	1.9	18.7	15	27	21
0.3	99.7	27.3	0.8	1.5	1.6	13.1	10	20	15
0.15	94.7	15.7	0.6	1.1	1.3	8.1	5	13	9
0.075	83.9	9.6	0.3	0.7	1	5.5	2	6	4

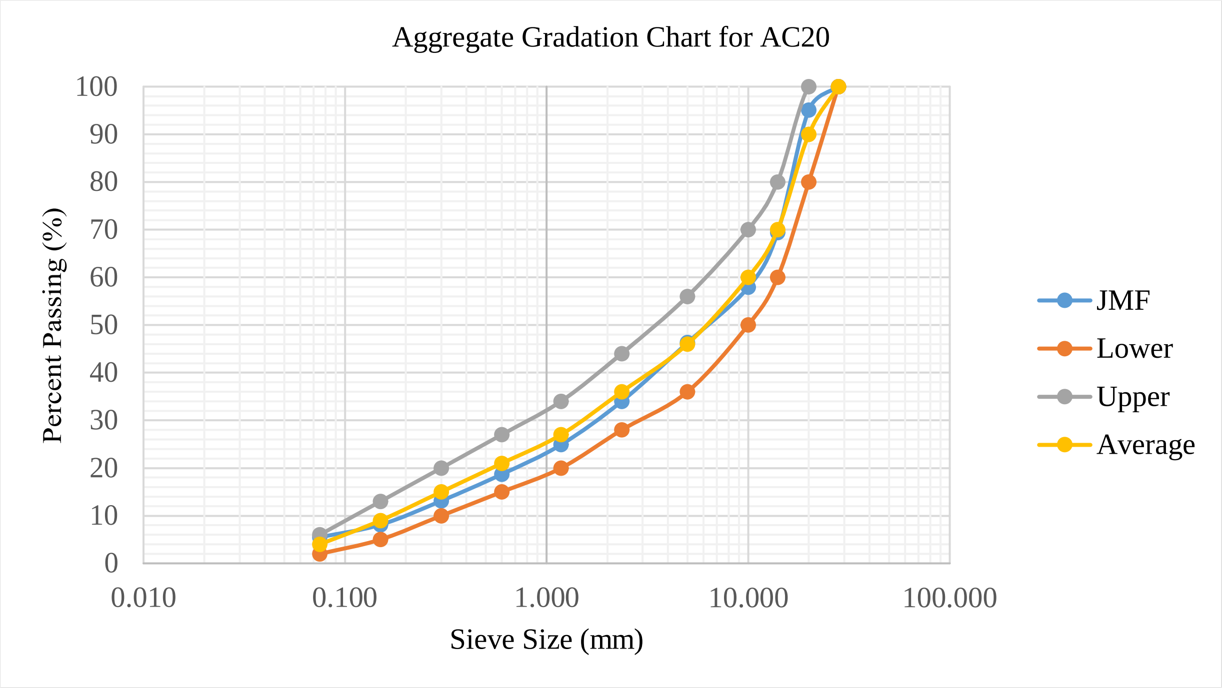

Figure 3. Aggregate gradation chart for AC20

Table 6. Lab Mix Gradation of AC 14

Sieve Size in mm	Filler	3-0 mm	5-3 mm	10-5 mm	14-10 mm	JMF	Lower	Upper	Average
20	100	100	100	100	100	100.0	100	100	100.0
14	100	100	100	100	99	99.9	85	100	92.5
10	100	100	100	99	33	89.6	72	94	83.0
5	100	100	100	26	2	55.7	52	72	62.0
2.36	100	99.4	72.6	11	2	46.8	37	55	46.0
1.18	100	47.3	16.2	5	1	35.4	26	41	33.5
0.6	100	43	14.9	3	1	18.5	16	28	22.0
0.3	99.8	34	11	2	1	14.6	12	20	16.0
0.15	97.2	27	7	1	0	11.3	8	15	11.5
0.075	88.1	13	2	1	0	5.9	4	10	7.0

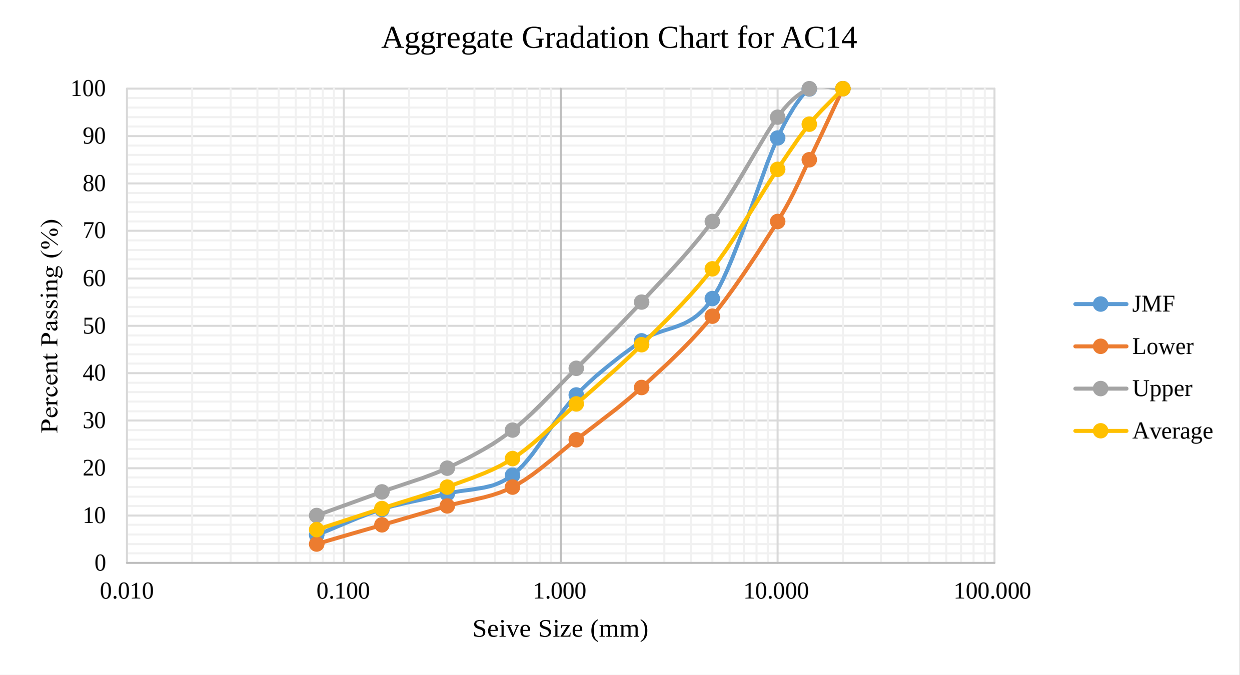

FIGURE 4. AGGREGATE GRADATION CHART FOR AC14

3.2.2 Asphalt Binder

Asphalt bitumen penetration grade PG 60/70, which is currently in use for construction of road and obtained from China State Construction Engineering Corporation (CSCEC) was used. The Engineering properties of asphalt binder used in the study are presented in table 7 below.

TABLE 7. TEST RESULTS OF PENETRATION GRADE 60/70 ASPHALT BINDER

Test	Standard	Result	Specifications
Penetration @ 25 ^{0}C, 100g. 5s	ASTM D5	62	60 – 70
Ductility @ 25 ^{0}C, 5 cm/min	ASTM D113	130	Min 100
Softening point (Ring and Ball test), ^{0}C	ASTM D36	51	49 – 56
Flash point (Cleveland Open Cup), ^{0}C	ASTM D92	292	Min 250
Loss on heating	ASTM D6	0.095	Max 0.2
Specific gravity @25^{o}C	ASTM D70	1.032	1.01 – 1.06
Solubility in Trichloroethylene (%)	ASTM D2042	99.9	Min 99.0
Drop in penetration after heating	ASTM D5	17.85	Mx 20

3.3.3 Hydrated Lime

In this study, hydrated lime which is one of the natural anti-stripping additives or adhesion agents was used, which has some benefits when mixed with asphaltic mixture, including stripping reduction, binder stiffening, improvement in resistance to fracture growth, and increasing expected pavement life. Tororo hydrated lime currently used as an additive in the preparation of asphalt mixture for construction of roads for the above-mentioned road projects was used. Hydrated lime over other anti-stripping additives has chosen to employ while evaluating the moisture sensitivity of water-based foamed warm mix asphalt mixes due to its availability, affordability, environmental advantages and having a track record of efficacy in the area of study.

In this study, dry lime (Tororo hydrated lime used as active filler in the asphalt mixture for construction of roads in Uganda) was added in to two different types of aggregates in the method of pre-mix process to investigate its effectiveness on improvement of foamed warm mix asphalt mixtures resistance potential to moisture-induced damage. The optimum content of hydrated lime showed the best strength against moisture induced damage of asphalt mixes was selected as 1.5% of the total weight of aggregates based on the previous studies on the subject matter, which was obtained after preliminary tests.

The summary of studies regarding the effect of hydrated lime additives on moisture sensitivity of asphalt mixtures is presented in table 8 below.

TABLE 8. SUMMARY OF STUDIES ON HYDRATED LIME ADDITIVES ON ASPHALT MIXTURES

S/No.	Author	Studies conducted on	Optimum lime content
1	Adelia D. Nataadmadja, Eduardi Prahara, and Oki Setyandito [2]	The effect of hydrated lime addition in improving the moisture resistance of hot mix asphalt (HMA)	1.5%
2	Ahmed Hussein Ahmed and Dr. Mohammed Qadir Ismael [5]	Effect of hydrated lime on moisture susceptibility of asphalt mixtures	1.5%
3	Asres Simeneh [10]	The Effect of hydrated lime additives on moisture sensitivity and overall performance of HMA mixtures	1.5%
4	Sahar Hussein Ali and Mohammed Qadir Ismael [55]	Improving the moisture damage resistance of HMA by using ceramic fiber and hydrated lime	1.5%
5	Francisco T. Sacramento Aragão, Junghun Lee, Yong-Rak Kim and Pravat Karki [22]	Material-Specific Effects of Hydrated Lime on the Properties and Performance Behavior of Asphalt Mixtures and Asphaltic Pavements	1.5%
6	Cheng, Jianchuan, Junan Shen, and Feipeng Xiao [16]	Moisture susceptibility of warm-mix asphalt mixtures containing nanosized hydrated lime	1.5%
7	Hawraa J. Aljbouri, Amjad K. Albayati [29]	The Effect of Nano-Hydrated Lime on the Durability of Hot Mix Asphalt	1.5%
8	V. Mouillet, D. Séjourné, V. Delmotte, H.-J. Ritter, D. Lesueur [62]	Method of quantification of hydrated lime in asphalt mixtures	1.7%

3.2.4 Application of Water

In this study, we used free water system of foaming effect technology to produce warm mix asphalt mixtures. Water is used to prepare a water-based foamed warm mix asphalt (WBFWMA) mixtures which adds benefits by eliminating the need of expensive additives (organic and chemical additives) and special asphalt bitumen by mixing a small amount of water usually with a mass ratio of 1% to 2% to the asphalt binder into the hot asphalt to create microscopic bubbles (micropores) in the asphalt binder [1].

In the study distilled water was used for production of warm mix asphalt by foaming effect of using a free water system with an amount of 1.5% to the weight of asphalt binder, which was injected by a syringe to the hot bitumen at a temperature of 130 ^{0}C – 135 ^{0}C. Water was used an alternative additive to produced WBFWMA, since it's readily available, safe, affordable, eco-friendly, and easy to apply. It also doesn't require any special equipment, tests, or laboratory setup, nor does it require any additional or specialized testing. However, it has a disadvantage for facilitating the moisture damage of asphalt mixture because of the direct application of water to the asphalt binder, that makes water to retain in the mix that later brings moisture sensitivity problem.

3.3 Laboratory Tests

The laboratory tests were conducted to evaluate the effect of mixing and compaction temperature along with the types of additives used in preparation of foamed warm mix asphalt on the moisture-induced damage resistance potential of WBFWMA mixtures.

The test was started by preparing the hot mix asphalt mixtures using Marshall method to determine the optimum binder contents for two nominal size aggregates (20mm and 14mm). The aggregate and bitumen for HMA was heated at a temperature of 160 ^{0}C to 165 ^{0}C. The determination of OBC was carried out on HMA by varying the bitumen contents of 4.0%, 4.5%, 5.0%, 5.5% and 6.0% at the same mixing and compaction temperature of 160 ^{0}C to 165 ^{0}C for both AC14 and AC20. Three specimens were prepared for each binder content with one more extra loose mix used to calculate the specific gravity and volumetric properties of the asphalt mixtures. The specimens were compacted with a Marshall compaction hammer with a number of 75 blows on either side. To determine the optimum binder content (OBC) of the mixes, maximum stability, maximum density and 4% air voids was considered. Following this, the optimum asphalt binder is obtained from control mixes produced from aggregates of 20mm and 14mm nominal sizes for hot mix asphalt mixtures.

After obtaining the optimum binder contents for respective nominal size aggregates, the moisture sensitivity test was done in compliance with AASHTO T283, the Modified Lottman test for quantitative evaluation on the stripping potential of compacted asphalt specimens. Performance tests of lime treated and untreated laboratory-prepared asphalt mixtures were carried out on moisture-conditioned and unconditioned specimens. Specimen preparation for indirect tensile strength tests for both HMA mixtures and WBFWMA mixtures is the same, apart from the mixing and compaction temperature that uses 160 ^{0}C to 165 ^{0}C for HMA and 130 ^{0}C to 135 ^{0}C for WBFWMA. The reason for this is that both types of asphalt mixtures operate on the identical principles of moisture sensitivity; the only variables that alter are the production temperature and the types of additives utilized to produce WBFWMA.

In this study, the foaming technology of warm mix asphalt technology using free water system was evaluated. The performance of WBFWMA mixtures with hydrated lime additives were evaluated and compared to the conditioned (wet) and control (dry) mixtures with unmodified WBFWMA mixtures of the same mix proportion. Besides, hot mix asphalt mixtures without hydrated lime additives have also been evaluated to elaborate the extent of moisture-induced damage in different types of asphalt mixture. For specimen preparation of foamed warm mix asphalt with lime additives, the dry hydrated lime was premixed properly with the aggregate before the application of the asphalt binder. The methodology and process for producing asphalt samples and the types of tests for moisture sensitivity of WBFWMA mixtures are comparable and adapted from the methodologies and procedures utilized for HMA.

For the purpose of this study the foamed warm mix asphalt using free water system is produced by introducing a tap water at the rate of 1.5% by binder weight that was injected into the asphalt binder using a syringe which was heated up to a mixing and compaction temperature of 130 ^{0}C to 135 ^{0}C. Immediately after injecting the water to the bottom part of the asphalt binder, the asphalt and the water was mixed rapidly by using a hand mixer, in order to allow the steam to disperse completely to the asphalt binder. During mixing of the hot binder and water, the hot plate was used to maintain the mixing and compaction temperature to avoid dropping in temperature of the bitumen due to addition of cold water. The representative picture of applying water and thoroughly mixing of the binder to create the foamed bitumen is shown in appendix B.

