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

THE EFFECT OF HYDRATED LIME ADDITIVES ON MOISTURE SENSITIVITY AND OVERALL PERFORMANCE OF HOT MIX ASPHALT MIXTURES

By

Asres Simeneh

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

Advisor
Dr. Bikila Teklu

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Addis Ababa University
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Department of Civil Engineering

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Approved by Board of Examiners:

Dr.Bikila Teklu	__________________	__________________
Advisor	*Signature*	*Date*
______________________	__________________	__________________
External Examiner	*Signature*	*Date*
______________________	__________________	__________________
Internal Examiner	*Signature*	*Date*
______________________	__________________	__________________
Chair Person	*Signature*	*Date*

DECLARATION

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

Name Asres Simeneh

Signature ______________

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

Date December, 2013

ABSTRACT

Well-designed asphalt mixtures can be expected to serve successfully for many years under a variety of loading and environmental conditions. However, Stripping is one of the common types of pavement failure found in asphaltic pavements. Besides high traffic impact stress, climatic factor such as temperature and moisture have also profound effect on the durability of hot mix asphalt pavements. One of this research's goal is to evaluate and compare the stripping performance of unmodified and lime modified hot mix asphalt using two different types of lime application.

The research study utilized laboratory evaluations to study effects of hydrated lime additive on moisture susceptibility and important physical properties of Hot Mix Asphalt mixtures. The evaluation involved six mix designs from two aggregate sources and one bitumen source. Out of the six, two are used as control and the other four are checked for the advantages of hydrated lime additives.

Laboratory testing was accomplished in the first phase with the production of Marshall compacted specimens to determine the performance of Hot Mix Asphalt using Marshall Mix design methods and parameters such as air voids, voids in mineral aggregate, voids filled with asphalt cement, Marshall Stability and flow are measured. The result shows superior advantage on hydrated lime additive on stability and other important physical properties of Hot Mix Asphalt. Beside this, the optimum asphalt content is determined for phase two test.

For the selected optimum bitumen content on the second phase, six samples from each mix were prepared to conduct the moisture susceptibility test. Three of the six samples are conditioned with saturation and freeze-thaw cycles and the other three were unconditioned. Finally the tensile strength test for each group was conducted. The tensile strength ratio according to AASHTO T 283 proved that that hydrated lime additive has an advantage on moisture susceptibility

The research concludes that adding hydrated lime in Hot Mix Asphalt improves the performance of mixtures and increases the life of highways. Furthermore, both dry lime and lime slurry hydrated lime application methods used in this research have good results compared with the unmodified samples.

Key Words

Hot Mix Asphalt, Moisture damage, Moisture susceptibility, Stripping, Anti-strip additives, Lime, Marination, Asphalt, Marshall Mix design.

To
Engineer Yitatek Alamirew

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CHAPTER ONE

INTRODUCTION

1.1. Introduction

Hot Mix Asphalt pavements serve in a multitude of traffic and environmental conditions, demanding that the materials and design meet specific engineering requirements. Therefore the main objective of HMA mix design is to determine the combination of asphalt cement and aggregate that will give long lasting performance as part of the pavement structure. Mix design involves laboratory procedures developed to establish the necessary proportion of materials for use in the HMA. These procedures include determining an appropriate blend of aggregate sources to produce a proper gradation of mineral aggregate, and selecting the type and amount of asphalt cement to be used as the binder for that gradation.

Well-designed asphalt mixtures can be expected to serve successfully for many years under a variety of loading and environmental conditions. However, Stripping of aggregate from asphalt binder has been a common problem that results in premature pavement [01].In addition to this rutting most commonly occurs early in a pavement's life. Also moisture affects asphalt pavements in two important ways. First, moisture can enter the interface between the bitumen and aggregate destroying the bond between those two key components of the pavement. Second, moisture can penetrate the bitumen itself softening it and reducing its cohesive strength. Both damage mechanisms can reduce the pavement's integrity and shorten its effective life [02].

Moisture induced damage of HMA pavement can drastically reduce a pavement's expected design life. Once the HMA mixture is damaged, a significant reduction in the HMA's internal strength occurs. The moisture damage within the asphalt pavement's structure can manifest into various types of pavement distresses such as rutting, and raveling.

Furthermore fatigue cracking occurs when pavements are excessively stiff or the structural layers are too thin to support the traffic that they carry. Fatigue results from excessive tension in the pavement structure often caused by overweight vehicles, shear stresses caused by traffic movement, or by rapid temperature change in the pavement

For over thirty years it has been well established that hydrated lime reacts with acid components of bitumen to produce beneficial changes to reduce the above effects and for contribution to the creation of high performance asphalt mixes [03]. Adding lime in HMA improve the mixtures in many ways and increasing the life of highways. Lime contributes to both the mechanical and rheological properties of asphalt mixtures, improving moisture sensitivity resistance and fracture toughness along with reducing the rate of oxidative aging for many types of bitumen. Considerable laboratory research has been performed to quantify the benefits of hydrated lime.

It is possible to add lime either of on the aggregate with different moisture and marination condition or on the HMA mix. Studies have shown that lime reduces the potential for moisture to disrupt the adhesive bond that exists between the asphalt binder and aggregate. Some individuals attribute the increase in adhesive strength to changes in the surface chemistry or molecular polarity of the aggregate surface. The result is a stronger bond at the interface between the aggregate and asphalt binder.

This thesis provides a conclusive investigation of different test methods to evaluate moisture sensitivity of HMA mixes. The goal of this study was to determine the moisture damage resistance of compacted asphalt specimens modified with hydrated lime. The effectiveness of lime additives were evaluated by comparing test results conducted on unmodified (virgin) and hydrated lime modified specimens. The different performance tests were conducted on the aggregate, asphalt binder, and uncompact specimens. All tests on aggregate, asphalt binder, loose mixtures, and compacted specimens were conducted according to respective testing standards which is applicable in Ethiopia.

In addition to this a statistical analysis is used to determine the best method of introducing lime into a HMA mix as an aggregate additive to mitigate moisture damage. The laboratory tests evaluated various materials (i.e., aggregates, binders, and Lime) using multiple test methods and conditioning procedures.

1.2. Statement of the problem

For over a century, paved roadways have been constructed using asphalt concrete mixes across the world. However, a major problem still exists involving premature distresses and pavement failures, e.g. rutting, cracking, potholes etc. In spite of the fact that the highway engineers discover different methods and procedures of mix design over years, up to now it couldn’t be imaginable to avoid premature distresses and pavement failures.

Stripping of aggregate from asphalt binder has been a common and the core problem that results in premature pavement failures in Ethiopia. Ethiopia being in tropical climate receives seasonal and a significant amount of sun light and rainfall within the year. Besides climatic factor such as temperature and moisture, high traffic impact stresses also have profound effect on the durability of Hot Mix Asphalt pavements against stripping failures.

Stripping happens when water infiltrates between an asphalt film and the aggregate surface, and replaces the asphalt aggregate's coating. This situation causes a loss of bond between the aggregate and the asphalt cement. The most serious consequence of stripping is the loss of strength and integrity of the pavement. Stripping failures within the asphalt pavement structure can facilitate or translate into various types of pavement failure such as fatigue cracking, rutting, raveling and potholes. This condition makes driving dangerous, and driving comfort and safety are often compromised. The damage of asphalt pavements due to moisture also can significantly increase the maintenance costs of a pavement and ultimately, reduce the life of the pavement [04].

Due to these problems, it has been seen increased interest to improve HMA mixture properties for better performance and safe riding comfort. Therefore, it is crucial to evaluate stripping performance on modified binder with the addition of hydrated lime as anti-stripping additive to an HMA mix.

The need for evaluating the effectiveness of hydrated lime additives to the HMA mixes is an important consideration in order to reduce stripping and related problems and to create high pavements performance, and also to find mixtures that can resist stripping problems due to moisture damage.

To date, field data and laboratory evaluations of tensile strength in accordance with AASHTO T-283 which is also accepted by ERA and AACRA still provide the most accurate prediction of moisture sensitivity. Although widely accepted as the standard, this laboratory evaluation has a low correlation to actual performance. Test methods need to be developed that couple the laboratory evaluation of moisture sensitivity to the observed field behavior of fatigue cracking, rutting, and raveling.

After adopting the use of lime as an aggregate additive in HMA, many researchers has observed a reduction in HMA field distresses. However, a quantifiable mechanism to measure the enhanced bonding between the aggregate and asphalt binder continues to elude researchers. In addition, the method of introducing the lime as an aggregate additive to the HMA mix is also subject to question. This is because of in the field; the application of dry lime to moist aggregates does not always result in uniform coverage on the aggregate's surface. So that, the research doing for this thesis trying to consider these effects.

As part of their pavement structure, currently a large portion of surfaced roads in Ethiopia constructed using asphalt. These surfacing, and to some extent base layers, are used in a large variety of traffic loading and environmental conditions.

1.3. Objective of the study

This thesis presents a study of the numerous benefits of adding hydrated lime to asphalt mixtures. It will highlight current work evaluating lime's unique characteristics as active mineral filler as they relate to moisture sensitivity, rutting, fatigue, and oxidative aging. The primary objective of this research is to evaluate the stripping, strength and other HMA performance under different mix proportions with addition of lime. In achieving the main objective, the secondary objectives of the research are;

i. To evaluate stripping performance or moisture susceptibility of unmodified and lime modified binder of HMA mix using statistical methods.

ii. To investigate the changes on overall physical properties such as stability, flow, $V_{a,}$ VMA etc... Performance of both asphalt mixes with and without lime additives.

iii. To investigate the feasibility of using hydrated lime additives for the improvement of paving mixture quality through laboratory examination.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

The best efforts of highway engineers in the design and construction of asphalt pavements are often undermined by environmental factors such as water, temperature variations, sunlight, etc. These individual factors are not individually harmful, but when coupled with large volumes of traffic, they frequently lead to significant problems with the durability of the pavements. In this case, moisture can be a major environmental contributor to the premature deterioration of asphalt pavements. Its effects can be minimized in some cases, eliminated by proper construction practices that emphasize good design, mixing, and compaction. Despite these efforts, when a highway failure occurs, most of the time water is cited as the prime suspect. In addition, many other factors such the material's characteristics affect the performance of the mixtures. Some binder/aggregate combinations are simply more susceptible to moisture induced damage.