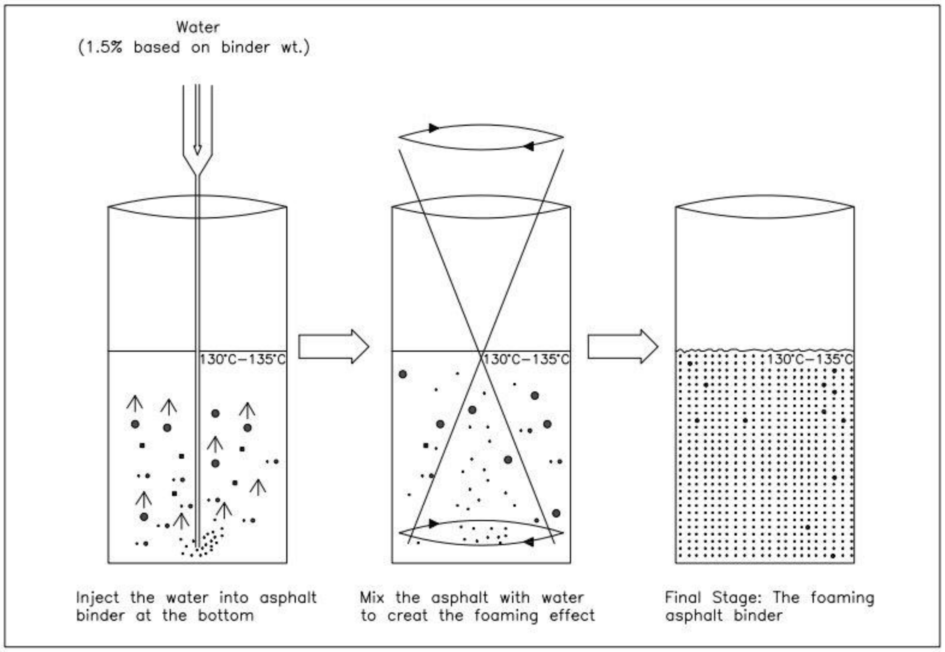

FIGURE 5. PROCEDURE FOR PRODUCING FOAMED ASPHALT BINDER

After the foam formed throughout the asphalt binder, the asphalt binder was then immediately (within 5 minutes) mixed with the aggregate at the same temperature of 130 ^{0}C to 135 ^{0}C. The number of compactions for specimens used for indirect tensile strength was used as 35 blows on either side of the specimen by using the Marshall compactor. The number of bows for ITS specimens was determined by trials for 7% air voids content. For Marshall stability analysis, 3 samples for each type of mixes, a total of 18 samples and for indirect tensile strength test, 6 samples (3 controlled + 3 conditioned) for each type of mixes, a total of 36 samples were prepared for both AC14 and AC20. The volumetric properties of prepared samples were evaluated and the results are shown in chapter four. The laboratory sample preparation plan consists of lime modified and unmodified samples of foamed warm mix as well as hot mix asphalt mixtures for both types of asphalt mixes. The procedure of asphalt mix design to prepare the required samples for ITS test is shown in the chart below [10].

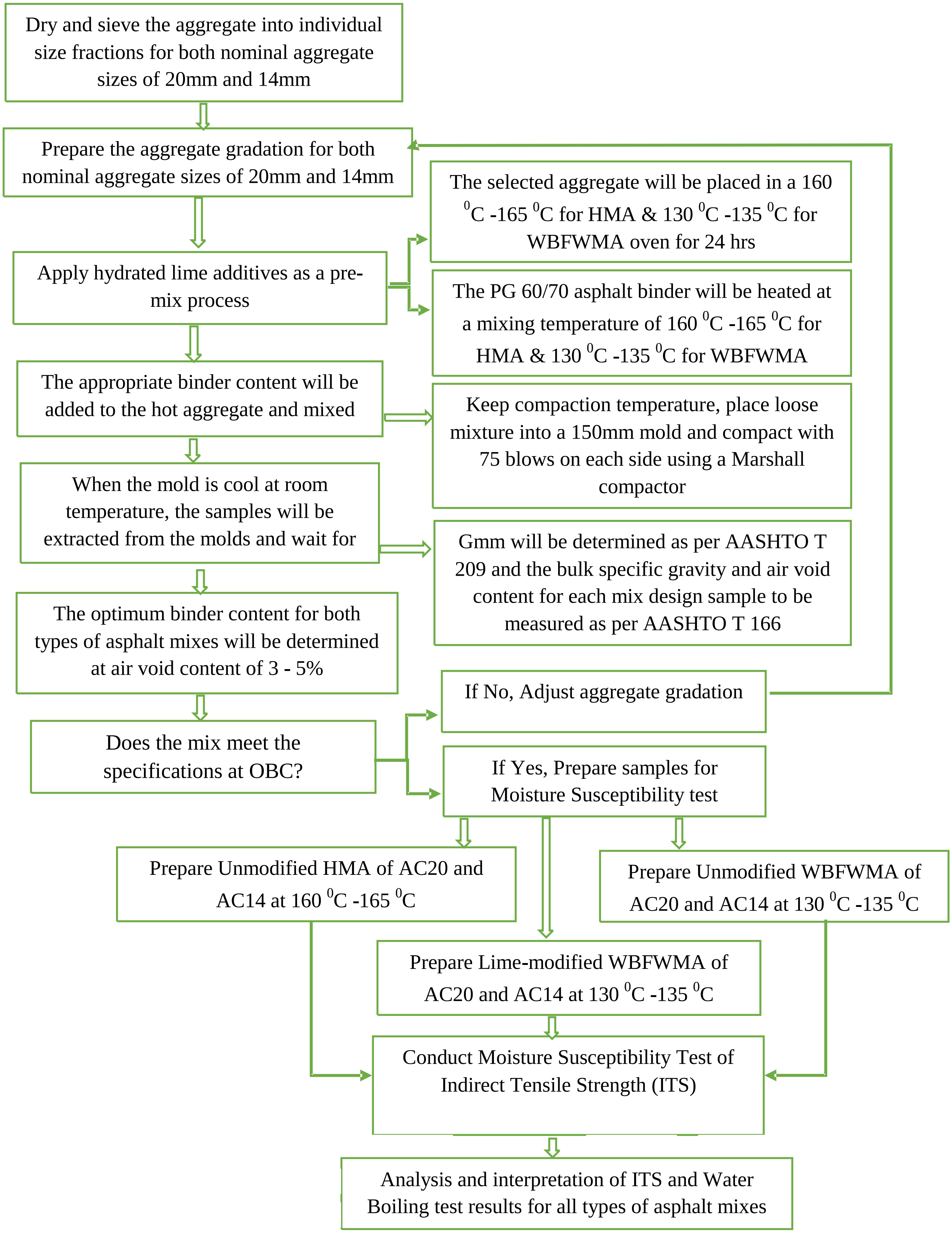

FIGURE 6. FLOW CHART OF THE ASPHALT MIX DESIGN PROCEDURE

3.4 Moisture Conditioning

Moisture conditioning of the prepared samples for ITS test is one of the important steps of the test procedures conducted to predict the moisture damage resistance potential of hot and water-based foamed warm mix asphalt mixtures produced at respective mixing and compaction temperatures. The study evaluates the moisture sensitivity of hot and water-based foamed warm mix asphalt mixtures by comparing the various properties of the mixes before and after moisture conditioning. The properties of the asphalt mixtures before and after moisture conditioning are referred to as “dry” or “unconditioned” and “wet” or “conditioned” respectively [6].

The moisture conditioning process consists of preparing six specimens for each type of hot and water-based foamed warm mix of unmodified and lime modified samples for both types of mixes (AC20 and AC14). The prepared six samples were divided into two groups of three specimens each, in which the average air voids content for each subset should be similar. The first group of specimens was tasted in dry state (unconditioned), whereas the second group was tested in saturated state (conditioned).

For conditioning of specimens, the following procedure was followed. The compacted asphalt specimens were wrapped with plastic film and put in the plastic bag filled with water to put in the freezer at -17 ^{0}C for 18 hours. In the following day, these specimens were removed from the freezer and soaked in a water bath with a temperature of 60 ^{0}C for 24 hours. During soaking into the hot water bath, the plastic film and plastic bag were removed. Then after, the specimens were removed from the hot water bath and soaked in another water bath with a temperature of 25 ^{0}C for 2 hours to bring the specimens to the testing (room) temperature. Subsequently, the specimens were removed from the water bath and both dry and conditioned specimens were tested for indirect tensile strength (ITS). A representative picture of conditioning and testing procedure is shown in appendix B.

3.5 Moisture Susceptibility Test

The ability of an asphalt pavement to lose strength, stiffness, and durability due to water causing the aggregates and asphalt binder to lose their adhesive characteristics is referred to as "moisture susceptibility". Moisture-induced damage is one of the major potential challenges with the application of warm-mix asphalt mixtures. Besides its several benefits, one of the main issues with warm mix asphalt is its poor resistance to damage caused by moisture. Therefore, the purpose of this study is to evaluate if adding hydrated lime additives as an adhesion agent can result in producing warm mix asphalt mixtures that are more resistant to damage caused by moisture. In this study, moisture susceptibility testing was used to compare lime-modified and unmodified WBFWMA mixtures with HMA to assess the effects of mixing and compaction temperature along with type of additives used for sample mix preparation on moisture sensitivity of asphalt mixtures [33]. AASHTO T 283 (Modified Lottman Test) for quantitative evaluation of the stripping and moisture sensitivity was used to analyze and compare test results for moisture sensitivity of Hot Mix Asphalt (HMA) and Water-Based Foamed Warm Mix Asphalt

(WBFWMA). The test measures the strength of the bonds that form between aggregates and asphalt binder in the presence of water.

3.5.1 Indirect Tensile Strength

Indirect tensile strength is one of the quantitative test methods of measuring the moisture susceptibility of asphalt mixtures. Two mixture properties which are determined by indirect tensile strength test are tensile strength and tensile strain at failure. Tensile strength is used to evaluate moisture susceptibility of asphalt mixture that measures ITS before and after conditioning of the specimen. Whereas tensile stain at failure is useful for predicting cracking potential of asphalt mixtures.

After measuring the thickness and diameter of the specimen, the test was conducted at room temperature (25 ^{0}C) at a deformation rate of 50.8 mm/min by loading a cylindrical specimen with a single load, which acts parallel to the vertical diameter plane and the maximum load, P was recorded when the specimen cracked. Following this, the ITS for each specimen was calculated by the following formula in which the summary of the result is presented in chapter four.

$$ITS = \frac{2000xP}{\pi Dt}$$

ITS – in kPa

P – applied load at failure in N

D – diameter of specimen in mm

t – thickness of specimen in mm

$$\varepsilon_t = 0.52X_t$$

ε_t – tensile strain at failure, mm/mm

X_t – horizontal deformation across specimen, mm

3.5.2 Tensile Strength Ratio (TSR)

Tensile strength ratio is the percentage of average indirect tensile strength (ITS) values of conditioned (wet) specimens to the unconditioned (dry) specimens of the same mixtures.

$$\% TSR = \frac{\text{Average tensile strength of Conditioned samples}}{\text{Average tensile strength of unconditioned samples}} X 100$$

According to the standards, TSR value of above 80% indicated satisfactory resistance against moisture-induced damage.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The optimum binder contents (OBC) for respective asphalt mixtures were determined according to the Marshall mix design method. It is noteworthy that the mix design was performed on HMA for both types and nominal size aggregates. The optimum binder content in control samples prepared with aggregates of nominal size of 20mm and 14mm were found to be 5.1% and 5.4%, respectively. The detail analysis of optimum binder content determination is presented in appendix A.

The above-mentioned asphalt-binder contents were employed to prepare corresponding asphalt mixtures used for the study. In order to minimize the number of variables involved in assessing the moisture sensitivity of WBFWMA, the asphalt specimens for all types of mixes were prepared using the same binder content for respective AC20 and AC14 mixes.

4.1 Volumetric Analysis of Asphalt Mixtures

The volumetric analysis of prepared specimens used to evaluate the moisture sensitivity of asphalt mixtures was done. The summary of average volumetric characteristic test results for three distinct types of asphalt mixes, including unmodified HMA, unmodified WBFWMA, and lime-modified WBFWMA mixtures prepared from both types and nominal aggregate size (AC20 and AC14) are presented in table 9 below.

TABLE 9. SUMMARY OF TEST RESULTS FOR AC20 AND AC14

Aggregate Type	Description of Asphalt Mixture	% Binder	% Air-Void Va	% Voids in Mineral Aggregates VMA	% Voids Filled with Bitumen VFB	Marshall Stability (KN)	Flow (mm)	Indirect Tensile Strength-ITS-dry (kPa)	Indirect Tensile Strength-ITS-Wet (kPa)	Indirect Tensile Strength-ITS-Ratio (%)
Aggregate A	AC20-HMA- without lime	5.10	4.14	16.18	74.43	19.16	3.22	1094	908	83
	AC20-WBFWMA-with lime	5.10	4.08	16.03	74.56	18.56	2.92	1023	871	85
	AC20-WBFWMA - without lime	5.10	4.21	16.21	74.05	18.34	3.14	889	718	81
Aggregate B	AC14-HMA without lime	5.40	4.27	15.74	72.86	18.49	3.51	961	825	86
	AC14-WBFWMA-with lime	5.40	4.38	15.61	71.94	18.06	3.06	922	805	87
	AC14-WBFWMA-without lime	5.40	4.40	15.76	72.11	17.80	3.43	806	680	84
Specified Limits			3.0-5.0	Minimum 14.0	65-78	Minimum 9.0	2 – 4	Minimum 800	-	Minimum 80.0

Note: The detail information of each specimen for all types of mixes is attached in Appendix A.

a) Stability

The average Marshall stability values of different types of asphalt mixes prepared from two distinct types and nominal aggregate size are shown in figure 7 below. The result indicates for both AC14 and AC20, the average stability values for unmodified WBFWMA are decreased by approximately 4% when compared to HMA. The lime-modified WBFWMA, however, has increased stability values by 1.5% than unmodified WBFWMA in both cases. This implies that lime improves the stability of WBFWMA. The Marshall stability of asphalt mixtures increases with the rise in mixing and compaction temperature; this is due to the more adhesive forces caused by the decrease in the viscosity of the asphalt binder to reach the good workable and compaction condition [19].

On the other hand, AC14 has decreased stability values by 3.5% than AC20, which demonstrates that nominal aggregate size has an impact on the stability characteristics of asphalt mixtures. For all types of mixes, the average stability value has fulfilled the minimum specification requirements as per [61].

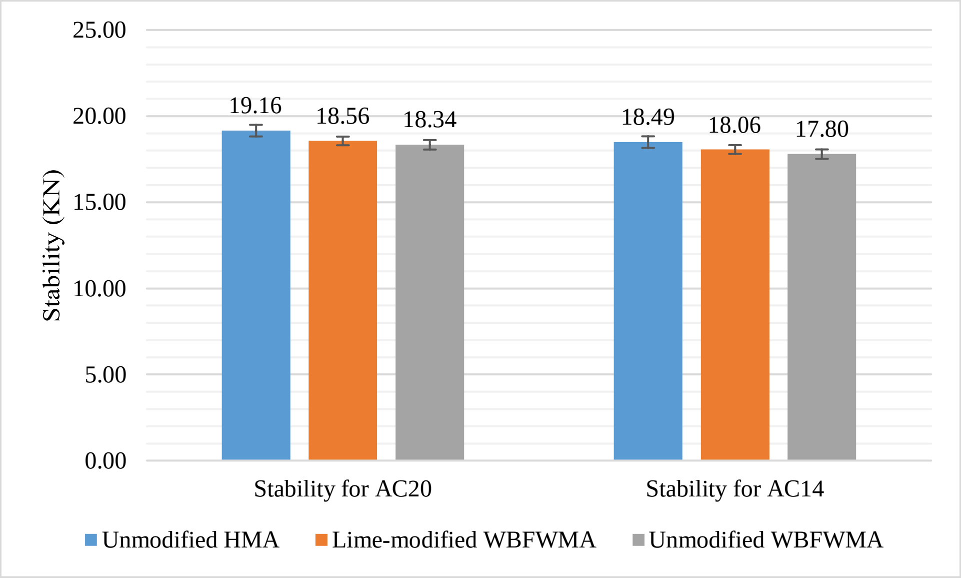

FIGURE 7. AVERAGE MARSHALL STABILITY VALUES FOR AC14 AND AC20

b) Flow

For both types of mixes produced from two distinct types and nominal size of aggregates (AC20 and AC14), the average flow value of the lime-modified WBFWMA is decreased by 9.0% compared to unmodified WBFWMA and HMA. Due to the fact that lime stiffens the mix, lime-modified WBFWMA has lower flow value than the unmodified counterpart. The higher mixing and compaction temperature in HMA caused higher plasticity characteristics than WBFWMA, revealed increased flow value. Since the percentage of voids in the mixture is higher at lower temperatures than at higher ones, the aggregate particle's ability to deform causes the flow value to increase as the compaction temperature decreases [47].

On the other hand, the flow values of AC14 mixes are increased by 9.0% compared to AC20. It indicates that, asphalt mixes produced with lower nominal aggregate size are more likely to rut or susceptible to permanent deformation under heavy traffic loads than mixes with larger aggregate size. The aggregate nominal size has a greater influence on the flow rate of asphalt mixes than mixing and compaction temperature. From this, AC14 is found more flexible than AC20 to withstand thermal stress that occurs due to temperature fluctuations and is recommended for pavement construction in such regions. For all types of mixes, the flow values obtained for both AC14 and AC20 are within the allowable limit of 2 – 4 mm as per [61].

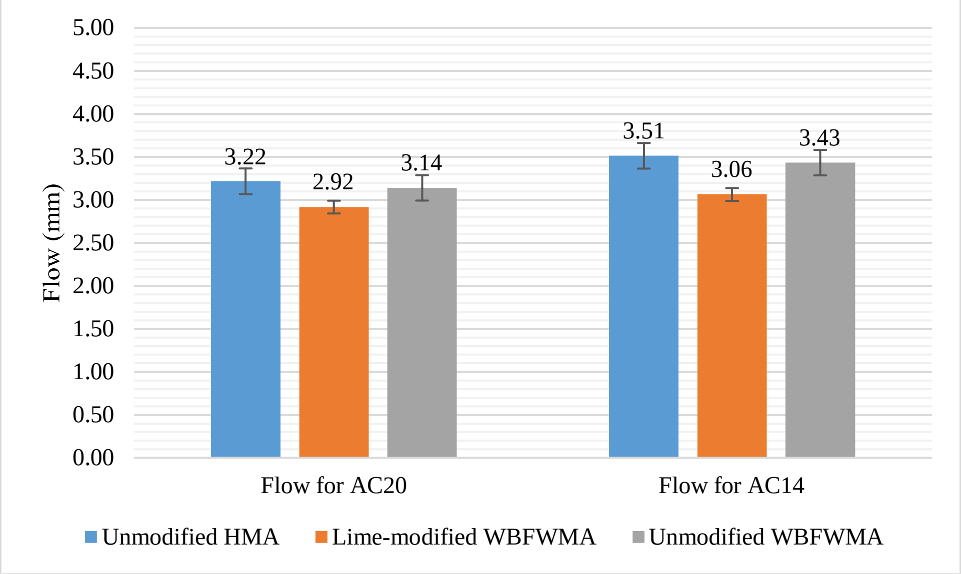

FIGURE 8. AVERAGE FLOW VALUES FOR DIFFERENT AC14 AND AC20

c) Air Voids

The unmodified WBFWMA has increased air voids than lime-modified WBFWMA by 1.7% and 3.2% respectively, for AC20. This is due to the lime addition that has an impact on the total air voids content in the mix. On the other hand, for AC14, the lime modified and unmodified WBFWMA has similar air voids content in contrast to AC20, however, has increased air voids by 3.0% than HMA. When the mixing and compaction temperature of the asphalt mixture decreased, the air voids content increased, hence WMA has a slightly increased air voids than HMA because of the reason for a greater viscosity of the asphalt binders under its lower mixing and compaction temperature [63].

Furthermore, the asphalt mixes with AC14 have increased air voids content than mixes with AC20 with 3.0%, 7.4% and 4.5% for HMA, lime-modified and unmodified WBFWMA respectively. This is due to the fact that it has more fine aggregates require extra bitumen to coat because of its larger surface area, results more voids left unfilled with bitumen. The finer aggregates in the mix, also need more compaction to achieve the required density that has an impact on air voids. The air voids content for all types of mixes produced from both types and nominal sizes of aggregates are within the specified limits of 3 – 5% as per [61].

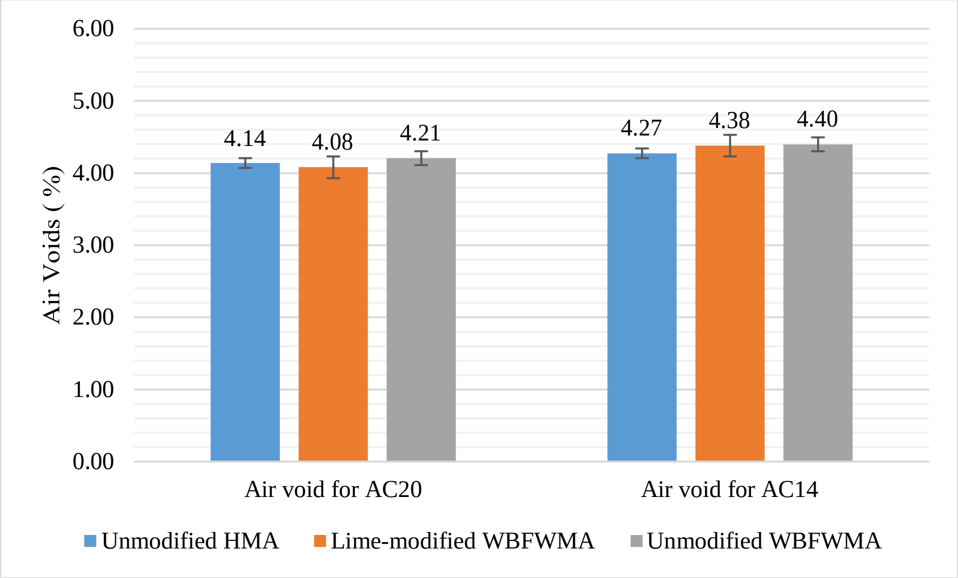

FIGURE 9. AVERAGE AIR VOIDS CONTENT FOR AC14 AND AC20

d) Voids in Mineral Aggregate (VMA)

The average VMA values of lime-modified WBFWMA are decreased by 1.2% than unmodified WBFWMA and HMA for both types of asphalt mixes. Mixing and compaction temperature has a significant effect on VMA because bitumen viscosity increases considerably with decreasing temperature, whereas bituminous mixes become more difficult to compact as a result of a drop in temperature, and as a result, the value of VMA increases [47].

Furthermore, for all similar types of asphalt mixes, the VMA values for AC14 are decreased by 2.8% than AC20. The VMA is the main volumetric properties of asphalt mixtures that determines mixtures performance. It is the total voids in the mix includes the voids filled with bitumen and air voids, which is influenced by mixing and compaction temperature, nominal aggregate size, additives used and filler content in the mix. The result shows that, the average values of VMA in WBFWMA is higher than the lime-modified counterpart. The VMA values of all types of mixes produced from both types and nominal sizes of aggregates are within the allowable limits as per [61].

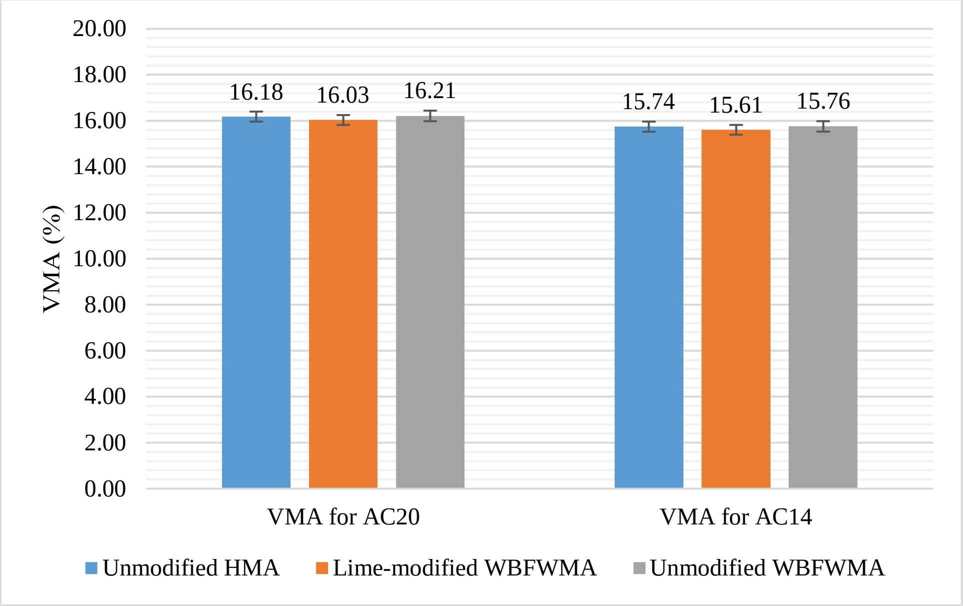

FIGURE 10. AVERAGE VMA VALUES FOR AC14 AND AC20

e) Voids Filled with Asphalt (VFA)

The average value of VFA for unmodified WBFWMA is decreased by 0.5% and 0.7% than lime-modified WBFWMA and HMA respectively, for AC20. On the other hand, the VFA for lime-modified WBFWMA is decreased by 0.3% and 1.3% compared to unmodified WBFWMA and HMA respectively. Due to the lubricating effect of the asphalt binder, which makes the mix more workable and enhances compaction, the average value of VFA in the asphalt mixture increases with the rise in mixing and compaction temperature [19].

Furthermore, VFA values for asphalt mixtures produced with AC14 are decreased by 2.1%, 2.6% and 3.5% of asphalt mixtures produced with AC20 for HMA, unmodified and lime-modified WBFWMA respectively. This is because of the lime addition that works as a filler and absorbs more bitumen, which leaves lower effective bitumen content that results more voids in the mix. The VFA is inversely related to the percent air voids in the total mix, more voids left unfilled with bitumen because of having more fine aggregates that need extra bitumen to coat its larger surface area. The VFA values for all types of asphalt mixes produced from both types of aggregates are within the allowable limits as per [61].

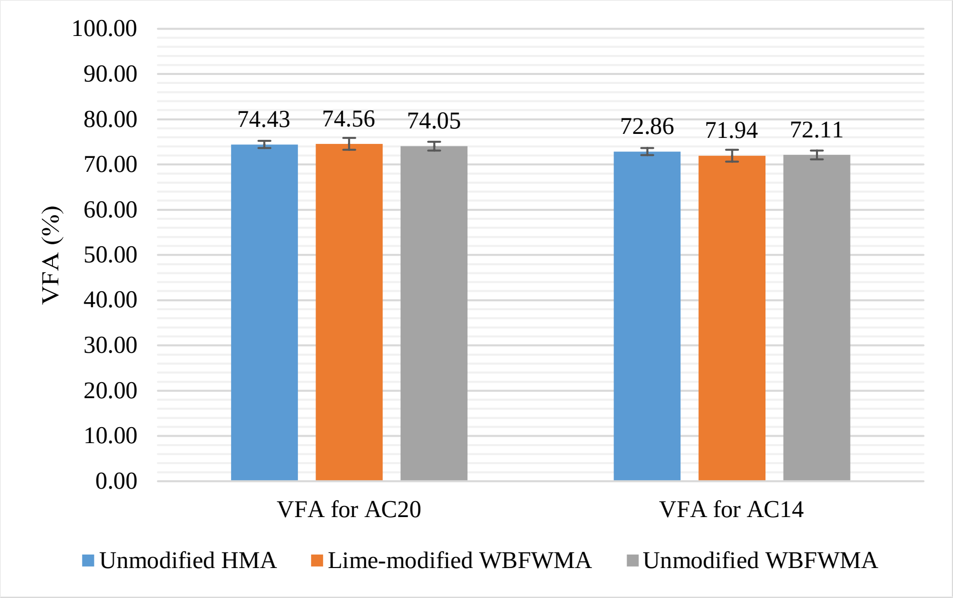

FIGURE 11. AVERAGE VFA VALUES FOR AC14 AND AC20

Note: *The 1% filler content used in preparation of asphalt mixtures has an impactful effect on the values of VFA, VMA and air voids shown above, in which all have an influence on mechanical properties of the asphalt mixture.*

4.2 Moisture Susceptibility Test Results

Following characterization of volumetric properties of WBFWMA and HMA, the specimens produced in this study were used to evaluate the moisture susceptibility of asphalt mixtures with the utilization of hydrated lime additive as anti-stripping agent.

4.2.1 Indirect Tensile Strength

The indirect tensile strengths (ITS) of asphalt specimens prepared for WBFWMA and HMA both in dry (controlled) and wet (conditioned) states were tested. The values for both wet and dry specimens were arranged and averaged to get the data shown in figures 12 to 15.

The average ITS values of WBFWMA are lower than HMA with the same mix proportions in both wet and dry conditions for AC20. In a dry state, the average ITS value of WBFWMA decreased from 1094 kPa of HMA to 889 kPa (81.3%), and in a wet condition with the same mix proportion, from 908 kPa to 718 kPa (79.1%). Lime-modified WBFWMA, on the other hand, has higher ITS values compared to the unmodified counterpart. The values are 1023 in a dry state and 871 in a wet condition, compared to 889 kPa and 718 kPa of unmodified WBFWMA, respectively.

Further to the above, the ITS values show differences in the moisture susceptibility test results of AC20 before and after conditioning for all types of asphalt mixes. The ITS values of unmodified WBFWMA decreased from 889 to 718 kPa (80.8%), following a single freeze-thaw cycle, while the ITS values of lime-modified WBFWMA and HMA mixtures with the same mix proportion decreased from 1023 to 871 kPa (85.1%) and from 1094 kPa to 908 kPa (83.0%) respectively. Figure 12 provides an overview of the strengths acquired and/or lost by the three types of asphalt mixes prepared for AC20 and exposed to different states of moisture conditioning.

The result indicates that, lime-modified mixes have a lower percentage drop (14.9%) in ITS compared to unmodified WBFWMA (19.2%). This proves that lime has a positive impact on tensile strength and moisture sensitivity resistance of asphalt mixtures.

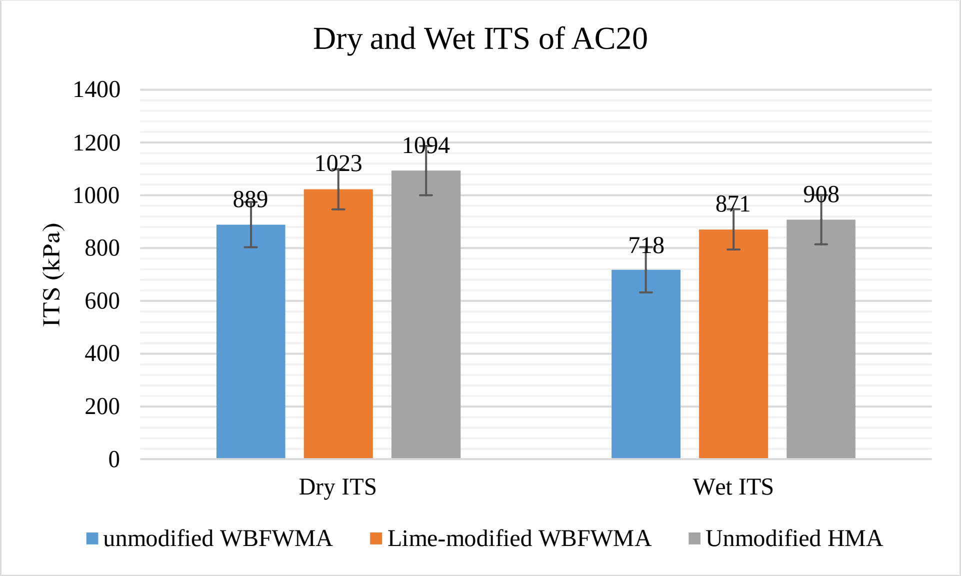

Figure 12. Dry and Wet ITS of WBFWMA and HMA for AC20

Similarly, AC14 asphalt mixes have demonstrated comparable response to the types of asphalt mixes and production temperature used in the WBFWMA. The dry unmodified WBFWMA has an average ITS value of 806 kPa which is lower (83.9%) than 961 kPa of HMA, whereas lime modified WBFWMA has a higher ITS value to the unmodified counterpart, which is 922 kPa. The wet (conditioned) ITS value of unmodified WBFWMA is 680 kPa, which is lower (82.4%) than 825 kPa of HMA. However, lime-modified WBFWMA has an average ITS value that is higher than unmodified WBFWMA, which is 805 kPa. The strength gain and/or loss of the three distinct types of asphalt mixes prepared for AC14 and exposed to various moisture conditioning are shown in figure 13.