Water affects asphalt concrete in various ways. It may act directly and literally strip binder from the aggregate. However, generally, the effects are more subtle. Water weakens the structure to a point where the mix can no longer sustain the traffic it was designed to support, and finally fails under the repeated loading.

Stripping produces several forms of distress, including localized bleeding, rutting, shoving, etc., and ultimately the complete failure of the asphalt pavement. Although it is not completely understood why stripping occurs in some pavements and not in others, it is not hard to conclude that stripping reduces the pavement's performance, increases its maintenance cost, produces an inferior riding quality, and ultimately produces an overall higher life cycle cost. For this reason, many highway agencies are requiring the use of Anti Strip Additives in the asphalt pavements to prevent the moisture induced damages. For many years, hydrated lime was widely used as an Anti-stripping additive to reduce the problem of stripping in the HMA. Different liquid Anti-stripping additive, have also been reported to produce results comparable to the hydrated lime, with easier application, safer operation and lower costs [5]. Based on a research conducted in the 1980s, different department of transportation in U.S specifies the use of hydrated lime as an Anti-Stripping Additives (ASA).

However practically in our country Ethiopia, it is not well experienced to use efficiently some important type of Anti-stripping additive including lime. The reason may be due to shortage of knowledge or skilled problems associated with applying mechanisms or else. Thus, for a better performance of roads a new initiation of evaluating these anti-stripping agents particularly hydrated lime with local aggregates is essential in order to applying during a time of construction.

2.2. Moisture Susceptibility

Moisture susceptibility is the tendency of HMA toward stripping. The loss of integrity of an HMA mix through the weakening of the bond between the aggregate and the binder is known as stripping. When a weakening in the bond occurs, loss of strength of the HMA can be sudden [6]. Stripping usually begins at the bottom of the HMA layer, and gradually travels upward. A typical situation is the gradual loss of strength over the years, which causes many surface manifestations like rutting, corrugations, shoving, raveling, cracking, etc. This makes identification of stripping very difficult. Also, it may take many years for the surface indicators to appear. To prevent moisture susceptibility, proper mix design is essential. However, even with a proper mix design, if the mix is not compacted properly, it may still be susceptible to moisture damage. Thus, HMA should be tested in a situation where moisture can infiltrate into the air voids of the mixture. For this reason, the tests for moisture susceptibility are done on mixes containing 7 ± 1 percent air voids. [7]

The presence of water in an asphalt pavement is unavoidable. Several sources can lead to the presence of water in the pavement. Water can infiltrate the pavement from the surface via cracks in the surface of the pavement, via the interconnectivity of the air-void system or cracks, from the bottom due to an increase in the ground water level, or from the sides.

2.3. Stripping Mechanisms

Stripping is a major distress occurring in HMA pavements in various parts of the world. Pavement performance is adversely affected by stripping and unforeseen increases in maintenance are often incurred. Environmental factors such as temperature and moisture can have a profound effect on the durability of hot mix asphalt pavements. When critical environmental conditions are coupled with traffic and poor materials, premature failure may occur as a result of stripping of the asphalt binder from the aggregate particles. [8]

Moisture affects asphalt pavements in two important ways. First, moisture can enter the interface between the bitumen and aggregate destroying the bond between those two key components of the pavement. Second, moisture can penetrate the bitumen itself softening it and reducing its cohesive strength. Both damage mechanisms can reduce the pavement's integrity and shorten its effective life. [9], [10]

Adhesive failure is the most commonly recognized result of moisture damage. It has long been observed that siliceous or igneous aggregates that contain large silica components are particularly susceptible to moisture damage in asphalt pavements. Those aggregates have an acid component that is incompatible with the acid components of bitumen, leading to relatively weak bonds [11].

Current research looking at the thermodynamics of aggregate/bitumen bonding has established that the several components of the surface free energy of the bitumen and the aggregate determine the strength of the bond connecting them. It has also shown that the free energy of water will dominate those adhesive bonds causing them to break apart [9].

Cohesive failure is more subtle. Bitumen was long thought to be impermeable to water which is not true. Several mechanisms can drive water into the binder causing it to soften. Once in the bitumen water will react with some acid components of the bitumen creating water soluble soaps which weaken the binder and, in turn, weaken the bonds between the binder and aggregate

Stripping usually begins in the bottom of the HMA layer, and travels upward. A typical situation is a gradual loss of strength over a period of years, which allows rutting and shoving to develop in the wheel path. Many times, if the stripping is begins in the bottom of the HMA layer, it difficult to identify because surface indicators may take years to show. Also, many surface indicators are possible and may include: rutting, shoving, corrugations, raveling, and cracking. It is necessary to look at the cores of the HMA mix to identify stripping. In some cases of stripping, a HMA mix has lost so much adhesion between the aggregate and asphalt that a core cannot be removed in one piece. [7]In general stripping of asphalt pavements can occur either of at the molecular level or macro-level. Each incidents discussed as below.

2.3.1. Molecular-level

Stripping of asphalt pavements occurs at the molecular level and is not entirely understood in spite of extensive research. It is thought to be associated with either one or both of the following two phenomena. First, water can interact with asphalt binder to cause a reduction in cohesion with subsequent reduction in stiffness and strength of the mix. Second, and more commonly believed, water can get between the asphalt film and the aggregate, break the adhesive bond, and strip the asphalt binder from the aggregate. [12]

The nature of the adhesive bond between the asphalt binder and aggregate is a subject of some debate. Adhesion is defined as that physical property or molecular force by which one body sticks to another. Several factors affect the adhesion of the asphalt binder to the aggregate, including: interfacial tension between the asphalt binder and the aggregate, chemical composition of the asphalt binder and aggregate, binder viscosity, surface texture of the aggregate, aggregate porosity, aggregate cleanliness, aggregate temperature and moisture content at the time of mixing.

Four general theories of adhesion exist to explain the adhesion of asphalt binder to aggregates. These include the Mechanical Interlocking Theory, the Chemical Reaction Theory, the Surface Energy Theory, and the Molecular Orientation Theory. The actual nature of adhesion is not fully explained by any one of these theories, but is partially explained in each theory. [12]

i. Chemical Reaction

The reaction of acidic and basic components of asphalt and aggregate form water insoluble compounds that resist stripping. A chemical bond forms that allows an asphalt-aggregate mix to resist stripping. The use of basic instead of acidic aggregates can lead to better adhesion of asphalt to aggregates.

ii. Surface Energy and Molecular Orientation

Surface energy can be described by how well asphalt or water coats aggregate particles. Water is a better wetting agent because of its lower viscosity and lower surface tension than asphalt. The structuring of asphalt molecules at an asphalt-aggregate interface is molecular orientation. The adhesion between asphalt and aggregate is facilitated by a surface energy reduction at the aggregate surface where asphalt is adsorbed onto a surface

iii. Mechanical Adhesion

Mechanical adhesion is a function of various aggregate physical properties, such as surface texture, porosity, absorption, surface coatings, surface area, and particle size. In short, an aggregate with desirable properties that will not show a tendency to moisture damage within an HMA is wanted.

Just as additive theories also different researches are done on the cohesive properties of HMA. Cohesion is developed in a mastic and is influenced by the rheology of the filled binder. The cohesive strength of mastic is a function of the interaction between the asphalt cement and mineral filler, not just of the individual components alone. The cohesive strength of mastic is weakened due to the presence of water through increased saturation and void swelling or expansion. The cohesive strength can be damaged in various mixtures by the diffusion of water into asphalt mastics. [03]

2.3.2. Macro-level

On macro level moisture can damage HMA basically in two ways:

(1) Loss of bond between asphalt cement or mastic and fine and coarse aggregate or
(2) Weakening of mastic due to the presence of moisture.

There are several ways that moisture affects bituminous mixtures. Once moisture accesses the mix, the mix structure is weakened. The mix losses stiffness and it fails under repeated traffic loading. There are five mechanisms for the asphalt film to be stripped from an aggregate surface. These mechanisms may act individually or together. A brief description of each mechanism follows.

i. Detachment

Detachment is the separation of an asphalt film from an aggregate surface by a thin film of water without an obvious break in the film. Adhesive bond energy theory explains the rationale behind detachment. In order for detachment not to happen, a good bond must develop between asphalt and aggregate; this is known as wettability. The binder will then peel cleanly from the aggregate. The thin film of water probably results from either aggregate that was not completely dried, interstitial pore water which vaporized and condensed on the surface, or possibly water which permeated through the asphalt film to the interface. As free surface energy of adhesion or surface tension decreases, the bond between the aggregate and asphalt increases. Consider a three-phase system of aggregate, asphalt, and water. Water reduces the surface energy of a system because aggregate surfaces have a stronger preference for water than asphalt. [12]

ii. Displacements

Displacement can occur at a break in the asphalt film at the aggregate surface where water can intrude and displace asphalt from aggregate. The break in an asphalt film can come from an incomplete coating of aggregate particles, inadequate coating at sharp edges of aggregates, or pinholes in the asphalt film. The pH of water at the point of film rupture can increase the process of displacement thereby increasing the separation of asphalt from aggregate. [12]

iii. Spontaneous Emulsification

Spontaneous emulsification occurs when an inverted emulsion of water droplets in asphalt cement forms rather than the converse. Investigators have noted that this process can be exacerbated under traffic on mixtures laden with free water and with the presence of clays and asphalt additives in the mix. Some experts conducted important experiments to demonstrate the formation of an emulsion and observed that once the emulsion formation penetrated to the substrate, the adhesive bond was broken. Many investigators have observed the formation of a brownish color on the surface of asphalt films in severely stripped mixtures as well as on asphalt films submerged in water. [13]

iv. Film rupture

Film rupture is reported to initiate stripping when film fissures occur at sharp aggregate contact, or points due to dust particles on the aggregate surface. The rupture may occur due to construction loads, operating traffic during service conditions, or could be environmentally induced by freeze-thaw cycling. Once a break in the film occurs, moisture has access to the interface and initiates stripping. [13]

v. Pore pressure

This mechanism precipitates from the presence of water in the pore structure of the HMA locations where segregation is prevalent at layer boundaries when heavy traffic loadings occur and during freeze-thaw cycling. Due to pore pressure, pavement layers are known to strip at the interfaces, pavement layers have been observed to disintegrate usually from bottom upward, and in a few instances disintegration within a layer in both directions. In a majority of cases, the binder layers disintegrate first followed by surface layers. Some researchers postulated a pore pressure mechanism produced the deterioration of the asphalt. [14]

Water and/or water vapor enters into the pavement overlay from underneath, primarily through the longitudinal and transverse joints cracks in the PCC pavement. Water vapor accumulated in the pavement layers during the day condenses during the night resulting in saturation of the asphalt overlay. With saturation, the pore water pressure developed by differential thermal expansion and cyclic stresses from the traffic ruptures the asphalt-aggregate bond causing stripping.

vi. Hydraulic scouring

Hydraulic scour (stripping) occurs at a pavement surface and is a result of repeated traffic tires on a saturated pavement surface. Water is sucked into a pavement by tire rolling action. Hydraulic scour may occur due to osmosis or pullback. Osmosis is the movement of water molecules from an area of high concentration to an area of low concentration. In the case of HMA, osmosis occurs in the presence of salts or salt solutions in aggregate pores. The movement of these molecules creates a pressure gradient that sucks water through the asphalt film. The salt solution moves from an area of high concentration to an area of low concentration. Some researchers showed that there is a considerable amount of water that diffuses through the asphalt cement and that asphalt mastics can hold a significant amount of water. [14]

2.4. Physical Factors Affecting Stripping

Based on different researches conducted in all over the world, many factors contribute to affecting the moisture susceptibility and stripping of HMA. Some of the main physical factors are discussed below.

2.4.1. Influence of Aggregate

Due to the aggregate problem there are number of factors that influence the asphalt aggregate bond, surface texture, penetration of pores and cracks with asphalt, aggregate angularity, aging of the aggregate surface through environmental effects, adsorbed coatings on the surface of the aggregate, and the nature of dry aggregates versus wet aggregates.

Surface texture of the aggregate affects its ability to be properly coated, and a good initial coating is necessary to prevent stripping. Besides the importance of a good mechanical bond promoted by the surface texture, stripping has been determined to be more severe in angular aggregates because the angularity may promote bond rupture of the binder or mastic, leaving a point of intrusion for the water.

The coarse and fine aggregate characteristics are important factors related to moisture damage. There is some evidence that moisture damage can be minimal if stripping is restricted only to the coarse aggregate. If the fine aggregate strips, severe damage can occur because the fine aggregate constitutes the basic matrix of the mixture.

2.4.2. Void Content

The overall performance of a pavement is also dependent on the void content of the HMA. The chance of stripping increases as the percentage of air voids increases, as there is more room for moisture to enter the mix and induce hydrostatic forces in the mix.

Most mix designs specify an air void content of 3 to 5 percent. When the air void content is below 5 percent, HMA materials have been shown to be almost impervious to water. During construction, compaction control is not always good and high air void contents are a result. If an air void content is above 8 percent, water can readily seep into the material and finally it cause a problem stripping.

2.4.3. Addition of anti-strip additives (ASAs)

There are many ASAs available and they all work differently in improving the bond between the aggregate and the binder film. Thus, the use of a particular type of ASA also affects stripping in HMA. Also, each ASA has a different effect on various aggregate sources. Thus, this variability also effects stripping in HMA relative to the type of ASA used.

2.4.4. Mixing Temperature

Sometimes, the aggregates are not heated for sufficient time in an asphalt plant, which can lead to lower mixing temperatures. At lower mixing temperatures, the viscosity of the binder is lower, and thus, the binder will not be able to form a uniform film thickness around the aggregate.

2.4.5. HMA Storage Time

Every time a truck is loaded, there is a possibility that air gets into the storage silos. This air oxidizes the binder, thereby making it hard and brittle. Thus, it can easily strip off the aggregate.

2.4.6. PH Instability

Studies by Kennedy, Scott, and others have indicated that the stripping is also effected by the pH of the water coming in contact with the HMA [15]. The pH of contact water can cause the value of the contact angle to shift, thereby affecting the wetting characteristics of the interface region. The results indicated that coating retention decreased as the pH increased. These results strongly suggest that stabilization of the pH sensitivity at the binder/aggregate interface would minimize the potential for bond breakage, providing strong durable bonds and hence reducing stripping.

Factors such as temperature, air, and water have harmful effects on the durability of HMA. Other mechanisms, such as a high water table, freeze/thaw cycles, and aging of binder or HMA, can affect the durability of HMA. Other considerations, such as construction (segregation and raveling) and traffic, are also important.

2.5. Engineering and Construction Considerations

Moisture related distresses are also accelerated by mix design or construction issues, including those given in Table 2.1 below. The initiation of one or more of the previously described stripping mechanisms is attributable to engineering and/or construction problems. [12]

Research conducted at the National Center for Asphalt Technology (NCAT) under the Strategic Highway Research Program (SHRP) A-003B Project has shown that the physicochemical surface properties of mineral aggregate are more important for moisture induced stripping of the HMA compared to the properties of the binder. Some of the aggregates are inherently susceptible to stripping. However, there are also other external factors and in-place properties that lead to the deterioration of the HMA. These problems include, but are not necessarily limited to, inadequate pavement drainage, inadequate compaction, excessive dust coating on the aggregate, inadequate drying of aggregates, weak and friable aggregates, and the use of waterproofing membranes and seal coats. Each factor will be briefly described below. [12], [16]

2.5.1. Inadequate Pavement Drainage

Inadequate surfaces or sub-surfaces drainage produce water or moisture vapor, which is the necessary catalyst to induce stripping. There have been case histories where stripping was not a general phenomenon occurring on the entire project site but only in areas that were over-saturated with water due to inadequate drainage.[16]

Inadequate surface drainage and/or subsurface drainage allow the water that is necessary for stripping to occur to remain in the pavement system. Water can enter the pavement layers in numerous ways. Surface water can percolate down from the surface, usually through surface cracks. It can also seep in from the sides and bottom from sources such as ditches or high groundwater. Water can also enter the bottom of the pavement system by the upward forces of capillarity or as rising vapor condensation due to water in the subgrade or subbase. [12]

Inadequate surface drainage and/or subsurface drainage allow the water that is necessary for stripping to occur to remain in the pavement system. Water can enter the HMA pavement in many ways. It can enter as surface runoff from cracks and other openings. It can also enter from the sides and the bottom as seepage from ditches or from a high water table. Water often moves upward by the capillary action from the bottom of the pavement. Many sub-bases and sub-grades in the existing highways lack the desired permeability, and are therefore, saturated with capillary moisture. The air voids in the HMA can become saturated with water, even from the vapor condensation from water in the sub-grade and the sub-base. A temperature rise after this saturation, and traffic stresses can lead to significant void pressure when the voids are saturated. [12]

Table 2.1 Factors contributing to moisture related distress [17]

Mix Design	• Binder and aggregate chemistry • Binder content • Air voids • Additives
Production	• Percent aggregate coating and quality of passing the No. 200 sieve • Temperature at plant • Excess aggregate moisture content • Presence of clay
Construction	• Compaction—high in-place air voids • Permeability—high values • Mix segregation • Changes from mix design to field production (field variability)
Climate	• High-rainfall areas • Freeze–thaw cycles • Desert issues (steam stripping)
Other Factors	• Surface drainage • Subsurface drainage • Rehab strategies chip seals over marginal HMA materials • High truck ADTs.

If the HMA is permeable, water could flow out from the voids under the pressure and relieve the developed pressure. If not, the tensile stresses developing can break the bond between the binder and the aggregate. This damage due to void water pressure is internal and the exterior sides of the specimen do not show any signs of stripping unless they are opened for visual examination.

2.5.2. Inadequate Compaction

High air voids present in the asphalt layers allow the movement of water through these pore spaces. Studies have shown that at less than 4% to 5% air void content, the voids are generally not interconnected and, therefore, impervious to water. However, if good compaction control is not exercised, the pavement would have higher air content, leading to the ingress of water, causing moisture damage to the pavement. While most asphalt mixes are designed to have 3% to 5% air voids, many agencies allow a maximum air void content of 8% at construction assuming that the remaining compaction will occur under 2 to 3 years of traffic. If the pavement remains pervious for an extended period of time, stripping is likely to occur due to ingress of water and hydraulic pore pressures induced by traffic. [12], [16]

2.5.3. Excessive Dust Coating on the Aggregate

The problem created by excessive dust coating on the aggregate is two-fold. First, the presence of dust and clay coatings on the aggregate inhibits intimate contact between the binder film and the aggregate, thereby forming channels for penetrating water and complete wetting of the aggregate by the asphalt cement. Because the asphalt is adhered to the dust coating and not the aggregate itself, the binder is easily stripped from the aggregate. Some very clayey material may cause stripping by emulsifying the binder in the presence of water. Second, the presence of dust particles enhances the action of scouring under the effects of traffic. [12]

2.5.4. Action of the Traffic

After any rain shower, the water in the pavement is pressed into the underlying layer by truck tires. This causes tremendous hydrostatic stresses, leading to the breaking of the bond between the binder and the aggregate. This is especially severe in the case of open graded friction courses due to the high air content.