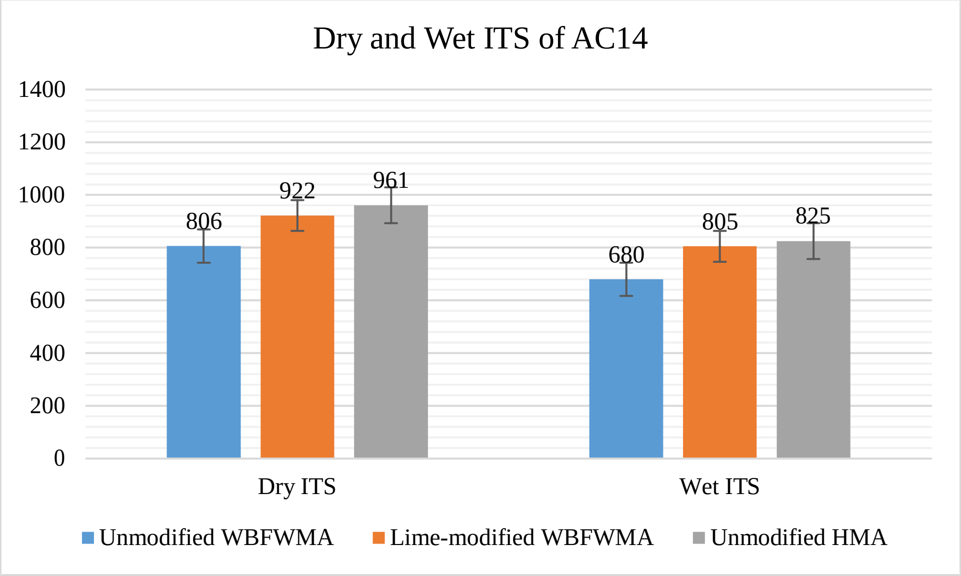

FIGURE 13. WET AND DRY ITS OF WBFWMA AND HMA FOR AC14

In addition to the above, an assessment has been conducted on the impact of nominal aggregate size on the moisture-induced damage resistance potential of asphalt mixtures. It was found that in all scenarios involving asphalt mixtures, both hot mix and water-based foamed warm mix asphalt mixtures, the ITS value for AC14 is lower than AC20, regardless of types of asphalt mixes used. From this, in a dry state the ITS for AC14 is decreased by 12.2%, 9.5% and 9.9% for HMA, lime-modified and unmodified WBFWMA respectively, compared to AC20 for similar type of asphalt mixtures. On the other hand, in wet condition the ITS for AC14 is decreased by 9.1%, 2.2% and 5.3% for HMA, lime-modified and unmodified WBFWMA respectively compared to AC20 for its counterpart asphalt mixtures.

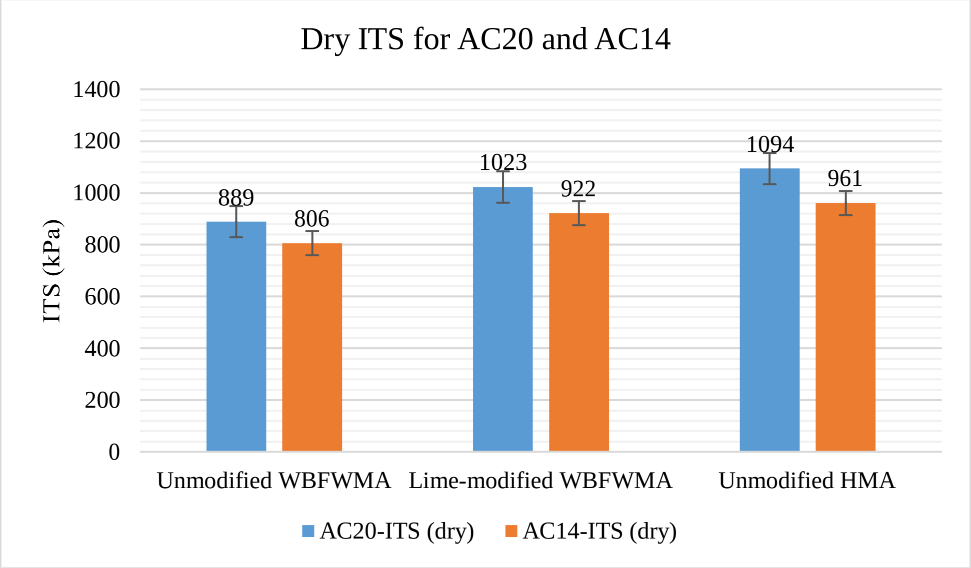

FIGURE 14. DRY ITS VALUES FOR AC20 VS AC14

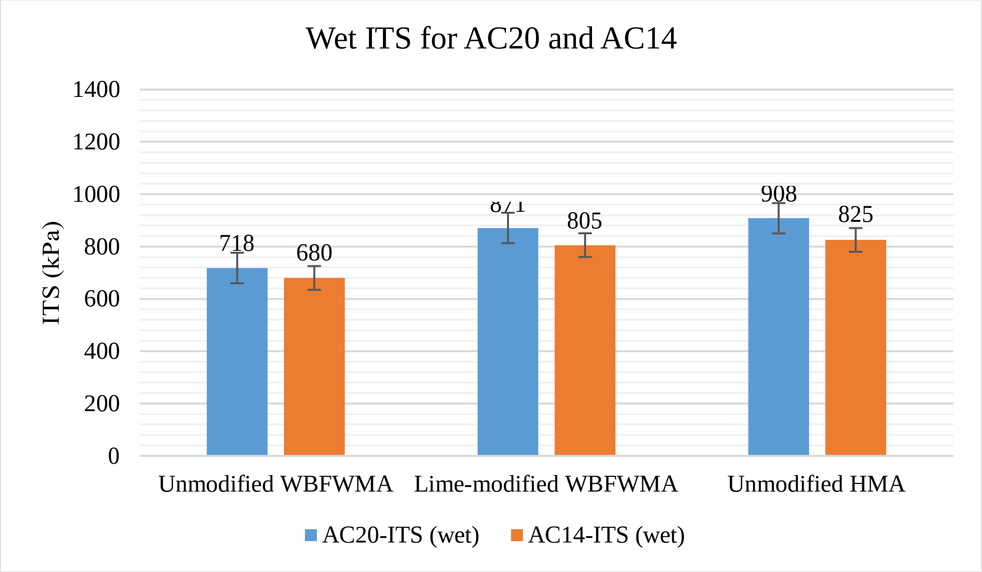

Figure 15. Wet ITS values for AC20 vs AC14

The test results have given the indication that both dry and wet indirect tensile strength of water-based foamed warm mix asphalt (WBFWMA) is lower than hot mix asphalt (HMA) produced with the identical materials and same mix proportions. However, the lime-modified water-based foamed warm mix asphalt has a higher indirect tensile strength value to the unmodified counterpart. The result shows that, lime additive and mixing and compaction temperature have a great impact on tensile strength than aggregate nominal size in the asphalt mixture.

4.2.2 Tensile Strength Ratio

Tensile strength ratio (TSR) is another method of evaluating the indirect tensile strength properties of asphalt mixtures. It is used to evaluate the value of the tensile strength of mixtures retained after subjected to moisture conditioning. The results indicate that TSR value of unmodified WBFWMA is lower than HMA of the same mix proportion and subjected to identical moisture conditioning. However, the TSR value for lime-modified WBFWMA prepared from both types and nominal aggregate size has increased value in all cases compared to unmodified WBFWMA.

The average TSR of unmodified WBFWMA of AC20 has a value of 0.81, which is lower than 0.85 and 0.83 of lime-modified WBFWMA and HMA respectively. Similarly, for AC14, the average TSR value of unmodified WBFWMA is 0.84, which is lower than lime-modified WBFWMA and HMA of 0.87 and 0.86 respectively, whereas the same is shown in figure 16.

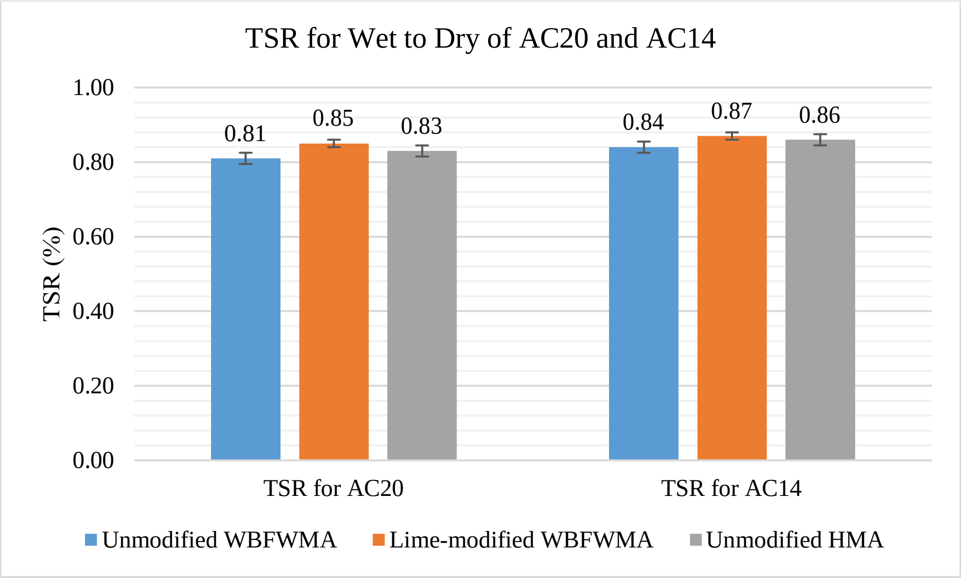

Figure 16. TSR of Wet to Dry for AC20 and AC14

From the results obtained, it is evidently confirmed that TSR of lime-modified WBFWMA consistently outperforms on unmodified WBFWMA for the same mix proportion and subjected to identical state of moisture conditioning. The tensile strength in asphalt mixture is greatly affected by mixing and compaction temperature and additives used, wherein, there is a little change in tensile strength with changes in aggregate gradation was expected since tensile strength should be more affected by stiffness of the asphalt cement than by aggregate properties [20]. Lime-modified WBFWMA has higher TSR value compared to unmodified WBFWMA, because of the reason that lime addition modifies the binder and improves the adhesion that helps to resist moisture-induced damage in asphalt mixtures.

4.3 Statistical Analysis of Indirect Tensile Strength

In the professional world, statistical analysis takes raw data and finds correlations between variables to reveal patterns and trends to relevant stakeholders. The t-test is the commonly used type of inferential statistics to analyze the differences between two different groups by assuming that the variances of the two groups are roughly equal and that the data in each group is normally distributed and independent of the others. In this study, a two-tailed t-test was carried out to verify whether statistically significant differences exist in terms of tensile strength and stripping properties between different types of asphalt mixtures produced by two distinct types of aggregates (20mm and 14mm) under different production temperatures and additives utilized, of these; unmodified foamed warm mix asphalt, lime-modified foamed warm mix asphalt and unmodified hot mix asphalt mixtures.

In two-tailed t-test statistics, the assumption is that both asphalt mix types, regardless of production temperatures and additives utilized in preparation of asphalt mixtures along with lime treatments to be normally distributed and independent of each other with common variance, test, at the 5% significance level. The hypothesis is that there is no difference between the two different types of asphalt mixes with respect to the mean of asphalt mix types with and/or without lime treatments.

TABLE 10. SUMMARY OF T-STATISTIC RESULTS FOR DRY ITS OF AC20

S/No.	#1			#2	
	WBFWMA without lime	WBFWMA with lime		WBFWMA without lime	HMA without lime
1	895.9	1,009.00		895.9	1,070.10
2	904.8	1,051.10		904.8	1,010.80
3	867.2	1,010.30		867.2	1,199.60
n_k	3	3		3	3
$Ti=\Sigma y_{ij}$	2667.90	3070.40		2667.90	3280.50
$\bar{y}_{ij}$	889.30	1023.47		889.30	1093.50
Sd	19.65	23.88		19.65	96.55
t-calculated	**-7.52**			**-3.55**	
df	**4**			**4**	
t-critical	**±2.78**			**±2.78**	
	t-calculated > t-critical			**t-calculated > t-critical**	
Decision	Reject null hypothesis			Reject null hypothesis	

TABLE 11. SUMMARY OF T-STATISTIC RESULTS FOR WET ITS OF AC20

S/No.	#1			#2	
	WBFWMA without lime	WBFWMA with lime		WBFWMA without lime	HMA without lime
1	740.5	901.4		740.5	944.8
2	704.1	880.9		704.1	812.5
3	709.8	830.4		709.8	967.7
n_k	3	3		3	3
$Ti=\Sigma y_{ij}$	2154.4	2612.7		2154.4	2725
$\bar{y}_{ij}$	718.13	870.90		718.13	908.33
Sd	19.58	36.54		19.58	83.78
t-calculated	**-6.38**			**-3.15**	
df	**4**			**4**	
t-critical	**±2.78**			**±2.78**	
	t-calculated > t-critical			**t-calculated > t-critical**	
Decision	Reject null hypothesis			Reject null hypothesis	

Table 12. Summary of T-statistics results for dry ITS of AC14

S/No.	#1			#2	
	WBFWMA without lime	WBFWMA with lime		WBFWMA without lime	HMA without lime
1	799.9	913.5		799.9	951.9
2	809.4	934.2		809.4	973.6
3	807.2	919.2		807.2	958
n_k	3	3		3	3
Ti=Σy_{ij}	2416.5	2766.9		2416.5	2883.5
$\bar{y}_{ij}$	805.50	922.30		805.50	961.17
Sd	4.97	10.69		4.97	11.19
t-calculated	**-17.16**			**-22.02**	
df	**4**			**4**	
t-critical	**±2.78**			**±2.78**	
	t-calculated > t-critical			**t-calculated > t-critical**	
Decision	Reject null hypothesis			Reject null hypothesis	

Table 13. Summary of T-statistics results for wet ITS of AC14

S/No.	#1			#2	
	WBFWMA without lime	WBFWMA with lime		WBFWMA without lime	HMA without lime
1	687.6	798.7		687.6	811.5
2	678	805.8		678	828.3
3	675.7	811.2		675.7	836.5
n_k	3	3		3	3
Ti=Σy_{ij}	2041.3	2415.7		2041.3	2476.3
$\bar{y}_{ij}$	680.43	805.23		680.43	825.43
s_d	6.31	6.27		6.31	12.74
t-calculated	**-24.30**			**-17.67**	
df	**4**			**4**	
t-critical	**±2.78**			**±2.78**	
	t-calculated > t-critical			**t-calculated > t-critical**	
Decision	Reject null hypothesis			Reject null hypothesis	

The results of a two-tailed t-statistical analysis of the indirect tensile strength values obtained from laboratory tests conducted on both types of aggregates prior to and following moisture conditioning of the asphalt mix specimens show that the null hypothesis is rejected in all cases because the computed t-value is greater than the critical value of the same at the 5% level of significance. Therefore, the temperature at which it is mixed and compacted, the technologies (additives) used in the production of warm mix asphalt mixtures, and the use of hydrated lime additives as an adhesion agent have a significant impact on the potential of asphalt mixtures to resist moisture-induced damage.

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to evaluate the effect of mixing and compaction temperature along with the application of hydrated lime additive and methodology used in terms of water-based foamed warm mix asphalt mixes' resistance to moisture-induced damage compared to hot mix asphalt mixtures. The results of the moisture susceptibility test of various asphalt mixes with and without hydrated lime additives, which were analyzed and discussed in the previous chapter, led to the following conclusions and recommendations.

5.1 Conclusion

This study evaluated the potential resistance to stripping of water-based foamed warm mix asphalt mixtures prepared with a free water system of foaming effect technology compared to hot mix asphalt by employing hydrated lime additives as anti-stripping agent. The aim was to assess the effects of this approach towards a more environmentally friendly method of producing warm mix asphalt mixtures.

- Water-based foamed warm mix asphalt mixture (WBFWMA) prepared by utilizing free water system of foaming effect technology has decreased ITS values compared to HMA of the same mix proportion for all mixes prepared with both types of aggregates, which indicates that WBFWMA is more susceptible to moisture than HMA.
- Its lower mixing and compaction temperatures, as well as the methodology (water-based process) utilized to produce foamed warm mix asphalt greatly affects the mechanical properties of asphalt mixes, hence, the mechanical strength of water-based warm mix asphalt has decreased in comparison to hot mix asphalt.
- Lime-modified WBFWMA has increased ITS values than unmodified counterpart for both wet and dry conditions of the same mix proportion. It revealed that lime has a promising effect on enhancing the mechanical strength by improving the adhesion of aggregates and bitumen that reduces the moisture sensitivity of asphalt mixtures.
- The pavement industry may experience moisture sensitivity problems while using water-based foamed warm mix asphalt since water is applied to produce WBFWMA, which may get trapped into the mixture and remain, causing moisture damage to the asphalt mixture.
- The mixing and compaction temperature, the lime-additive and the methodology used in the production of asphalt mixtures have a great impact on moisture sensitivity resistance of water-based foamed warm mix asphalt mixtures (WBFWMA).