Stripping can also be caused by the mechanism of hydraulic scouring; however, this is applicable only to the surface courses. Scouring starts at the surface and progresses downward. The water gets forced down into the pavement in the front of the tire, and it is immediately suctioned out of the pavement from behind the tire. This compression – tension cycle causes hydrostatic stresses leading to the stripping of the binder film from the aggregate surface.

2.5.5. Inadequate Drying of Aggregates

When the aggregate is coated with binder, a dry aggregate surface will better adhere to the binder than a wet surface. Aggregate that absorbs or adsorbs water will strip easily if not properly dried. As the hot binder is introduced to the wet aggregate surface, the moisture on the surface of the aggregate vaporizes and does not allow the binder to coat the aggregate well. This results from the asphalt being displaced from the aggregate by the thin layer of water already present. A dry aggregate surface will have increased adhesion with the asphalt cement compared to a moist or wet surface.

2.5.6. Weak Aggregates

If weak and friable aggregates are used in an asphalt mix, degradation takes place during rolling and later under heavy traffic loads. Degradation and delamination exposes new uncoated aggregate surfaces that can absorb moisture and initiate stripping problems.

2.5.7. Water Proofing Membranes and Seal Coats

If the source of moisture is from below the pavement, which is usually the case, the application of a water proofing membrane or a seal coat can be detrimental. The moisture that reaches the bottom of the pavement from ground water, shoulders, median, etc., migrates through the pavement by capillary action. Above the capillary fringe, the water moves as vapor, and if its movement is obstructed by a seal coat or a water proofing membrane, the vapor condenses under the sealing layer. It is again converted to vapor, when heated by the sun light, causing significant vapor pressure and leads to stripping in the pavement. [12]

Several additional factors have been suggested to also contribute to stripping, including the use of open-graded friction courses, the use of excess anti-strip additives, the use of siliceous aggregates, inadequate drying of aggregate; weak aggregate; overlays on deteriorated concrete pavements and the use of aggregates that have relatively high surface potentials, those that impart a high pH value to water in contact with their surfaces.

Weather conditions during construction have been related to stripping behavior. If the weather is cool and wet during construction, moisture damage is more likely to occur. During a pavement's life, environmental factors such as temperature fluctuations, freeze-thaw cycles, and wet-dry cycles have been suggested to influence stripping. All other factors being equal, it is suggested that increased repetitions of traffic loading accelerate stripping. There are many possible causes of stripping; however, all involve excess moisture in the HMA. There are many ways in which moisture can enter the HMA pavement layers: capillary action from the water table, run off from the road surface, and seepage from surrounding areas are a few examples. If adequate drainage is not present, air voids in the HMA may become saturated with moisture, thereby increasing pressure and weakening the bond.

2.6. Techniques for limiting moisture susceptibility

When subject to moisture, water-sensitive pavements may suffer accelerated damage leading to a reduced pavement life. If asphalt pavement does suffer from water sensitivity, serious distresses may occur. The best way to prevent stripping will be to test the mixture in the laboratory and to use an aggregate/binder combination that does not strip. However, this will not always be possible due to many reasons such as, lack of suitable aggregates, increased costs in the transportation of certain aggregates, political constraints, etc. Even in spite of having the mix not be susceptible to moisture in the laboratory, there is not much certainty that the mix will behave the same in the field. To make sure that a mix behaves the same in the field as in the lab, proper care should be taken in the construction of the pavement, such as providing proper drainage, especially sub-surface drainage, using proper compaction techniques and providing an adequate number of roller passes at the proper compaction temperature, etc.

Different types of aggregate pre-treatments have also shown to improve the moisture susceptibility of the mix. Some of the pre-treatments include pre-heating the aggregate to remove any excess moisture by evaporate the moisture, weathering, washing to remove very fine surface dirt, crushing, etc. It has also been shown that aggregates coated with asphalt or other recycled materials are better at resisting the moisture damage in the HMA than are virgin materials. [7]

However, even after taking all the above precautions, there is still a chance that a pavement will suffer damage due to moisture. One good way to alleviate or control this problem, various liquid or solid anti-stripping additives have been developed, which can be used to promote adhesion between asphalt and aggregate or increasing the resistance of the mix to moisture damage. However, the addition of an Anti-stripping Agent (ASA) from an approved list of sources should not be considered as "insurance" as some ASAs are aggregate and binder specific, and therefore, may not be effective in all mixes; they could even be detrimental at times. Thus, a proper study of the mix should be done by systematically testing the mix for moisture susceptibility by tests such as Indirect Tension Testing (ITS), Lottman's Laboratory Test, the Boiling Water Test, etc. in the laboratory.

2.6.1. Anti-Stripping Agents

Anti-stripping agents may be necessary if a particular mix design has been shown to be susceptible to moisture-induced damage. They are substances designed to chemically improve the adhesion between the asphaltic binder and the aggregates. They are available in both liquid and solid forms. Hydrated lime has been widely used as an ASA for reducing the moisture susceptibility of HMA. Some other solid ASAs used are Portland cement, fly-ash, flue dust, etc. The liquid ASAs used include liquid amines and diamines, liquid polymers, etc. However, if an additive is used when it is not needed or if it is used incorrectly, adverse effects may occur, including an increased economic cost and early maintenance and/or rehabilitation. [18]

2.6.2. Liquid Anti-Stripping Agents

Liquid anti-stripping agents are chemical compounds that contain amines. Recently, with the advent of new liquid ASAs in the market, and because of its cheaper cost and ease of application, liquid ASAs are gaining popularity. The mechanism by which liquid ASAs work is by reducing the surface tension between the aggregate surface and the asphalt binder. When surface tension is reduced, increased adhesion of the binder to the aggregate is promoted. Thus, most liquid anti-stripping agents are surface-active agents [19]. They are normally added in doses between 0.5 and 1.5 percent by weight of the binder (as recommended by the manufacturer).

The liquid ASA may be added either to the aggregate directly, or to the heated binder. Both of these procedures have certain concerns. An economical method of mixing the liquid anti-stripping agent with the asphalt is by heating the asphalt to a liquid state. The liquid asphalt commonly is mixed with the liquid anti-stripping agent prior to adding aggregate to the mix. [19] If added to the heated binder, care should be taken to ensure that the liquid ASA is heat stable, and will not disintegrate at such high temperatures. However, a more successful method of adding the additive is to apply it directly to the aggregate prior to the addition of the binder [7]. The main problem concerning added the liquid additives directly to the aggregate is that, uniform coating of all the aggregates is not ensured due to such a small quantity of the ASA.

2.6.3. Lime Additives

A number of additives including the liquid additives are used to reduce moisture sensitivity and stripping in all over the world. However know a day the most widely used anti-strip additive is hydrated lime. Pavement contractors usually prefer liquid anti-strip additives as they are relatively easy to use. By using diverse testing mechanisms especially in U.S state departments of transportation different researches were conducted to understand the relative effect or advantages of lime versus various liquid anti-strip agents. From these researches it is found or proved that lime is beneficial than other anti-stripping agents.

Addition of lime is the most accepted way to reduce the moisture susceptibility of HMA in many parts of the world. The anti-stripping mechanism of lime additives is not well understood. However, it is assumed that the mechanism by which hydrated lime improves the moisture susceptibility of the HMA involves a chemical interaction between the calcium in the lime with the silicates in the aggregate [5].

Depending upon how hydrated lime is introduced into the asphalt mixture it may coat the aggregate surface changing its bonding sites from acidic to basic. That transformation promotes strong bonds between the bitumen and aggregate preventing water from breaking them apart. In addition, hydrated lime reacts with the acid components of the bitumen forming water insoluble calcium salts. The removal of those acid components further protects the adhesive bond by eliminating the possibility of damaging soaps forming in the binder [11].

The general practice is to add 1 to 1.5 percent of lime by dry weight of aggregate to the mix. Hydrated lime has proven to work effectively in a wide variety of aggregate sources. If an aggregate has more fines present, it may be necessary to use more lime additive due to the increased surface area of the aggregate. Three forms of lime are used: hydrated lime ($Ca(OH)2$), quick lime (CaO), and Dolomitic limes.[19] Recent studies were evaluated the changes in rheology, aging kinetics, and oxidative hardening created by adding lime to HMA. Extensive binder and mixture tests measured improvements in high temperature performance (rutting resistance), fatigue cracking resistance, and low temperature fracture.

Researches done in all over the world show that hydrated lime has additional advantages other than moisture susceptibility. Researchers conducted in U.S indicate that the addition of hydrated lime to HMA increases stiffness. This helps to distribute and reduce the stresses and strains in the pavement structure created by traffic loads and generally reduce rutting (permanent deformation) potential. The results of laboratory wheel tracking tests conducted in Colorado, Georgia and Oregon State University indicate that hydrated lime increases resistance to rutting and permanent deformation. Creep tests in Texas also clearly show that hydrated lime promotes high temperature stability, thereby increasing resistance to rutting [02].

Rutting most commonly occurs early in a pavement's life. Its causes include specification of a binder that is too soft for the traffic conditions, excessive air voids, or lack of stone-on-stone contact in the mixture. Over time the mixture will stiffen as traffic further compacts the pavement and environmental conditions oxidize the bitumen increasing its viscosity. However, for the first several years that a pavement is in service it must be sufficiently stiff to resist rutting.

The fine particle size of hydrated lime (often 50% smaller than 5μ) contributes significantly to stiffening the mastic of the asphalt mixture. The mastic is the combination of bitumen and particles finer than 75μ that coat the aggregate and fill the spaces within the stone skeleton of the mixture. The lime is more effective filler than equivalently sized stone fillers due to its chemical activity [11].

As can be seen in tests measuring dynamic modulus (E), an important test in mixture design and prediction of life cycle performance, hydrated lime is superior to inert fillers in stiffening asphalt mixtures at high temperatures. While it is important for mixtures to be stiff at high pavement temperatures it is critical that the bitumen is able to relax at low temperatures to avoid thermal cracking. At low temperatures the chemical activity of hydrated lime is reduced. In that state it contributes to improved pavement toughness, and an increased capacity for the mastic to relax during times when thermal cracking is an issue [20].

Similarly Researches conducted in German prove and accept the practical effectiveness of hydrated lime in HMA to improve moisture sensitivity and stiffening. Field research on two road sections confirms that the addition of 1.0 to 1.5 percent hydrated lime by weight of the mixture can substantially improve rut resistance [02]. Also researches done in Czech under The Institute for Road Construction in Prague studied the influence of hydrated lime on HMA and constructed several test pavement sections to determine the long-term behavior of hydrated lime in HMA. About 18.5 percent hydrated lime by weight of the binder was added to mixtures and tested with the Nottingham Asphalt tester and by rutting tests. The results clearly show that hydrated lime improves stability and increases rutting resistance due to the filler effect, especially at elevated temperatures of between 30^0C and 40^0C. This program will continue and will be complemented with field pavement performance and cost evaluations [02].

Fatigue results from excessive tension in the pavement structure often caused by overweight vehicles, shear stresses caused by traffic movement, or by rapid temperature change in the pavement. It can also occur when a binder that is too stiff for traffic and climatic conditions is specified for the pavement. As pavement age's oxidation of the bitumen causes it to become brittle which also contributes to fatigue cracking.

As chemically active filler hydrated lime not only contributes to stiffening asphalt mixtures but also extends their fatigue life. Although, in general, stiffer asphalt mixes crack more readily, the addition of lime improves fatigue characteristics and reduces cracking. Cracking often occurs due to the formation of micro cracks. These micro cracks are intercepted and deflected by tiny particles of hydrated lime. Repeated experiments at the Texas Transportation Institute and elsewhere have demonstrated this phenomena under both dry and wet conditions [11].

One mechanism that explains hydrated lime's ability to extend fatigue life in pavements, at the same time stiffening them is called "crack pinning". The tiny hydrate particles intercept and deflect micro cracks as they form preventing them from merging into macro cracks that can reflect through the pavement layer. Because of lime's chemical activity it adsorbs acid components from the bitumen to its surface, increasing the effective volume of the particles making them more effective than inert fillers at intercepting the micro cracks [20].

Lime reduces cracking more than inactive fillers because of the reaction between the lime and the polar molecules in the asphalt cement, which increases the effective volume of the lime particles by surrounding them with large organic chains [21]. Consequently, the lime particles are better able to intercept and deflect micro cracks, preventing them from growing together into large cracks that can cause pavement failure.

In addition to these for over thirty years it has been well established that hydrated lime also reacts with acid components of bitumen to produce beneficial changes that contribute to the creation of high performance asphalt mixes. Extensive research in U.S shows that age hardening of many bitumen's or asphalt can be reduced by the addition of hydrated lime. As little as one-half of one percent hydrated lime, by dry weight is needed to achieve a reduction in age hardening. This reduction in hardening has been confirmed in a field study conducted by the Utah DOT [20].

Not only do acid components in the bitumen contribute to moisture sensitivity problems, they also react over time with the environment and are transformed into viscosity building **asphaltenes** which stiffen the bitumen and make it more brittle. When chemically active hydrate comes into contact with bitumen it quickly reacts with acid components of the binder to transform them into insoluble salts. When the acid components of the bitumen are removed its viscosity increases much more slowly over time. The lower viscosity insures that the pavement will remain ductile and able to withstand the rigors of traffic and climate without deteriorating [11].

In Belgium one Centre of researchers (CRR) verified that lime creates a significant improvement in adhesion between binders and aggregates and also identifies an improvement in resistance to the effects of oxidative hardening. The most significant research in Belgium monitored 15 test zones on the wearing course of selected road for up to 10 years following construction. In cooperation with a Dutch workgroup, Belgian researchers determined that after about seven years the asphalt zones that had been modified with hydrated lime were in significantly better condition than zones made with unmodified conventional bitumen's. [02]

The broad array of benefits that result from the addition of hydrated lime to hot mix asphalt work together to produce a superior and high performance product. Though the benefits have been described individually, all of them work synergistically, contributing in multiple ways to the improvement of the final product. Synergistic benefits also accrue when lime is used in conjunction with polymer modifiers. Research has shown that in some situations lime and polymers used together can produce improvements greater than each of them used alone.

2.7. Impact of Lime on Pavement Life and Life Cycle Costs (LCC)

The numerous benefits gained from adding hydrated lime to hot mix asphalt have a positive impact upon the life cycle costs of asphalt pavements. The impact on pavement life and its life cycle costs is the ultimate measure by which the effectiveness of an additive can be assessed. Regardless of how effective the additive is in improving the properties of the various components or the entire HMA mix, the ultimate challenge is to construct a less expensive pavement that will last longer. Therefore, the final link in assessing the effectiveness of lime on HMA pavements is to take the improvements that lime introduces on the various components and translate them into extension in pavement life and lower life cycle costs. This task is huge and requires evaluating multiple levels of material properties, pavement designs, and long term field performance.

Currently, there are two studies that have attempted to achieve such a goal using two different approaches. These studies are summarized below.

Scientists developed a life cycle cost analysis (LCCA) model to compare the life cycle costs for HMA pavements with and without lime [22]. The researchers surveyed in US on ten state DOTs and collected data on the topics of reasons for using lime in HMA mixtures, the cost of adding lime in HMA mixtures and the field performance of HMA mixtures. Reducing stripping was the most important attribute of using lime in HMA mixtures for all DOTs followed by altering the properties of fines. Improve aging resistance, stiffening the binder, and improve fracture toughness were ranked as lower importance which may be a direct result of the lack of information on the impact of lime on these properties. The cost of adding lime does not significantly vary among locations, but it significantly varies between non-marinated and marinated mixtures. The research developed a computerized LCCA model that incorporates initial costs, maintenance costs, and salvage values along with the performance of HMA pavements with and without lime to compare the effectiveness of adding lime.

The study was based on data gathered from states that use lime to treat HMA mixtures with known stripping problems. The LCCA data showed that the anti-stripping benefits of using lime in HMA mixtures results in a wide range of savings with an approximate average saving of $2.00/yd2.This translates into an approximate saving of $20/ton of HMA mix which compares very favorably with the average additional costs of using lime of $1.25/ton for non-marinated and $4.00/ton for marinated.

The researchers also conducted probabilistic LCCA of HMA pavements with and without lime. The probabilistic analysis accounts for the inherent variability in materials properties and cost and in the predicted field performance. The probabilistic analysis showed similar results to the deterministic analysis with one additional finding: in 79 to 96 percent of the time, the life cycle costs of HMA pavements with lime are less expensive than the life cycle costs of HMA pavements without lime. In other words, there is a 79 to 96 percent chance that using HMA mixtures with lime will be less expensive than using HMA mixtures without lime. [04]

In U.S the state of Nevada, a state with climatic zones ranging from desert to mountains, commissioned a study to quantify the benefits that accrue from the use of hydrated lime. The study examined equivalent lime treated and untreated pavements from both severe climatic zones, evaluating both pavement and laboratory samples as well as pavement histories as reflected in the state's maintenance management program. The study concluded that Nevada gained an average of three years additional life from pavements containing hydrated lime. That additional life translated into a 38% cost saving as compared to a 10% higher first cost of the asphalt mixtures. [20]

Additional studies are underway to evaluate the long-term performance of lime treated asphalt pavements. Based upon the results to date and testimonials from the many states of U.S that specify lime in their pavements the addition of hydrated lime is an inexpensive way to increase the life of asphalt pavements.

CHAPTER THREE

RESEARCH METHODOLOGY AND MATERIALS

3.1. Introduction

The goal of this study was to determine the moisture damage resistance of compacted asphalt specimens modified with lime. The effectiveness of this additives were evaluated by comparing test results conducted on unmodified (virgin) specimens. The test used in this study to compare the moisture damage resistance were the modified Lottman indirect tensile test (AASHTO T 283). In addition, other performance tests were conducted on the aggregate, asphalt binder, and un-compacted specimens. All tests on aggregate, asphalt binder, loose mixtures, and compacted specimens were conducted according to respective ERA, AASHTO and ASTM testing standards.

3.2. Experimental design

In this study, the effects of lime additive on HMA were evaluated in the laboratory. The research evaluated various materials (i.e., aggregates, binders, and lime) using multiple test methods and conditioning procedures.

Two aggregate sources were used with single type of asphalt binder (with penetration grade of 85 – 100) is used to formulate two aggregate asphalt binder combinations. Each of the two aggregate asphalt binder combinations as then subdivided into three mixtures that were defined by the method of lime application for same marination time. One of the three mixes was the control and did not utilize lime in the mix design. This mix is referred as "no-lime". The other two mixes were fabricated with lime treated aggregates dry lime to moist aggregates, lime slurry to dry aggregates with receiving a 48 hour marination time.

3.3. Materials selection

Several materials were required for producing asphalt specimens. Since the main objective of the study was to investigate the performance of lime with respect to overall parameters and moisture susceptibility of various mixtures, it was important to evaluate not only lime, but also various aggregate and binder sources. Usually certain aggregates have performed better than others with regard to moisture susceptibility. For this reason, two crushed stone aggregates obtained locally from two different sources.