*“**Note**: The study's findings and conclusions presented are solely based on and/or subjected to the asphalt mixtures that were prepared for water-based foamed warm mix asphalt (WBFWMA) by employing the free water system of foaming effect technology and may not be applicable to all other warm mix asphalt preparation methods.”*

5.2 Recommendation

Following the results obtained from the laboratory test conducted on WBFWMA the following recommendations were made.

- The result recommends to use lime-modified warm mix asphalt for the construction and maintenance of road pavements due to its numerous advantages to the pavement industry in terms of safety, health, environment, and cost benefits.
- The current study was conducted on WBFWMA mixtures prepared using the free water system of foaming effect technology that might hinder its effectiveness of the asphalt mixture performance because of the direct application of water into the hot bitumen to create foam.
- Further studies on warm mix asphalt mixture produced by employing organic and chemical additives is recommended for detail understanding of its effectiveness and practical use in the pavement industry.

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Appendices

Appendix A: Summary of Laboratory Test results

Appendix: A

I. Optimum Bitumen Content Determination for AC20

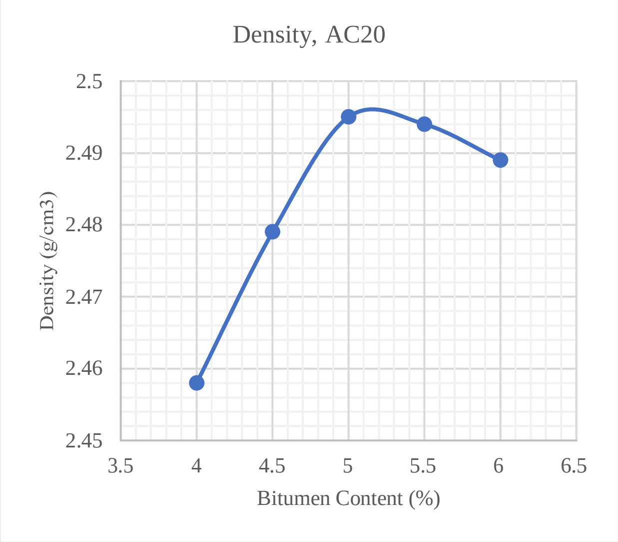
TABLE 1. SUMMARY OF VOLUMETRIC PROPERTIES OF AC20 MIXTURES

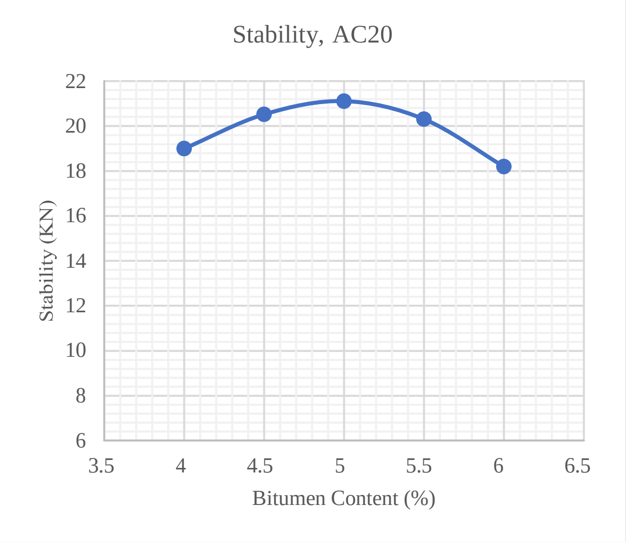
Compaction:			75 Blows														
Grade of Bitumen:			PG 60/70														
Bulk Specific Gravity of Bitumen:			1.032		Bulk Specific Gravity of Aggregate:				2.810	Prov Ring Factor			1.0				
Mix Type			AC20														
																Average	
Bitumen Content % Wt.	No. of Trials	Weight in Air (gm)	Weight in Water, gm	Saturated Weight, gm	Bulk Volume, cm3	Bulk SG	Max. SG	Va, %	VMA, %	VFM (%)	Prov Ring reading	Stability, KN	Correction Factor	Stability Corrected, KN	Flow, mm	Stability, KN	Flow, mm
Specification								3-5	min 14	65-75						min 9	2-4
4.0	1	1245.5	741.5	1250.2	508.8	2.448					17.7	17.7	1.04	18.4	2.21	19.00	2.10
	2	1240.8	746.0	1248.3	502.3	2.470					18.9	18.9	1.04	19.7	2.11		
	3	1237.1	747.7	1251.4	503.7	2.456					18.2	18.2	1.04	18.9	1.99		
						2.458	2.638	6.82	16.02	57.48							
4.5	1	1257.9	746.8	1254.1	507.2	2.480					19.7	19.7	1.04	20.5	2.49	20.52	2.40
	2	1261.8	749.5	1257.3	507.8	2.485					20.0	20.0	1.04	20.8	2.56		
	3	1248.1	752.7	1257.6	504.9	2.472					19.5	19.5	1.04	20.3	2.15		
						2.479	2.624	5.53	15.76	64.89							
5.0	1	1230.3	739.0	1231.1	492.1	2.500					20.6	20.6	1.04	21.4	2.92	21.11	2.90
	2	1240.7	744.8	1243.9	499.1	2.486					19.9	19.9	1.04	20.7	3.61		
	3	1234.1	744.0	1237.9	493.8	2.499					20.4	20.4	1.04	21.2	2.17		
						2.495	2.606	4.26	15.65	72.78							
5.5	1	1223.2	733.4	1224.4	491.0	2.491					18.8	18.8	1.04	19.5	3.29	20.31	3.40
	2	1241.1	745.1	1243.3	498.2	2.491					20.1	20.1	1.04	20.9	3.31		
	3	1245.2	748.3	1246.6	498.3	2.499					19.7	19.7	1.04	20.5	3.61		
						2.494	2.583	3.45	16.13	78.59							
6.0	1	1224.2	734.1	1225.4	491.3	2.492					17.1	17.1	1.04	17.8	3.59	18.20	3.90
	2	1240.1	744.6	1243.2	498.6	2.487					17.9	17.9	1.04	18.6	4.32		
	3	1243.9	746.0	1246	500.0	2.488					17.5	17.5	1.04	18.2	3.78		
						2.489	2.561	2.82	16.74	83.19							

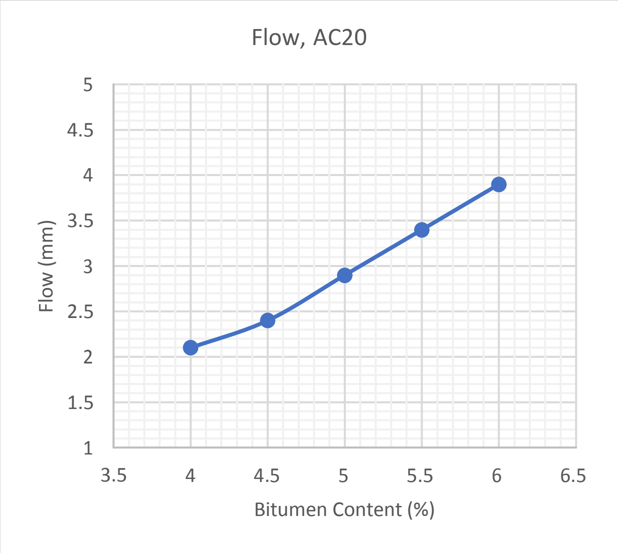
TABLE 2. SUMMARY OF VOLUMETRIC CHARACTERISTICS OF THE AC 20 MIXTURES

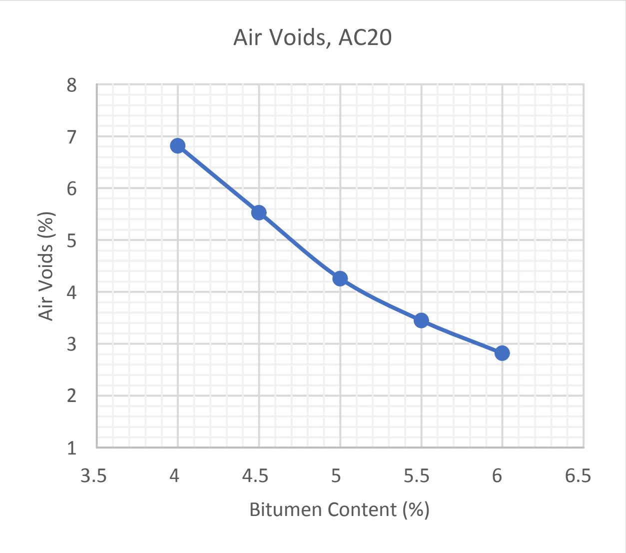
Bitumen Content %Wt	Bulk Density	Air Voids	VMA	VFA	Stability	Flow	Gmm
4.0	2.458	6.82	16.02	57.48	19.00	2.10	2.638
4.5	2.479	5.53	15.76	64.89	20.52	2.40	2.624
5.0	2.495	4.26	15.65	72.78	21.11	2.90	2.606
5.5	2.494	3.45	16.13	78.59	20.31	3.40	2.583
6.0	2.489	2.82	16.74	83.19	18.20	3.90	2.561

From the above results, graphs of density, stability, flow, air voids, voids in mineral aggregates and voids filled with bitumen, against the respective bitumen content were plotted and a line of best fit interested on each of the graph is shown in the figure below.









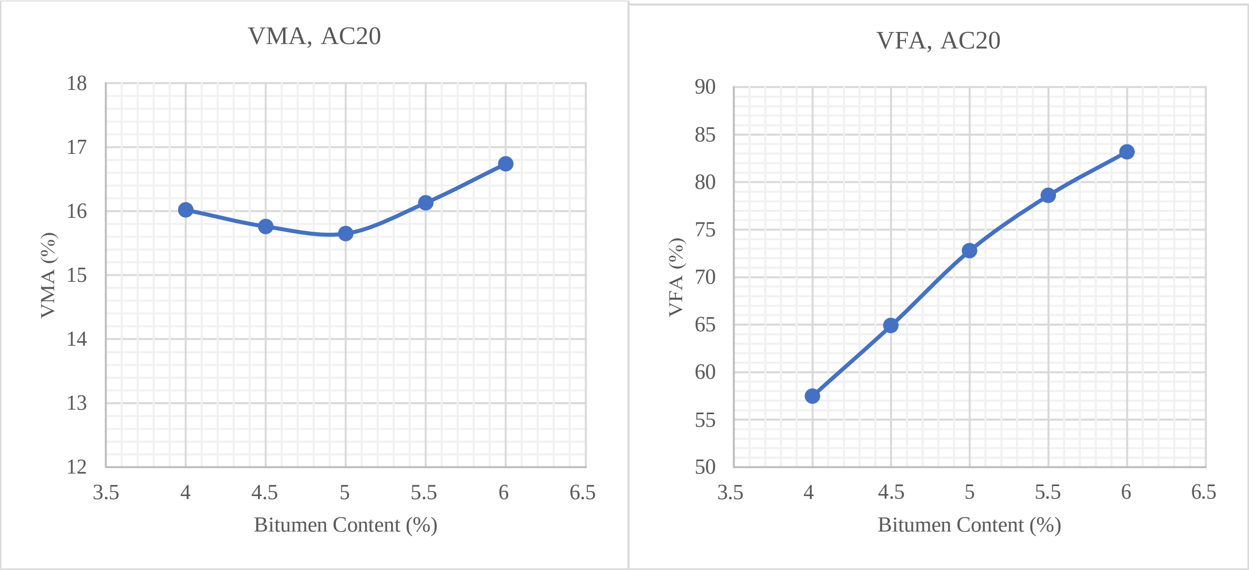


Figure 1. Graphs for volumetric characteristics of AC20 mixes

The bitumen contents corresponding to 4% air voids, maximum stability and maximum density were determined from the graphs. Optimum binder content was taken as the average of the above three respective binder contents as shown in the table below.

Parameter	Reading	Corresponding Bitumen Content
Maximum Stability (KN)	21.60	5.00
Maximum Density (g/cm3)	2.496	5.15
4% Air Voids	4.00	5.10
Average OBC		5.10

From the results obtained in the graph above; the optimum binder content is the average of the three i.e., at maximum density, maximum stability, and bitumen content at 4% air voids. Therefore, as per NAPA procedure of optimum binder content determination, it is 5.1%.

OBC = (5.00+5.15+5.10)/3 = 5.08, in which it is selected as OBC = 5.1%.

Verification of the volumetric characteristics of the asphalt mix using the optimum bitumen content of 5.1% was done and the respective results obtained are shown in the following table.

OBC @ 5.1% (Graphical) – AC20	**Results**	**Specifications**
Bulk Density (g/cm3)	2.482	
Air Voids (%)	4.14	3.0 – 5.0
VMA (%)	16.18	Min 15.0
VFB (%)	74.43	65.0 – 78.0
Stability (KN)	19.16	Min 9.0
Flow (mm)	3.22	2.0 – 4.0

II. Optimum Bitumen Content Determination for AC14

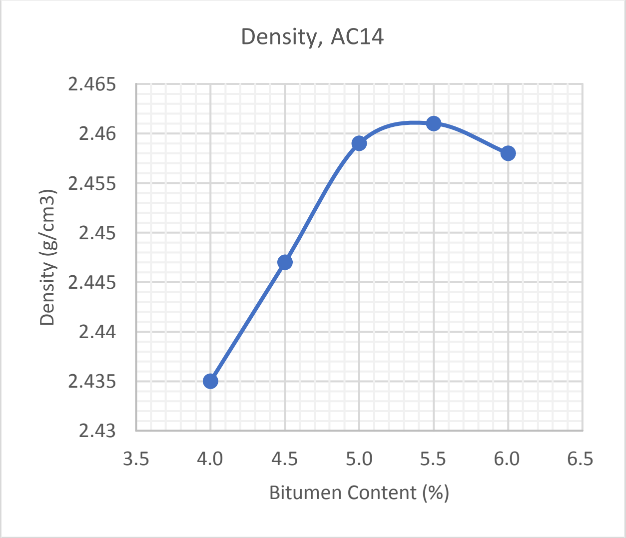
TABLE 31. SUMMARY OF VOLUMETRIC CHARACTERIZATION OF AC14 MIXTURES

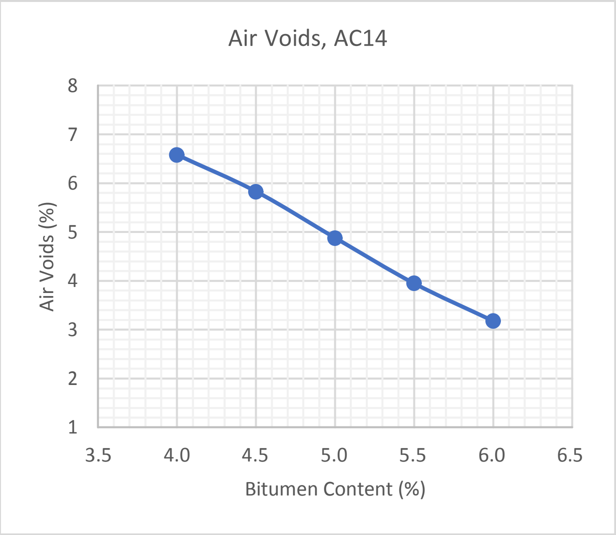
Compaction:			75 Blows														
Grade of Bitumen:			PG 60/70														
Bulk Specific Gravity of Bitumen:			1.032		Bulk Specific Gravity of Aggregate:				2.774	Prov ring Factor			1.0				
Mix Type			AC14														
																Average	
Bitumen Content % Wt.	No. of Trials	Weight in Air (gm)	Weight in Water, gm	Saturated Weight, gm	Bulk Volume, cm3	Bulk SG	Max. SG	Va, %	VMA, %	VFM (%)	Prov Ring reading	Stability, KN	Correction Factor	Stability Corrected, KN	Flow, mm	Stability, KN	Flow, mm
Specification								3-5	min 15	65-75						min 9	2-4
4.0	1	1242.1	739.9	1251	511.1	2.431					17.2	17.2	1.04	18.3	2.34	18.37	2.30
	2	1244.5	741.8	1252.2	510.4	2.438					18.0	18.0	1.04	18.7	2.28		
	3	1243.7	745.4	1255.8	510.4	2.437					17.8	17.8	1.04	18.5	2.27		
						2.435	2.607	6.58	15.72	58.13							
4.5	1	1243.9	750.6	1258.7	508.1	2.448					18.5	18.5	1.04	19.2	2.69	19.41	2.70
	2	1246.1	751.5	1260.6	509.1	2.448					18.9	18.9	1.04	19.7	2.75		
	3	1238.0	750.8	1257.4	506.6	2.444					18.6	18.6	1.04	19.3	2.66		
						2.447	2.598	5.83	15.77	63.04							
5.0	1	1220.2	736.3	1232.0	495.7	2.462					20.4	20.4	1.04	21.2	3.12	20.63	3.20
	2	1231.5	743.6	1244.4	500.8	2.459					18.3	18.3	1.04	19.0	3.28		
	3	1222.2	739.1	1236.8	497.7	2.456					20.8	20.8	1.04	20.8	3.21		
						2.459	2.585	4.88	15.80	69.09							
5.5	1	1215.5	734.7	1228.1	493.4	2.464					20.9	20.9	1.04	21.7	3.71	21.01	3.70
	2	1230.8	742.4	1243.0	500.6	2.459					19.0	19.0	1.04	19.8	3.64		
	3	1232.0	745.1	1245.9	500.8	2.460					20.7	20.7	1.04	21.5	3.75		
						2.461	2.562	3.95	16.17	75.56							
6.0	1	1213.3	731.8	1225.2	493.5	2.459					18.6	18.6	1.04	19.3	3.62	19.20	3.90
	2	1228.8	742.3	1242.1	499.8	2.459					18.7	18.7	1.04	19.4	4.08		
	3	1233.6	743.6	1245.7	502.1	2.457					18.2	18.2	1.04	18.9	3.99		
						2.458	2.539	3.18	16.70	80.94							