The first one is get from quarry site of Enei Construction P.L.C around kality (kiliminto). This aggregate used for construction of different road projects in Addis Ababa such as Shola - lem hotel etc, in addition to that it also supplied to different construction purposes including the condominium houses found in production nearby areas. The second aggregate is taking from Ethiopian Railway Cooperation (ERC) used for construction of LRT project in Addis Ababa.

Both Aggregates are natural aggregates extracted from larger rock formations through an open excavation (quarry) reduced to usable sizes by mechanical crushing. The aggregates geology can be classified under igneous rocks specifically under the category of basalt. Igneous rocks are primarily crystalline and are formed by the cooling of molten rock material beneath the earth's crust (magma). Since basalt stones are effectively hard, resistant to stripping, tough, good surface texture and crushed shape usually we used them for hot mix asphalt mixture. Up to 150kg of aggregate from each source was used to produce over 200 asphalt specimens tested in this study.

The asphalt binder used for testing was obtained from CORE consulting engineers. Approximately 30 liters of penetration grade 85 – 100 binder was required to produce the specimens. The 85 – 100 penetration grade is a common type of asphalt used locally on the Addis Ababa roads since the climate is relatively mild. The asphalt was then heated and separated into small trays on a weekly basis to allow for quicker heating during asphalt mixing. The hydrated lime additive used in testing were produced in sankale lime factory and supplied to the market on local vendors.

3.4. Aggregate Tests and preparation

Important properties and performance tests were conducted when selecting aggregates for the asphalt mix design. First, the bulk and apparent specific gravities were calculated for the range of aggregates. Then performance tests for durability, angularity, and clay content were conducted.

Because of about 85% of the volume or around 95% in mass of dense graded HMA is made up of aggregates, HMA pavement performance is greatly influenced by the characteristics of the aggregates. Aggregates in HMA can be divided into three types according to their size: coarse aggregates, fine aggregates, and mineral filler. Coarse aggregates are generally defined as those retained on the 2.36-mm sieve. Fine aggregates are those that pass through the 2.36-mm sieve and are retained on the 0.075-mm sieve. Mineral filler is defined as that portion of the aggregate passing the 0.075-mm sieve. Mineral filler is a very fine material with the consistency of flour and is also referred to as mineral dust or rock dust.

Gravel refers to a coarse aggregate made up mostly of rounded particles. Gravels are often dredged from rivers and are sometimes mined from deposits. Because of the rounded particle size, gravels are not suitable for use in HMA mixtures unless they are well crushed. Poorly crushed gravels will not interlock when used in HMA, and the resulting mixture will have poor strength and rut resistance. Crushed stone is coarse aggregate that is mined and processed by mechanical crushing. It tends to be a very angular material and, depending on its other properties, can be well suited for use in HMA pavements. One potential problem with crushed stone is that the particles sometimes will tend to be flat, elongated, or both, which can cause problems in HMA mixtures.

Ideally, the particles in crushed stone aggregate should be cubicle and highly angular. The fine aggregate, or sand, used in HMA can be natural sand, manufactured sand, or a mixture of both types. Natural sand is dredged from rivers or mined from deposits and is then processed by sieving to produce a fine aggregate having the desired particle size distribution. Manufactured sand is produced by crushing quarried stone and, like natural sand, sieving to produce the desired gradation.

The particles in manufactured sands tend to be more angular than those in natural sand and often will produce HMA mixtures having greater strength and rut resistance compared to those made with natural sand. However, this is not always true, and care is needed when selecting fine aggregate for use in HMA mixtures.

Pavement engineers have worked for many years to relate specific aggregate properties to HMA performance. Rutting, raveling, fatigue cracking, skid resistance, and moisture resistance have all been related to aggregate properties. It is essential that engineers and technicians responsible for HMA mix design thoroughly understand aggregate properties, how they relate to HMA pavement performance, and how aggregate properties are specified and controlled as part of the mix design process.

Generally aggregates for HMA are required to be resistant to abrasion, sound, clean, and hydrophobic. In addition to this the aggregate should be Toughness and Abrasion Resistance Aggregates through internal friction and must transmit the wheel loads to the underlying layers and also be resistant to abrasion and polishing due to traffic. Aggregates are subject to crushing and abrasive wear during manufacturing, placing, and compaction of HMA. They must be hard and tough to resist crushing, degradation; disintegration when stockpiled fed through a HMA facility, placed with paver, compacted with rollers, and travelled over with trucks.

As stated previously for this research two different sources of aggregates were used and the corresponding physical characteristics of each type of aggregate were as shown the table below.

Table 3.1: quality tests of the aggregates used for laboratory test

Type of tests	**Aggregate A**	**Aggregate B**	**Specification (ERA)**
LAA (%), Grading A (AASHTO T 96)	13	14	< 30 (wearing course) < 35 (other)
Elongation Index (%), (BS 812 Part 105.1)	22	21	
Flakiness Index (%), (BS 812 Part 105.1)	24	23	< 45 per cent
Soundness loss by NaSO4 (%), (AASTO T 104)	3.3	4.1	< 12 percent
ACV (%), (BS 812 Part 110)	12	15	< 25 For weaker
TFV Dry (KN) (BS 812 Part 111)	275	265	
TFV Wet (KN) (BS 812 Part 111)	180	160	
	19 mm pass - 4.75 mm retained		
Bulk specific gravity AASHTO T 85	2.577	2.784	N/A
Bulk specific gravity (SSD) AASHTO T 85	2.635	2.850	N/A
Apparent specific gravity AASHTO T 85	2.736	2.983	N/A
Water Absorption (%) AASHTO T 85	2.250	2.400	< 1
	4.75 mm pass – 0.075 mm retained		
Bulk specific gravity AASHTO T 84	2.543	2.755	N/A
Bulk specific gravity (SSD) AASHTO T 84	2.621	2.831	N/A
Apparent specific gravity AASHTO T 84	2.757	2.982	N/A
Water Absorption (%) AASHTO T 84	3.050	2.750	< 2

Aggregate A = source from ERC LRT project, Aggregate B = Source from Enei construction

Average Aggregate Specific Gravity. Because the aggregate used in producing asphalt concrete is almost always a blend of two or more aggregates, usually having different values for bulk specific gravity, volumetric calculations such as the ones described below must be done using an average bulk specific gravity for the aggregate blend. This average value can be calculated using the following equation:

$$\mathbf{G_{sb}} = \frac{\mathbf{P_{s1}+P_{s2}+P_{s3}+\ \dots}}{\left(\frac{\mathbf{P_{s1}}}{\mathbf{G_{sb1}}}\right)+\left(\frac{\mathbf{P_{s2}}}{\mathbf{G_{sb2}}}\right)+\left(\frac{\mathbf{P_{s3}}}{\mathbf{G_{sb3}}}\right)+\ \dots} \quad \dots\dots\dots\dots\dots\dots\dots\dots\ \textbf{eq. 3.1}$$

Where

G_{sb}=overall bulk specific gravity for aggregate blend

P_{s1}= volume % of aggregate 1 in aggregate blend

G_{sb1}= bulk specific gravity for aggregate 1

P_{s2}=volume % of aggregate 2 in aggregate blend

G_{sb2}= bulk specific gravity for aggregate 2

P_{s3} =volume % of aggregate 3 in aggregate blend

G_{sb3}= bulk specific gravity for aggregate 3

The particle size distribution, or gradation, of an aggregate is one of the most influential aggregate characteristics in determining how it will perform as a pavement material. In HMA, gradation helps determine almost every important property including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and moisture susceptibility. Because of this, gradation is a primary concern in HMA mix design and thus most agencies specify allowable aggregate gradations.

Gradation is usually determined by sieve analysis. Sieve analysis involves passing the material through a series of sieves stacked with progressively smaller openings from top to bottom, and then weighing the material retained on each sieve. The gradation normally is expressed as total percent passing various sieve sizes. It is unlikely that a single natural or quarried material will meet the specifications necessary. Two or more aggregates of different gradations are typically blended to meet specification limits. The nature of particle size distribution can be examined by graphically representing the gradation by a cumulative percent passing on a semi-log scale.

Sieves typically used for sieve analysis and gradation specifications for aggregates in HMA are 2 inches (50.8 mm), 1.5 inches (38 mm), 1 inch (25.4 mm), 0.75 inch (19mm), 0.5 inch (12.5mm), 0.375 inch (9.5mm), No. 4 (4.75mm), No. 8 (2.36mm), No. 16 (1.18mm), No. 30 (0.6mm), No. 50 (0.3mm), No. 100 (0.15mm), and No. 200 (0.075mm) respectively.

Theoretically, it would seem reasonable that the best gradation for HMA is one that gives the densest particle packing. The gradation having maximum density provides increased stability through increased inter-particle contacts and reduced voids in the mineral aggregate. However, there must be sufficient air void space to permit enough asphalt cement to be incorporated to ensure durability, while still leaving some air space in the mixture to avoid bleeding and/or rutting. A tightly packed aggregate (low voids in mineral aggregate) also results in a mixture that is more sensitive to slight changes in asphalt content.

Specification of aggregate gradation for HMA mix is established on different manuals such as ASTM, AASHTO, etc. and also in our country on manuals of Ethiopian Road Authority (ERA) and Addis Ababa City Road Authority (AACRA).

Asphaltic concrete (AC) is a dense, continuously graded mix which relies for its strength on both the interlock between aggregate particles and, to a lesser extent, on the properties of the bitumen and filler. The mix is designed to have low air voids and low permeability to provide good durability and good fatigue behavior but this makes the material particularly sensitive to errors in proportioning, and mix tolerances are therefore very narrow[23]. The following table indicates of particle size distributions for wearing course material specified by ASTM to produced workable mixes that have not generally suffered from deformation failures.

Table 3.2: ASTM specification for surface hot mix asphalt surface layer

Test sieve (mm)	Percent passing test sieve			
	Fine	Average	Coarse	Specification
19	100	100	100	100
12.5	100	95	90	90 - 100
9.5	-	-	-	-
4.75	74	59	44	44 - 74
2.36	58	43	28	28 - 58
0.3	21	13	5	5 - 21
0.075	10	6	2	2 - 6

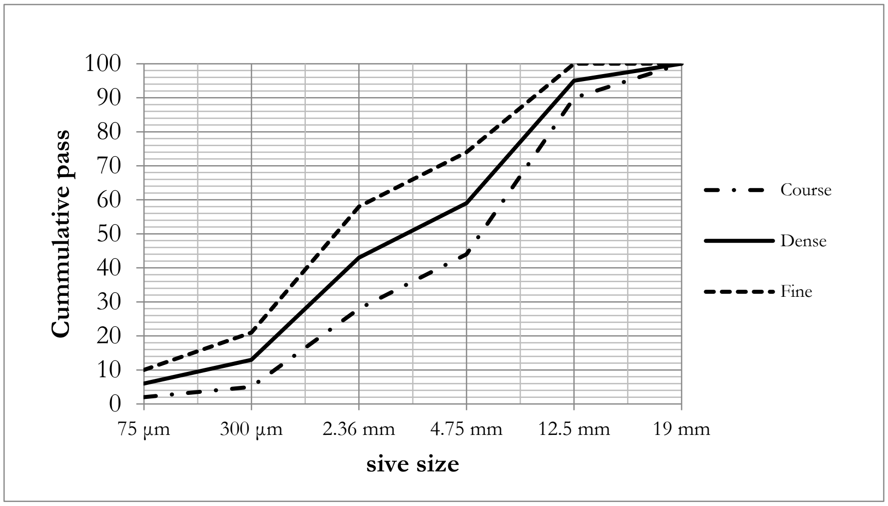


Figure 3.1: Aggregate gradation chart for ASTM Specification

Based on the specification for gradation indicated on the above table and figure, for this reaserch or thesis a nominial size of mix aggrigate is selected to be 12.5 mm.

3.5. Asphalt binder test and result

Asphalt binders, sometimes referred to as asphalt cement binders or simply asphalt cement, are an essential component of asphalt concrete they are the cement that holds the aggregate together. Asphalt binders are a co-product of refining crude petroleum to produce gasoline, diesel fuel, lubricating oils, and many other petroleum products. Asphalt binder is produced from the thick, heavy residue that remains after fuels and lubricants are removed from crude oil.

This heavy residue can be further processed in various ways, such as steam reduction and oxidation, until it meets the desired set of specifications for asphalt binders. For demanding, high-performance applications, small amounts of polymers are sometimes blended into the asphalt binder, producing a polymer-modified binder. In general asphalts can be classified into three general types:

- Asphalt cement
- Asphalt emulsion
- Cutback asphalt

Cutbacks and emulsions are used almost entirely for cold mixing and spraying and will not use for hot mix asphalt mixture. Because of its chemical complexities, asphalt specifications have been developed around physical property tests, such as penetration, viscosity and ductility. These tests are performed at standard test temperatures, and the results are used to determine if the material meets the specification criteria.

Asphalt binders have been mixed with crushed aggregate to form paving materials for over 100 years. They are a very useful and valuable material for constructing flexible pavement worldwide. However, asphalt binders have very unusual engineering properties that must be carefully controlled in order to ensure good performance. One of the most important characteristics of asphalt binders that must be addressed in test methods and specifications is that their precise properties almost always depend on their temperature.

Asphalt binders tend to be very stiff and brittle at low temperatures, thick fluids at high temperatures, and leathery/rubbery semi-solids at intermediate temperatures. Such extreme changes in properties can cause performance problems in pavements. At high temperatures, a pavement with a binder that is too soft will be prone to rutting and shoving. On the other hand, a pavement that contains a binder that is too stiff at low temperatures will be prone to low-temperature cracking.

There is an extreme change in modulus that occurs in asphalt binders over the range of temperatures. Specifications for asphalt binders must control properties at high, low, and intermediate temperatures. Furthermore, test methods used to specify asphalt binders usually must be conducted with very careful temperature control; otherwise, the results will not be reliable. Asphalt binders are also very sensitive to the time or rate of loading. When tested at a fast loading rate, an asphalt binder will be much stiffer than when tested at a slow loading rate. Therefore, time or rate of loading must also be specified and carefully controlled when testing asphalt binders.

3.5.1. Asphalt Specifications and Grades

Asphalt cements can be graded according to four different systems

- Penetration
- Viscosity
- Viscosity after aging
- Performance grade (PG)

Penetration grading describes relative hardness based on the penetration test. In penetration grading, the higher the number the softer the asphalt. A 200-300 penetration grade asphalt is softer than a 40-50 penetration grade.

The viscosity grading use a numbering system to describe relative viscosity. The higher the number the more viscous (or thicker) the asphalt. In the viscosity after aging system asphalt is classified after it has been artificially aged. The performance grade, or PG system, describes asphalt based on the pavement temperatures under which the asphalt is expected to perform. The PG system is a part of the superpave system. A PG 64-28 asphalt is designed for pavement temperatures as high as 64ºC and as low as -28°C.

For this research experimental works bitumen of penetration grade 85/100 is used and collected from CORE consulting Engineers P.L.C. The main reason of using this grade is because of its common type of asphalt that widely use in most road projects in our country to construct roads especially places where relatively mild climates like Addis Ababa.

Approximately 20 Kg binder was consuming to produce more than 200 specimens. A series of tests including penetration, specific gravity, softening point, flash point, ductility, and solubility in carbon tetrachloride were conducted for the basic characterization properties of penetration grade asphalt. The test results are shown in Table 3.3, which complies with the requirement of ERA specifications.

Table 3.3: Laboratory test result of 85 – 100 asphalt binder

Test Name	Result	Specification For 80/100
AASHTO T 44 Solubility in Trichloroethylene (%)	99.8	99.0 min
AASHTO T 47, Loss on Heating (%)	20	100 max
AASHTO T 48, Flash point, ºF	590	232 min
AASHTO T 49 Penetration at 25 ºC, 100g, 5sec	90	85 - 100
AASHTO T 51, Ductility at 25 ºC (Cm)	100+	100+
Penetration of residue percent of original, at 25 ºC, 100g, 5sec	89	50 min.
Ductility of residue, cm	100+	75 min.
AASHTO T 53, Softening Point (ºC)	52.5	42 - 51
AASHTO T 228-06, Specific gravity at 25 ºC (Kg/m3)	1022	1020 ±

In addition to aggregate and asphalt binder, the hydrated lime used was added constantly in 1.5% in the total weight of the AC mixes. This value of lime additive is selected because of it is a common practice of using Hydrated Lime Content between 1% and 3% (percent of dry weight of aggregate).[20] For example the required hydrated lime application rate in the Nevada DOT specification is not less than 1 percent and not more than 2.5 percent of the mass of the dry aggregate.[26] Most of the time this range contracted specifically with in the gap of between 1 percent and 2 percent.

For this research 1.5% of hydrated lime is selected as most U.S DOTs recommend or specify the required hydrated lime application rate is not less than 1 percent and not more than 2.5 percent of the mass of the dry aggregate [26]. Therefore for each of the samples prepared for marshal test specimens 1.5% of 1200gm (total mass of aggregate) which is 18gm of hydrated lime is used. The only test done on the lime additive is determination of specific gravity and it is obtained as 2.747. Which can be used to find the average aggregate specific gravity.

Similar to the aggregate source, the binder source will also affect the ability of lime to prevent or minimize moisture induced damage of asphalt pavements. Asphalt cement generally is obtained from distillation of crude petroleum using different refining techniques. At ambient temperatures asphalt cement is a semi-solid material that must be heated to mix with an aggregate. Asphalt is strong and durable cement with excellent adhesive and waterproofing characteristics.

3.6. Un-compacted Asphalt Mix Test

Theoretical Maximum Specific Gravity and Density (AASHTO T 209)

The theoretical maximum specific gravity of an asphalt concrete mixture is the specific gravity of the mixture at zero air void content. It is one of the most difficult tests performed in paving materials laboratories and also one of the most important. Like bulk specific gravity, theoretical maximum specific gravity in and of itself does not affect the performance of a paving mixture. However, it is essential in determining volumetric factors that are good indicators of performance, such as air void content, VMA and the amount of binder absorbed by the aggregate particles.

Maximum specific gravity is determined by measuring the specific gravity of the loose paving mixture, after removing all of the air entrapped in the mixture by subjecting the mixture to a partial vacuum (vacuum saturation). The loose mix is prepared by gently heating the sample in an oven until it can be easily broken apart. The mixture is then removed from the oven and occasionally stirred while cooling, to make sure that it remains broken up as much as possible into separate particles of asphalt-coated aggregate.

For this test, asphalt mix specimens for each mix variation were prepared and cured for two hours. Mixes were then cooled in a loose, un-compacted state and placed in a vacuum container filled with distilled water. A high vacuum pump attached to the container and activated for at least 15 minutes, removing entrapped air.

Shaking of the container was required to remove air bubbles. After vacuum saturation, the container was removed from the pump and filled to the calibrated level with water. Then the mass of the container, specimen, and water was determined. This value, along with the dry mass of the specimen and mass of the container filler with just water, was used to determine the theoretical maximum specific gravity by the following equation:

Theoretical Maximum Specific Gravity = $A/ (A + D - E)$…………………….. eq. 3.2

Where:
A = mass of oven dry specimen (g);
D = mass of container filled with 25°C water (g);
E = mass of container filled with specimen and water (g);

The theoretical maximum specific gravities of each mix design is shown in the tables used for air voids calculation.