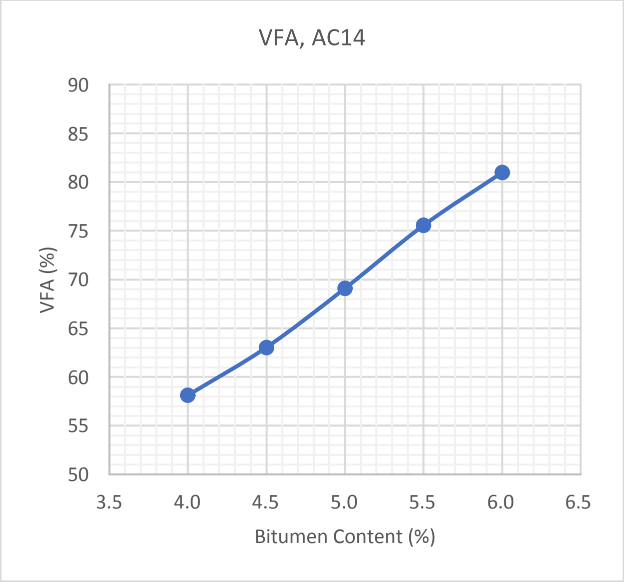
Table 4. Summary of Volumetric Characteristic properties of AC 14 Mixtures

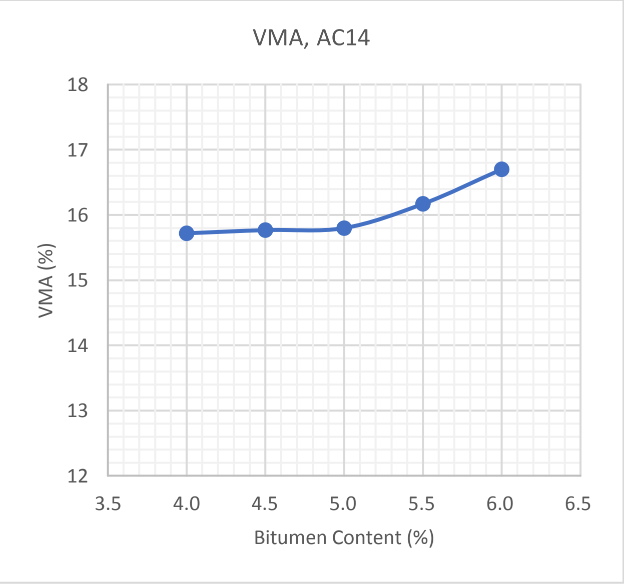
Bitumen Content %Wt	Bulk Density	Air Voids	VMA	VFA	Stability	Flow	Gmm
4.0	2.435	6.58	15.72	58.13	18.37	2.30	2.607
4.5	2.447	5.83	15.77	63.04	19.41	2.70	2.598
5.0	2.459	4.88	15.80	69.09	20.63	3.20	2.585
5.5	2.461	3.95	16.17	75.56	21.01	3.70	2.562
6.0	2.458	3.18	16.70	80.98	19.20	3.90	2.539

From the above results, graphs of density, stability, flow, air voids, voids in mineral aggregates and voids filled with bitumen, against the respective bitumen content were plotted and a line of best fit interested on each of the graph is shown in the figure below.









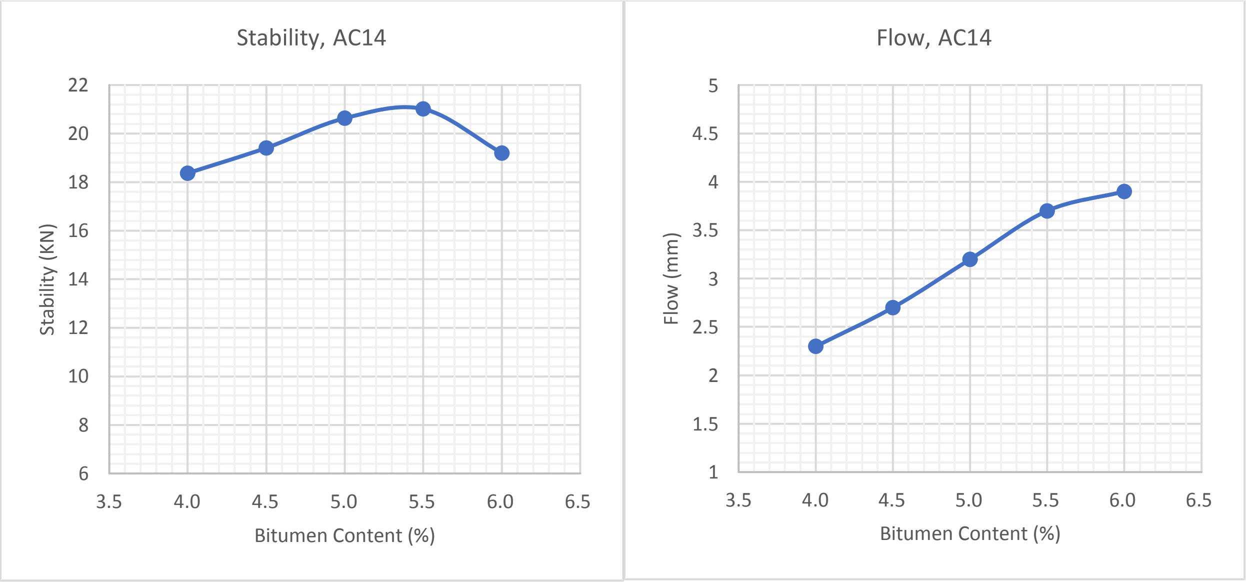


Figure 2. Graphs for volumetric characteristics of AC14 mixes

The bitumen contents corresponding to 4% air voids, maximum stability and maximum density were determined from the graphs. Optimum binder content was taken as the average of the above three respective binder contents as shown in the table below.

Parameter	Reading	Corresponding Bitumen Content
Maximum Stability (KN)	21.20	5.40
Maximum Density (g/cm3)	2.461	5.35
4% Air Voids	4.0	5.45
Average OBC		5.40

From the results obtained in the graph above, the optimum content is the average of the three i.e., at maximum density, maximum stability, and bitumen content at 4% air voids. Therefore, as per NAPA procedure of optimum binder content determination, it is 5.4%.

OBC = (5.40+5.35+5.45)/3 = 5.40, in which it is selected as OBC = 5.4%.

Verification of the volumetric characteristics of the asphalt mixes using the optimum bitumen content of 5.4% was done and the respective results obtained are shown in the following table.

OBC @ 5.4% (Graphical) – AC14	**Results**	**Specifications**
Bulk Density (g/cm3)	2.471	
Air Voids (%)	4.27	3.0 – 5.0
VMA (%)	15.74	Min 15.0
VFB (%)	72.86	65.0 – 78.0
Stability (KN)	18.49	Min 9.0
Flow (mm)	3.51	2.0 – 4.0

III. Effective Specific Gravity of Mixed Aggregates

Maximum specific gravity of mix (Gmm) for both AC20 and AC14 at each bitumen content as per MS-2 is shown in the table below.

Bitumen Content (%)	4.0	4.5	5.0	5.5	6.0
$Gmm_{(AC20)}$	2.638	2.624	2.606	2.583	2.561
$Gmm_{(AC14)}$	2.607	2.598	2.585	2.562	2.539

As per the results shown in the above table, the effective specific gravity of mixed aggregate (Gse) for both AC20 and AC14 mixes is calculated as follows.

$Gse = \{(Pmm-Pb)/((Pmm/Gmm) - (Pb/Gb))\}$

$Gse\ (4.0\%)_{AC20} = \{(100-4.0) / ((100/2.638) - (4.0/1.032))\} = 2.821$

$Gse\ (4.5\%)_{AC20} = \{(100-4.5) / ((100/2.624) - (4.5/1.032))\} = 2.830$

$Gse\ (5.0\%)_{AC20} = \{(100-5.0) / ((100/2.606) - (5.0/1.032))\} = 2.833$

$Gse\ (5.5\%)_{AC20} = \{(100-5.5) / ((100/2.583) - (5.5/1.032))\} = 2.830$

$Gse\ (6.0\%)_{AC20} = \{(100-6.0) / ((100/2.561) - (6.0/1.032))\} = 2.828$

$Gse\ (4.0\%)_{AC14} = \{(100-4.0) / ((100/2.607) - (4.0/1.032))\} = 2.784$

$Gse\ (4.5\%)_{AC14} = \{(100-4.5) / ((100/2.598) - (4.5/1.032))\} = 2.798$

$Gse\ (5.0\%)_{AC14} = \{(100-5.0) / ((100/2.585) - (5.0/1.032))\} = 2.807$

$Gse\ (5.5\%)_{AC14} = \{(100-5.5) / ((100/2.562) - (5.5/1.032))\} = 2.804$

$Gse\ (6.0\%)_{AC14} = \{(100-6.0) / ((100/2.539) - (6.0/1.032))\} = 2.800$

Where, Gse = Effective specific gravity of aggregate

Gmm = Maximum specific gravity (ASTM D2041) of paving mixtures (no air voids)

Pmm = Percent by weight of total loose mix = 100

Pb = Asphalt content, percent by total weight of mixture at which ASTM D 2041 test was performed

Gb = Specific gravity of asphalt bitumen

A summary of bulk and apparent specific gravity of aggregates used for AC20 and AC14 mixes are shown in the table below.

	Aggregate Size	Bulk Specific Gravity (Dry)	Apparent Specific Gravity	Water Absorption
Aggregate for AC20	20 - 10mm	2.838	2.897	0.72
	10 - 5mm	2.836	2.902	0.8
	5 - 3mm	2.759	2.836	1.0
	3mm down	2.780	2.887	1.34
	Filler (quarry dust)	2.775	2.775	-
Aggregate for AC14	14 - 10mm	2.784	2.852	0.86
	10 - 5mm	2.779	2.849	0.88
	5 - 3mm	2.771	2.851	1.01
	3mm down	2.765	2.874	1.37
	Filler (quarry dust)	2.759	2.759	-

The blending proportion of aggregates used for AC20 and AC14 asphalt mixes is shown in the table below.

Aggregate size	20/14 - 10mm	10 - 5mm	5 - 3mm	3mm down	Filler (quarry dust)
Proportion AC14	15.0	40.0	10.0	34.0	1.0
Proportion AC20	43.0	11.0	4.0	41.0	1.0

Bulk Specific Gravity of Aggregate (Gsb)

$\text{Gsb}_{(AC20)} = (P1+P2+P3+...) / (P1/G1+P2/G2+P3/G3+...)$

$= 100 / [(43/2.838) + (11/2.836) + (4/2.759) + (41/2.780) + (1/2.775)] = 2.810$

$= 2.810$

$\text{Gsb}_{(AC14)} = (P1+P2+P3+...) / (P1/G1+P2/G2+P3/G3+...)$

$= 100 / [(15/2.784) + (40/2.779) + (10/2.771) + (34/2.765) + (1/2.759)] = 2.774$

$= 2.774$

Apparent Specific Gravity of Aggregate (Gsa)

$\text{Gsa}_{(AC20)} = (P1+P2+P3+...) / (P1/G1+P2/G2+P3/G3+...)$

$= 100 / [(43/2.897) + (11/2.902) + (4/2.836) + (41/2.920) + (1/2.775)] = 2.904$

$= 2.904$

$\text{Gsa}_{(AC14)} = (P1+P2+P3+...) / (P1/G1+P2/G2+P3/G3+...)$

$= 100 / [(15/2.852) + (40/2.849) + (10/2.851) + (34/2.874) + (1/2.759)] = 2.857$

= 2.857

Where, Gsb = bulk specific gravity for blended aggregate

Gsb = bulk specific gravity for blended aggregate

p1, p2, p3 = individual percentages by weight of aggregate

G1, G2, G3 = individual bulk specific gravities of aggregate

IV. Maximum Specific Gravity (Density) for AC20

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Maximum Specific Gravity (Density)-ASTM D2041-95

Sample Reference	AC20	Date of Sampling
Location	CSCEC Laboratory	Date of Testing
Source	5.10% bitumen	Technician
Description	HMA without lime	
Temperature		

	Test Numbers			1	2		
1	Weight of pyconometer, water and sample (g)	A		9975.5	9985.0		
2	Weight of pyconometer and sample (g)	B		3669.0	3647.0		
3	Weight of pyconometer and water (g)	C		8519.0	8540.5		
4	Weight of pyconometer (g)	D		1295.5	1293.5		
5	Mass of water used (g)	E	A-B	6306.5	6338.0		
6	Mass of sample used (g)	F	B-D	2373.5	2353.5		
7	Specific gravity of water (g/cm3)	G		1.00	1.00		
8	Mass of water displaced (g)	H	C-D-E	917.0	909.0		
9	Density (g/cm3)		F*G/H	2.588	2.589		
10	Average density (g/cm3)			2.589			

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Maximum Specific Gravity (Density)-ASTM D2041-95

Sample Reference	AC20	Date of Sampling	
Location	CSCEC Laboratory	Date of Testing	
Source	5.10% bitumen	Technician	
Description	WBFWMA with lime		
Temperature			

	Test Numbers			1	2		
1	Weight of pyconometer, water and sample (g)	A		9974.3	9980.0		
2	Weight of pyconometer and sample (g)	B		3668.8	3641.7		
3	Weight of pyconometer and water (g)	C		8517.0	8538.5		
4	Weight of pyconometer (g)	D		1295.9	1295.3		
5	Mass of water used (g)	E	A-B	6305.5	6338.3		
6	Mass of sample used (g)	F	B-D	2372.9	2346.4		
7	Specific gravity of water (g/cm3)	G		1.00	1.00		
8	Mass of water displaced (g)	H	C-D-E	915.6	904.9		
9	Density (g/cm3)		F*G/H	2.592	2.593		
10	Average density (g/cm3)			2.592			

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Maximum Specific Gravity (Density)-ASTM D2041-95

Sample Reference		AC20		Date of Sampling			
Location		CSCEC Laboratory		Date of Testing			
Source		5.10% bitumen		Technician			
Description		WBFWMA without lime					
Temperature							
Test Numbers				1	2		
1	Weight of pyconometer, water and sample (g)	A		9977.4	9982.0		
2	Weight of pyconometer and sample (g)	B		3670.0	3643.1		
3	Weight of pyconometer and water (g)	C		8521.7	8540.8		
4	Weight of pyconometer (g)	D		1297.5	1297.0		
5	Mass of water used (g)	E	A-B	6307.4	6338.9		
6	Mass of sample used (g)	F	B-D	2372.5	2346.1		
7	Specific gravity of water (g/cm3)	G		1.00	1.00		
8	Mass of water displaced (g)	H	C-D-E	916.8	904.9		
9	Density (g/cm3)		F*G/H	2.588	2.593		
10	Average density (g/cm3)			2.590			
	Remarks:						

Lab Technician:

Signature: Date:

V. Maximum Specific Gravity (Density) for AC14

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Maximum Specific Gravity (Density)-ASTM D2041-95

Sample Reference	AC14	Date of Sampling	
Location	CSCEC Laboratory	Date of Testing	
Source	5.40% bitumen	Technician	
Description	HMA without lime		
Temperature			

	Test Numbers			1	2		
1	Weight of pyconometer, water and sample (g)	A		9963.7	9968.5		
2	Weight of pyconometer and sample (g)	B		3658.4	3660.0		
3	Weight of pyconometer and water (g)	C		8515.1	8518.0		
4	Weight of pyconometer (g)	D		1292.6	1293.5		
5	Mass of water used (g)	E	A-B	6305.3	6308.5		
6	Mass of sample used (g)	F	B-D	2365.8	2366.5		
7	Specific gravity of water (g/cm3)	G		1.00	1.00		
8	Mass of water displaced (g)	H	C-D-E	917.2	916.0		
9	Density (g/cm3)		F*G/H	2.579	2.584		
10	Average density (g/cm3)			2.581			

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Maximum Specific Gravity (Density)-ASTM D2041-95

Sample Reference	AC14	Date of Sampling
Location	CSCEC Laboratory	Date of Testing
Source	5.40% bitumen	Technician
Description	WBFWMA with lime	
Temperature		

	Test Numbers			1	2		
1	Weight of pyconometer, water and sample (g)	A		9963.1	9965.4		
2	Weight of pyconometer and sample (g)	B		3657.5	3657.8		
3	Weight of pyconometer and water (g)	C		8515.0	8515.6		
4	Weight of pyconometer (g)	D		1296.4	1295.9		
5	Mass of water used (g)	E	A-B	6305.6	6307.6		
6	Mass of sample used (g)	F	B-D	2361.1	2361.9		
7	Specific gravity of water (g/cm3)	G		1.00	1.00		
8	Mass of water displaced (g)	H	C-D-E	913.0	912.1		
9	Density (g/cm3)		F*G/H	2.586	2.590		
10	Average density (g/cm3)			2.588			

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Maximum Specific Gravity (Density)-ASTM D2041-95

Sample Reference	AC14	Date of Sampling	
Location	CSCEC Laboratory	Date of Testing	
Source	5.40% bitumen	Technician	
Description	WBFWMA without lime		
Temperature			

	Test Numbers			1	2		
1	Weight of pyconometer, water and sample (g)	A		9961.3	9965.8		
2	Weight of pyconometer and sample (g)	B		3655.8	3658.6		
3	Weight of pyconometer and water (g)	C		8514.5	8516.1		
4	Weight of pyconometer (g)	D		1294.2	1295.3		
5	Mass of water used (g)	E	A-B	6305.5	6307.2		
6	Mass of sample used (g)	F	B-D	2361.6	2363.3		
7	Specific gravity of water (g/cm3)	G		1.00	1.00		
8	Mass of water displaced (g)	H	C-D-E	914.8	913.6		
9	Density (g/cm3)		F*G/H	2.582	2.587		
10	Average density (g/cm3)			2.584			

Remarks:

Lab Technician:

Signature: Date:

VI. Marshall Stability Analysis Results for AC20

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Marshall Stability Analysis of Bituminous Mix ASTM D1559, AASHTO T245

Location	CSCEC Laboratory		
Source	Lab Trial Mix	Grade of Bitumen	60/70
Type of Mix	AC20	Number of Blows	75 x 2
Mix Temperature	165 C	Date of Sampling	
Proving Ring factor		Date of Testing	
Sample Reference	5.1% bitumen HMA without lime	Technician	

S/No.	Description			Test Numbers			Average
				1	2	3	
1	Bulk Specific gravity of total aggregate	Gsb		2.810			
2	Effective specific gravity of total aggregate	Gse		2.828			
3	Specific gravity of bitumen	Gb		1.032			
4	Bitumen % by weight of total mix	Pb		5.10			
5	Aggregate % by weight of total mix	Ps	100-Pb	94.9			
6	Maximum specific gravity of mix	Gmm		2.589			
7	Absorbed bitumen % by weight of total aggregate	Pba	100x{(Gse-Gsb)*Gb (Gse*Gsb)}	0.23			
8	Effective bitumen % by weight of total mix	Pbe	Pb-(Pba*Ps/100)	4.88			
9	Weight of specimen in air	Wa		1231.7	1234.1	1233.9	1233.23
10	Weight of specimen in water	Ww		739.1	739.8	742.7	740.53
11	Weight of specimen in air (SSD)	Wssd		1234.7	1237.9	1239.7	1237.43
12	Volume of specimen	V	Wssd-Ww	495.6	498.1	497.0	496.90
13	Bulk specific gravity of compacted specimen	Gmb	Wa/V	2.485	2.478	2.483	2.482
14	Effective volume of bitumen	Vb	Gmb*Pbe/Gb	11.75	11.71	11.74	11.73
15	Effective volume of aggregate	Vagg	Ps*Gmb/Gsb	83.93	83.67	83.85	83.82
16	% of air voids from Gmm	Vv	{(Gmm-Gmb)/Gmm}*100	4.01	4.30	4.11	4.14
17	% Voids in mineral aggregate	VMA	100-Vagg	16.07	16.33	16.15	16.18
18	% Voids filled with bitumen	VFB	100*(Vma-Vv)/Vma	75.06	73.65	74.58	74.43
19	Marshall Stability (PR Reading)			16.77	20.60	17.89	18.42
20	Marshall Stability (KN)			16.77	20.60	17.89	18.42
21	Correction Factor			1.04	1.04	1.04	1.04
22	Corrected Marshall Stability (KN)			17.44	21.42	18.61	19.16
23	Flow (mm)			3.13	3.38	3.14	3.22

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Marshall Stability Analysis of Bituminous Mix ASTM D1559, AASHTO T245

Location	CSCEC Laboratory		
Source	Lab Trial Mix	Grade of Bitumen	60/70
Type of Mix	AC20	Number of Blows	75 x 2
Mix Temperature	135 C	Date of Sampling	
Proving Ring factor		Date of Testing	
Sample Reference	5.1% bitumen WBFWMA with lime	Technician	

S/No.	Description			Test Numbers			Average
				1	2	3	
1	Bulk Specific gravity of total aggregate	Gsb		2.81			
2	Effective specific gravity of total aggregate	Gse		2.828			
3	Specific gravity of bitumen	Gb		1.032			
4	Bitumen % by weight of total mix	Pb		5.10			
5	Aggregate % by weight of total mix	Ps	100-Pb	94.90			
6	Maximum specific gravity of mix	Gmm		2.592			
7	Absorbed bitumen % by weight of total aggregate	Pba	$\frac{100x\{(Gse-Gsb)*Gb}{(Gse*Gsb)\}}$	0.23			
8	Effective bitumen % by weight of total mix	Pbe	Pb-(Pba*Ps/100)	4.88			
9	Weight of specimen in air	Wa		1229.5	1228.0	1227.1	1228.20
10	Weight of specimen in water	Ww		737.8	739.3	736.3	737.80
11	Weight of specimen in air (SSD)	Wssd		1233	1233.9	1229	1231.80
12	Volume of specimen	V	Wssd-Ww	494.7	494.6	492.7	494.00
13	Bulk specific gravity of compacted specimen	Gmb	Wa/V	2.485	2.4828	2.4906	2.486
14	Effective volume of bitumen	Vb	Gmb*Pbe/Gb	11.75	11.736	11.773	11.75
15	Effective volume of aggregate	Vagg	Ps*Gmb/Gsb	83.94	83.85	84.112	83.97
16	% of air voids from Gmm	Vv	{(Gmm-Gmb)/Gmm}*100	4.11	4.21	3.91	4.08
17	% Voids in mineral aggregate	VMA	100-Vagg	16.06	16.15	15.89	16.03
18	% Voids filled with bitumen	VFB	100*(Vma-Vv)/Vma	74.39	73.92	75.37	74.56
19	Marshall Stability (PR Reading)			18.32	18.78	16.45	17.85
20	Marshall Stability (KN)			18.32	18.78	16.45	17.85
21	Correction Factor			1.04	1.04	1.04	1.04
22	Corrected Marshall Stability (KN)			19.05	19.53	17.11	18.56
23	Flow (mm)			3.12	2.88	2.75	2.92

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Marshall Stability Analysis of Bituminous Mix ASTM D1559, AASHTO T245

Location	CSCEC Laboratory		
Source	Lab Trial Mix	Grade of Bitumen	60/70
Type of Mix	AC20	Number of Blows	75 x 2
Mix Temperature	135 C	Date of Sampling	
Proving Ring factor		Date of Testing	
Sample Reference	5.1% bitumen WBFWMA without lime	Technician	

S/No.	Description			Test Numbers			Average
				1	2	3	
1	Bulk Specific gravity of total aggregate	Gsb		2.81			
2	Effective specific gravity of total aggregate	Gse		2.828			
3	Specific gravity of bitumen	Gb		1.032			
4	Bitumen % by weight of total mix	Pb		5.10			
5	Aggregate % by weight of total mix	Ps	100-Pb	94.9			
6	Maximum specific gravity of mix	Gmm		2.590			
7	Absorbed bitumen % by weight of total aggregate	Pba	100x{(Gse-Gsb)*Gb (Gse*Gsb)}	0.23			
8	Effective bitumen % by weight of total mix	Pbe	Pb-(Pba*Ps/100)	4.88			
9	Weight of specimen in air	Wa		1205.0	1197.3	1200.4	1200.90
10	Weight of specimen in water	Ww		724.9	720.2	720.2	721.77
11	Weight of specimen in air (SSD)	Wssd		1211.1	1202.8	1203.5	1205.80
12	Volume of specimen	V	Wssd-Ww	486.2	482.6	483.3	484.03
13	Bulk specific gravity of compacted specimen	Gmb	Wa/V	2.4784	2.4809	2.4838	2.481
14	Effective volume of bitumen	Vb	Gmb*Pbe/Gb	11.715	11.727	11.74	11.73
15	Effective volume of aggregate	Vagg	Ps*Gmb/Gsb	83.701	83.787	83.882	83.79
16	% of air voids from Gmm	Vv	{(Gmm-Gmb)/Gmm}*100	4.31	4.21	4.10	4.21
17	% Voids in mineral aggregate	VMA	100-Vagg	16.299	16.213	16.118	16.21
18	% Voids filled with bitumen	VFB	100*(Vma-Vv)/Vma	73.564	74.028	74.55	74.05
19	Marshall Stability (PR Reading)			18.56	14.75	19.59	17.63
20	Marshall Stability (KN)			18.56	14.75	19.59	17.63
21	Correction Factor			1.04	1.04	1.04	1.04
22	Corrected Marshall Stability (KN)			19.302	15.34	20.374	18.34
23	Flow (mm)			2.98	3.32	3.12	3.14

Remarks:

Lab Technician:

Signature: Date:

VII. Marshall Stability Analysis Results for AC14

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Marshall Stability Analysis of Bituminous Mix ASTM D1559, AASHTO T245

Location	CSCEC Laboratory		
Source	Lab Trial Mix	Grade of Bitumen	60/70
Type of Mix	AC14	Number of Blows	75 x 2
Mix Temperature	165 C	Date of Sampling	
Proving Ring factor		Date of Testing	
Sample Reference	5.4% bitumen HMA without lime	Technician	

S/No.	Description			Test Numbers			Average
				1	2	3	
1	Bulk Specific gravity of total aggregate	Gsb		2.774			
2	Effective specific gravity of total aggregate	Gse		2.787			
3	Specific gravity of bitumen	Gb		1.032			
4	Bitumen % by weight of total mix	Pb		5.40			
5	Aggregate % by weight of total mix	Ps	100-Pb	94.6			
6	Maximum specific gravity of mix	Gmm		2.581			
7	Absorbed bitumen % by weight of total aggregate	Pba	100x{(Gse-Gsb)*Gb (Gse*Gsb)}	0.17			
8	Effective bitumen % by weight of total mix	Pbe	Pb-(Pba*Ps/100)	5.24			
9	Weight of specimen in air	Wa		1221.6	1224.9	1222.0	1222.8
10	Weight of specimen in water	Ww		741.4	743.6	742.8	742.6
11	Weight of specimen in air (SSD)	Wssd		1235.6	1238.4	1238.6	1237.5
12	Volume of specimen	V	Wssd-Ww	494.2	494.8	495.8	494.9
13	Bulk specific gravity of compacted specimen	Gmb	Wa/V	2.472	2.476	2.465	2.471
14	Effective volume of bitumen	Vb	Gmb*Pbe/Gb	12.54	12.56	12.505	12.54
15	Effective volume of aggregate	Vagg	Ps*Gmb/Gsb	84.3	84.422	84.052	84.26
16	% of air voids from Gmm	Vv	{(Gmm-Gmb)/Gmm}*100	4.228	4.0858	4.5059	4.27
17	% Voids in mineral aggregate	VMA	100-Vagg	15.7	15.578	15.948	15.74
18	% Voids filled with bitumen	VFB	100*(Vma-Vv)/Vma	73.08	73.772	71.746	72.86
19	Marshall Stability (PR Reading)			16.22	19.6	17.5	17.78
20	Marshall Stability (KN)			16.22	19.6	17.5	17.78
21	Correction Factor			1.04	1.04	1.04	1.04
22	Corrected Marshall Stability (KN)			16.87	20.405	18.20	18.49
23	Flow (mm)			3.31	3.65	3.58	3.51

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Marshall Stability Analysis of Bituminous Mix ASTM D1559, AASHTO T245

Location	CSCEC Laboratory		
Source	Lab Trial Mix	Grade of Bitumen	60/70
Type of Mix	AC14	Number of Blows	75 x 2
Mix Temperature	135 C	Date of Sampling	
Proving Ring factor		Date of Testing	
Sample Reference	5.4% bitumen WBFWMA with lime	Technician	

S/No.	Description			Test Numbers			Average
				1	2	3	
1	Bulk Specific gravity of total aggregate	Gsb		2.774			
2	Effective specific gravity of total aggregate	Gse		2.787			
3	Specific gravity of bitumen	Gb		1.032			
4	Bitumen % by weight of total mix	Pb		5.40			
5	Aggregate % by weight of total mix	Ps	100-Pb	94.6			
6	Maximum specific gravity of mix	Gmm		2.588			
7	Absorbed bitumen % by weight of total aggregate	Pba	100x{(Gse-Gsb)*Gb (Gse*Gsb)}	0.17			
8	Effective bitumen % by weight of total mix	Pbe	Pb-(Pba*Ps/100)	5.24			
9	Weight of specimen in air	Wa		1219.2	1218.7	1214.9	1217.6
10	Weight of specimen in water	Ww		740.1	743.1	736.4	739.9
11	Weight of specimen in air (SSD)	Wssd		1233.4	1234.4	1227.9	1231.9
12	Volume of specimen	V	Wssd-Ww	493.3	491.3	491.5	492.0
13	Bulk specific gravity of compacted specimen	Gmb	Wa/V	2.472	2.481	2.472	2.475
14	Effective volume of bitumen	Vb	Gmb*Pbe/Gb	12.54	12.585	12.541	12.56
15	Effective volume of aggregate	Vagg	Ps*Gmb/Gsb	84.28	84.593	84.295	84.39
16	% of air voids from Gmm	Vv	{(Gmm-Gmb)/Gmm}*100	4.501	4.151	4.489	4.38
17	% Voids in mineral aggregate	VMA	100-Vagg	15.72	15.407	15.705	15.61
18	% Voids filled with bitumen	VFB	100*(Vma-Vv)/Vma	71.36	73.055	71.416	71.94
19	Marshall Stability (PR Reading)			18.31	17.84	15.96	17.37
20	Marshall Stability (KN)			18.31	17.84	15.96	17.37
21	Correction Factor			1.04	1.04	1.04	1.04
22	Corrected Marshall Stability (KN)			19.04	18.554	16.598	18.06
23	Flow (mm)			2.75	3.09	3.35	3.06

Remarks:

Lab Technician:

Signature:

Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Marshall Stability Analysis of Bituminous Mix ASTM D1559, AASHTO T245

Location	CSCEC Laboratory		
Source	Lab Trial Mix	Grade of Bitumen	60/70
Type of Mix	AC14	Number of Blows	75 x 2
Mix Temperature	135 C	Date of Sampling	
Proving Ring factor		Date of Testing	
Sample Reference	5.4% bitumen WBFWMA without lime	Technician	

S/No.	Description			Test Numbers			Average
				1	2	3	
1	Bulk Specific gravity of total aggregate	Gsb		2.774			
2	Effective specific gravity of total aggregate	Gse		2.787			
3	Specific gravity of bitumen	Gb		1.032			
4	Bitumen % by weight of total mix	Pb		5.40			
5	Aggregate % by weight of total mix	Ps	100-Pb	94.6			
6	Maximum specific gravity of mix	Gmm		2.584			
7	Absorbed bitumen % by weight of total aggregate	Pba	100x{(Gse-Gsb)*Gb (Gse*Gsb)}	0.17			
8	Effective bitumen % by weight of total mix	Pbe	Pb-(Pba*Ps/100)	5.24			
9	Weight of specimen in air	Wa		1194.5	1188.0	1188.3	1190.27
10	Weight of specimen in water	Ww		727.2	724.0	720.3	723.83
11	Weight of specimen in air (SSD)	Wssd		1212.0	1202.6	1202.4	1205.67
12	Volume of specimen	V	Wssd-Ww	484.8	478.6	482.1	481.83
13	Bulk specific gravity of compacted specimen	Gmb	Wa/V	2.464	2.4822	2.4648	2.470
14	Effective volume of bitumen	Vb	Gmb*Pbe/Gb	12.5	12.594	12.505	12.53
15	Effective volume of aggregate	Vagg	Ps*Gmb/Gsb	84.02	84.65	84.057	84.24
16	% of air voids from Gmm	Vv	{(Gmm-Gmb)/Gmm}*100	4.648	3.9381	4.6114	4.40
17	% Voids in mineral aggregate	VMA	100-Vagg	15.98	15.35	15.943	15.76
18	% Voids filled with bitumen	VFB	100*(Vma-Vv)/Vma	70.91	74.344	71.076	72.11
19	Marshall Stability (PR Reading)			17.95	17.2	16.16	17.11
20	Marshall Stability (KN)			17.95	17.23	16.16	17.11
21	Correction Factor			1.04	1.04	1.04	1.04
22	Corrected Marshall Stability (KN)			18.67	17.919	16.806	17.80
23	Flow (mm)			3.15	3.59	3.56	3.43

Remarks:

Lab Technician:

Signature: Date:

VIII. Indirect Tensile Strength (ITS) Test Results for AC20

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Indirect Tensile Strength (Moisture Susceptibility)-AASHTO T283

Bitumen Content			5.10%			Date:			
Mix Type			HMA without lime		AC20				
Location: CSCEC Laboratory			Dry			Conditioned			
Sample Code			Blows	35	35	35	35	35	35
1	Diameter	mm	D	102	102	102	102	102	102
2	Thickness	mm	t	65.3	66.1	65.9	65.5	66.4	66.4
3	Dry Mass	g	A	1234.9	1236.2	1212.2	1222.6	1231.2	1226.5
4	SSD Mass	g	B	1241.6	1242.5	1232.2	1234.2	1237.2	1232.6
5	Mass in Water	g	C	727.1	724.5	731.6	725.9	724.5	723.3
6	Volume (B-C)	cm3	E	514.5	518	500.6	508.3	512.7	509.3
7	Bulk Specific Gravity (A/E)	g/cm3	F	2.40	2.386	2.421	2.405	2.401	2.408
8	Correction Factor	-	C'	1.00	1.00	1.00	1.00	1.00	1.00
9	Corrected Specific Gravity	g/cm3	F'	2.40	2.386	2.421	2.405	2.401	2.408
10	Maximum Specific Gravity	Gmm	G	2.589	2.589	2.589	2.594	2.594	2.594
11	Air Voids (100 x (G-F')/G)	%	H	7.3	7.8	6.5	7.3	7.4	7.2
12	Volume of Air Voids (H x E/100)		I	37.5	40.5	32.4	37.0	38.1	36.5
13	Corrected Load Reading	KN		11.19	10.70	12.66	9.91	8.64	10.29
14	Tensile Strength {2xP/(PIxtxD)}	kPa		1070.1	1010.8	1199.6	944.8	812.5	967.7
15	Average TS	kPa		1094			908		

		Results	Specification
Tensile Strength Dry	kPa	1094	Min 800 kPa
Tensile Strength Conditioned	kPa	908	N/A
Tensile Strength Ratio (W/D)*100	%	83%	>80%

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Indirect Tensile Strength (Moisture Susceptibility)-AASHTO T283

Bitumen Content			5.10%				Date:		
Mix Type			WBFWMA with lime			AC20			
Location: CSCEC Laboratory			Dry				Conditioned		
Sample Code			Blows	35	35	35	35	35	35
1	Diameter	mm	D	102	102	102	102	102	102
2	Thickness	mm	t	66.1	64.7	64.9	66.3	66.0	65.8
3	Dry Mass	g	A	1232.3	1223.0	1236.8	1228.8	1233.1	1232.1
4	SSD Mass	g	B	1239.6	1229.3	1245.2	1233.4	1237.0	1242.0
5	Mass in Water	g	C	725.6	724.5	731.6	722.2	725.5	731.3
6	Volume (B-C)	cm3	E	514.0	504.8	513.6	511.2	511.5	510.7
7	Bulk Specific Gravity (A/E)	g/cm3	F	2.397	2.423	2.408	2.404	2.411	2.413
8	Correction Factor	-	C'	1.00	1.00	1.00	1.00	1.00	1.00
9	Corrected Specific Gravity	g/cm3	F'	2.397	2.423	2.408	2.404	2.411	2.413
10	Maximum Specific Gravity	Gmm	G	2.590	2.590	2.590	2.592	2.592	2.592
11	Air Voids (100 x (G-F')/G)	%	H	7.4	6.5	7.0	7.3	7.0	6.9
12	Volume of Air Voids (H x E/100)		I	38.2	32.6	36.1	37.1	35.8	35.4
13	Corrected Load Reading	KN		10.68	10.89	10.50	9.57	9.31	8.75
14	Tensile Strength {2xP/(PIxtxD)}	kPa		1009.0	1051.1	1010.3	901.4	880.9	830.4
15	Average TS	kPa		1023			871		

		Results	Specification
Tensile Strength Dry	kPa	1023	Min 800 kPa
Tensile Strength Conditioned	kPa	871	N/A
Tensile Strength Ratio (W/D)*100	%	85%	>80%

Remarks:

Lab Technician:

Signature:

Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Indirect Tensile Strength (Moisture Susceptibility)-AASHTO T283

Bitumen Content			5.10%				Date:		
Mix Type			WBFWMA without lime		AC20				
Location: CSCEC Laboratory			Dry				Conditioned		
Sample Code			Blows	35	35	35	35	35	35
1	Diameter	mm	D	102	102	102	102	102	102
2	Thickness	mm	t	65.1	64.6	64.3	64.6	63.5	64.4
3	Dry Mass	g	A	1230.2	1233.4	1239.5	1233.6	1234.5	1241.8
4	SSD Mass	g	B	1231.3	1234.7	1243.5	1238.7	1239.2	1246.3
5	Mass in Water	g	C	724	720.4	723.9	726.1	728.8	730.2
6	Volume (B-C)	cm3	E	507.3	514.3	519.6	512.6	510.4	516.1
7	Bulk Specific Gravity (A/E)	g/cm3	F	2.425	2.398	2.385	2.407	2.419	2.406
8	Correction Factor	-	C'	1.00	1.00	1.00	1.00	1.00	1.00
9	Corrected Specific Gravity	g/cm3	F'	2.425	2.398	2.385	2.407	2.419	2.406
10	Maximum Specific Gravity	Gmm	G	2.592	2.592	2.592	2.592	2.592	2.592
11	Air Voids (100 x (G-F')/G)	%	H	6.4	7.5	8.0	7.2	6.7	7.2
12	Volume of Air Voids (H x E/100)		I	32.7	38.5	41.4	36.7	34.1	37.0
13	Corrected Load Reading	KN		9.34	9.36	8.93	7.66	7.16	7.32
14	Tensile Strength {2xP/(PIxtxD)}	kPa		895.9	904.8	867.2	740.5	704.1	709.8
15	Average TS	kPa		889			718		

		Results	Specification
Tensile Strength Dry	kPa	889	Min 800 kPa
Tensile Strength Conditioned	kPa	718	N/A
Tensile Strength Ratio (W/D)*100	%	81%	>80%

Remarks:

Lab Technician:

Signature:

Date:

IX. Indirect Tensile Strength (ITS) Test Results for AC14

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures									
Indirect Tensile Strength (Moisture Susceptibility)-AASHTO T283									
Bitumen Content			5.40%				Date:		
Mix Type			HMA without lime			AC14			
Location: CSCEC Laboratory			Dry				Conditioned		
Sample Code			Blows	35	35	35	35	35	35
1	Diameter	mm	D	102	102	102	102	102	102
2	Thickness	mm	t	63.5	62.6	62.9	63.1	63.4	63.6
3	Dry Mass	g	A	1223.4	1226.2	1217.2	1224.3	1221.3	1220.6
4	SSD Mass	g	B	1234.1	1232.2	1226.2	1229.0	1227.7	1228.6
5	Mass in Water	g	C	721.0	719.4	718.1	717.5	718.4	719.0
6	Volume (B-C)	cm3	E	513.1	512.8	508.1	511.5	509.3	509.6
7	Bulk Specific Gravity (A/E)	g/cm3	F	2.38	2.391	2.396	2.394	2.398	2.395
8	Correction Factor	-	C'	1.00	1.00	1.00	1.00	1.00	1.00
9	Corrected Specific Gravity	g/cm3	F'	2.38	2.391	2.396	2.394	2.398	2.395
10	Maximum Specific Gravity	Gmm	G	2.581	2.581	2.581	2.587	2.587	2.587
11	Air Voids (100 x (G-F')/G)	%	H	7.6	7.4	7.2	7.5	7.3	7.4
12	Volume of Air Voids (H x E/100)		I	39.1	37.7	36.5	38.2	37.2	37.8
13	Corrected Load Reading	KN		9.68	9.76	9.65	8.20	8.41	8.52
14	Tensile Strength {2xP/(PIxtxD)}	kPa		951.9	973.6	958.0	811.5	828.3	836.5
15	Average TS	kPa		961			825		

		Results	Specification
Tensile Strength Dry	kPa	961	Min 800 kPa
Tensile Strength Conditioned	kPa	825	N/A
Tensile Strength Ratio (W/D)*100	%	86%	>80%

Remarks:

Lab Technician:

Signature: Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Indirect Tensile Strength (Moisture Susceptibility)-AASHTO T283

Bitumen Content			5.40%				Date:		
Mix Type			WBFWMA with lime			AC14			
Location: CSCEC Laboratory			Dry				Conditioned		
Sample Code			Blows	35	35	35	35	35	35
1	Diameter	mm	D	102	102	102	102	102	102
2	Thickness	mm	t	62.0	62.3	62.5	62.7	63.0	62.2
3	Dry Mass	g	A	1222.3	1226.9	1229.0	1225.5	1229.1	1231.0
4	SSD Mass	g	B	1235.0	1233.1	1235.4	1238.9	1237.2	1238.3
5	Mass in Water	g	C	721.6	720.0	722.8	725.7	724.4	722.0
6	Volume (B-C)	cm3	E	513.4	513.1	512.6	513.2	512.8	516.3
7	Bulk Specific Gravity (A/E)	g/cm3	F	2.381	2.391	2.398	2.388	2.397	2.384
8	Correction Factor	-	C'	1.00	1.00	1.00	1.00	1.00	1.00
9	Corrected Specific Gravity	g/cm3	F'	2.381	2.391	2.398	2.388	2.397	2.384
10	Maximum Specific Gravity	Gmm	G	2.588	2.588	2.588	2.591	2.591	2.591
11	Air Voids (100 x (G-F')/G)	%	H	8.0	7.6	7.4	7.8	7.5	8.0
12	Volume of Air Voids (H x E/100)		I	41.1	39.0	37.7	40.2	38.4	41.2
13	Corrected Load Reading	KN		9.07	9.32	9.2	8.02	8.13	8.08
14	Tensile Strength {2xP/(PIxtxD	kPa		913.5	934.2	919.2	798.7	805.8	811.2
15	Average TS	kPa		922			805		

		Results	Specification
Tensile Strength Dry	kPa	922	Min 800 kPa
Tensile Strength Conditioned	kPa	805	N/A
Tensile Strength Ratio (W/D)*100	%	87%	>80%

Remarks:

Lab Technician:

Signature:

Date:

Laboratory Performance Evaluation of Hydrated Lime Additives on Moisture Susceptibility of Water-Based Foamed Warm Mix Asphalt (WBFWMA) Mixtures

Indirect Tensile Strength (Moisture Susceptibility)-AASHTO T283

Bitumen Content			5.40%				Date:		
Mix Type			WBFWMA without lime			AC14			
Location: CSCEC Laboratory			Dry				Conditioned		
Sample Code			Blows	35	35	35	35	35	35
1	Diameter	mm	D	102	102	102	102	102	102
2	Thickness	mm	t	63.0	62.8	63.2	63.3	63.0	63.4
3	Dry Mass	g	A	1221.3	1220.6	1218.4	1223.4	1222.8	1221.1
4	SSD Mass	g	B	1228.5	1228	1226.7	1230.9	1230.0	1229.8
5	Mass in Water	g	C	718.2	717.8	716.1	717.7	718.0	719.7
6	Volume (B-C)	cm3	E	510.3	510.2	510.6	513.2	512.0	510.1
7	Bulk Specific Gravity (A/E)	g/cm3	F	2.393	2.392	2.386	2.384	2.388	2.394
8	Correction Factor	-	C'	1.00	1.00	1.00	1.00	1.00	1.00
9	Corrected Specific Gravity	g/cm3	F'	2.393	2.392	2.386	2.384	2.388	2.394
10	Maximum Specific Gravity	Gmm	G	2.584	2.584	2.584	2.588	2.588	2.588
11	Air Voids (100 x (G-F')/G)	%	H	7.4	7.4	7.7	7.9	7.7	7.5
12	Volume of Air Voids (H x E/100)		I	37.7	37.8	39.1	40.5	39.5	38.3
13	Corrected Load Reading	KN		8.07	8.14	8.17	6.97	6.84	6.86
14	Tensile Strength {2xP/(PIxtxD)}	kPa		799.9	809.4	807.2	687.6	678.0	675.7
15	Average TS	kPa		806			680		

		Results	Specification
Tensile Strength Dry	kPa	806	Min 800 kPa
Tensile Strength Conditioned	kPa	680	N/A
Tensile Strength Ratio (W/D)*100	%	84%	>80%

Remarks:

Lab Technician:

Signature: Date:

Appendix B: Representative Pictures During Laboratory Testing

Appendix: B

I. Materials used for Preparation of Asphalt Mixtures

Aggregates and Hydrated Lime	
	
20mm nominal size aggregate	14mm nominal size aggregate
Asphalt Binders	
	
Hot Asphalt Binder	Foamed Asphalt Binder

II. Preparation of Asphalt Mixtures

	
Weighing of aggregates as per blending proportions	
 Adding of dry lime in a pre-mix process	 Adding of asphalt binder
 Heating of aggregate and asphalt binder	 Mixing

III. Preparation of Foamed Asphalt Binder

 Checking the temperature of hot binder	 Measuring 1.5% of water by binder weight
 Injecting cold water to the hot binder	 Mixing of the water and hot binder to create foam
 Hot and Foamed Binder	 Foamed Binder

IV. Testing for Marshall Stability and Flow

Marshall Specimens

Weight in air

Weight in water

Weight SSD

Soaking of specimens at 60 ^{0}C

Testing for Marshall Stability and Flow

V. Moisture Conditioning and ITS testing for trial asphalt specimens

Trial Samples for ITS

Checking of temperature @60 ^{0}C for soaking

Hot water bath @ 60 ^{0}C

Trial Specimens soaked @ 60 ^{0}C

Measuring of thickness and diameter of the specimen

Testing for indirect tensile strength