3.7. Asphalt mix design

3.7.1. Marshall Mix design

For this study the Marshall Mix Design method for HMA mixtures was used to identify the optimum asphalt binder contents for all mixtures. Therefore preparing Marshall Specimens using the Marshall procedures for individual specimens are necessary. Dry and sieve aggregates into sizes (preferably individual sizes) and store in clean sealable containers. Separate enough material to make 2 (types of aggregate) × 15 (samples for five bitumen and three samples for each bitumen) × 3 (Three lime application) = 90 specimens of approximately 1200gm each. Next weigh out aggregate for each lime treated conditions of specimens placing each in a separate container and heat to mixing temperature determined from the asphalt property. Then heat sufficient asphalt cement to prepare the total specimens on each step. Asphalt contents should be selected at 0.5 percent increments with at least two asphalt contents above "optimum" and at least two below "optimum."

It is necessary to mix asphalt cement and aggregate until all the aggregate is coated. It is helpful to work on a heated table. Mixing can be by hand, but a mechanical mixer is preferred. Also it is essential to check temperature of freshly mixed material; if it is above the compaction temperature, allow it to cool to compaction temperature; if it is below compaction temperature, discard the material and make a new mix.

3.7.2. Specimen preparation

A total of 6 mix designs were developed: (two aggregate sources) x (one asphalt binder) x (three lime treatments). Therefore it is necessary to prepare the proper materials before go into the mix procedure. Aggregates should be oven dry after the lime application.

There was a significant amount of testing conducted throughout the progression of this study and, as such, there were several procedures followed for mix design, sample preparation, sample conditioning, and physical testing. The laboratory sampling plan consisting of preparing both lime treated and non-lime treated samples. The following flow chart shows the procedure of asphalt mix design.

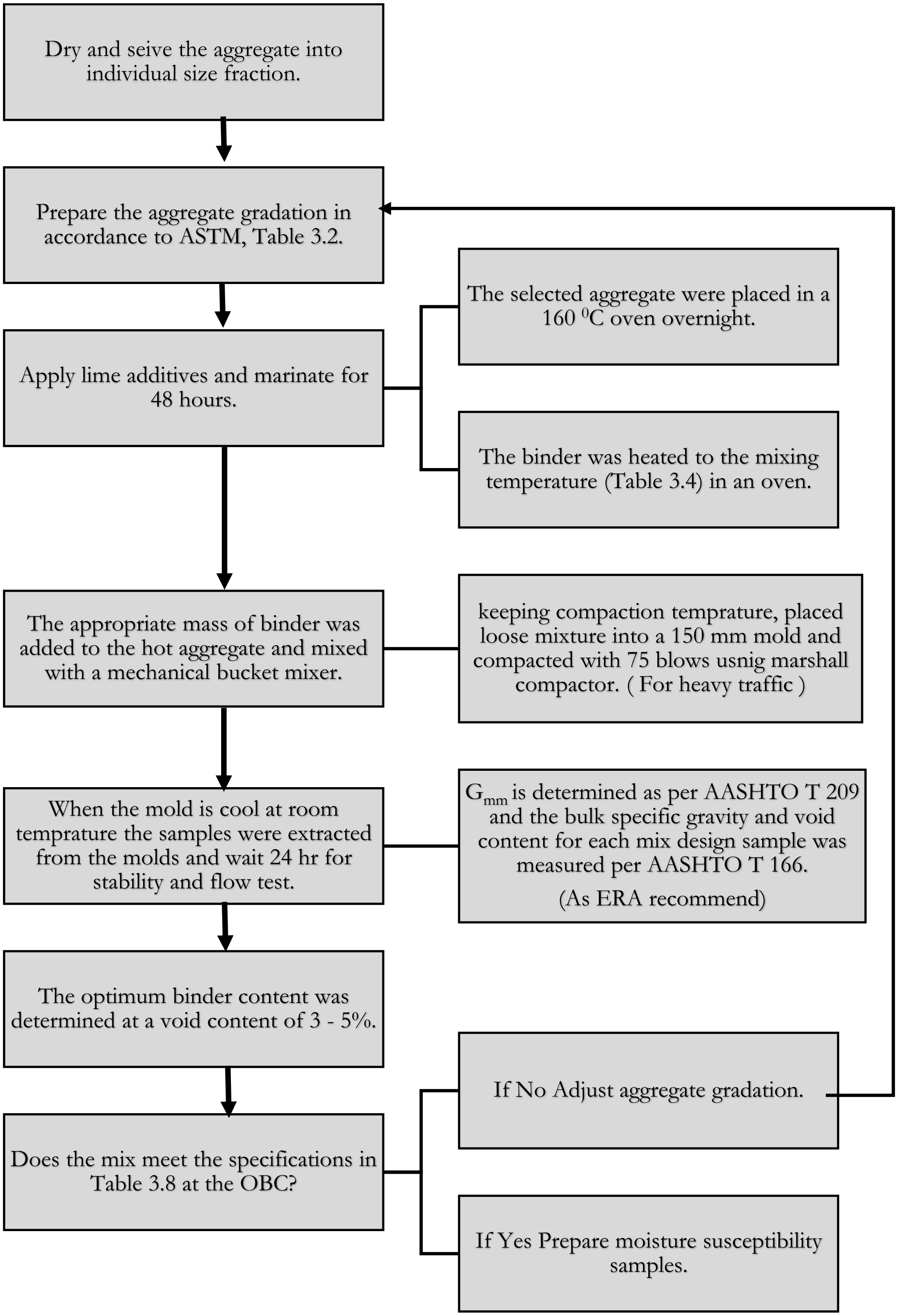


Figure 3.2: Flowchart of the asphalt mix design procedure.

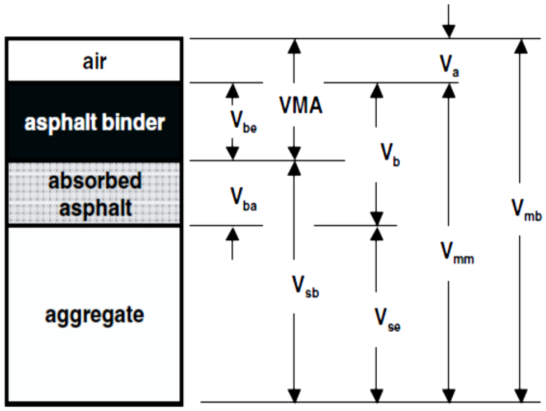
The temperature to which the asphalt must be heated to produce viscosities of 170 ± 20 centistokes kinematic and 280 ± 30 centistokes kinematic shall be established as the mixing temperature and compaction temperatures, respectively. These temperatures can be estimated from a plot of the viscosity (log-log centistokes scale) versus temperature (log degrees Rankine scale, $^{o}R = {}^{o}F + 459.7$) relationship for the asphalt cement to be used.

3.7.3. Weight Volume relationships on compacted hot mix asphalt and volumetric analysis

Asphalt concrete primarily consists of three different components or phases: aggregate, asphalt binder and air. Materials like concrete, which consist of particles held together by a cement of any type, are called composites. Some asphalt concrete mixtures contain small amounts of other additives, such as cellulose fibers, mineral fibers, ground rubber, and polymers. Although such additives may affect workability and performance significantly, these additives almost always represent a very small percentage of the overall volume and mass of the asphalt concrete. Engineers and technicians should remember the three major components of asphalt concrete aggregate, asphalt, and air. These three components are the key to understanding volumetric analysis. The composition of asphalt concrete can be described in terms of either weight or volume.

The asphalt binder content of a mixture, for example, is often given in terms of percent of total mix weight, whereas air void content is always given as a percent of total volume. It must be given this way, since the mass of air voids in an asphalt concrete specimen is essentially zero. Although composition of asphalt concrete mixtures can be given in terms of weight, traditionally the most common and most important method of describing and analyzing asphalt concrete composition is by volume. This is what it meant by the term "volumetrics" or "volumetric analysis" of asphalt concrete characterizing the composition of an asphalt concrete mixture by relative proportions by volume of aggregate, asphalt, and air voids. Although this may sound like a simple task, it can become quite complicated when absorption of asphalt by the aggregate must be accounted for or when only incomplete information on a mixture is available. It is essential that engineers and technicians responsible for developing asphalt concrete mix designs or performing quality control operations have a thorough understanding of volumetric analysis.

Figure 3-3 illustrates the definitions of variables used to define various volumes as used in volumetric analysis. The volume of permeable pores in the aggregate surface containing asphalt shows up in three different terms: the aggregate bulk volume (V_{sb}), the total asphalt volume (V_b), and the absorbed asphalt volume (V_{ba}). Also, in this manual the convention adopted for volume terms is that the capital letter V followed by a subscript denotes the absolute volume of a particular component, whereas V followed by capital letters denotes a percentage by volume. Thus, VMA represents the absolute volume of voids in the mineral aggregate (in units of cm^3, for example), whereas VMA indicates the voids in the mineral aggregate as a volume percentage. A set of variables similar to those given in Figure 3-3 can be defined for the mass terms used in volumetric analysis:



M_{be} = Mass of effective asphalt binder
M_{ba} = Mass of absorbed asphalt binder
M_s = Mass of aggregate, total
M_b = Mass of asphalt binder, total
M_{se} = Mass of aggregate, effective (excluding surface pores filled with asphalt)
M_a = Mass of air voids
M_{mb} = Mass of specimen, total
V_{be} = Volume of effective asphalt binder
V_{BE} = Effective asphalt content, percent by volume
V_{ba} = Volume of absorbed asphalt binder
V_{BA} = Absorbed asphalt binder, percent by total mix volume
V_{ma} = Volume of voids in mineral aggregate
VMA = Voids in mineral aggregate, percent by volume
V_{sb} = Volume of aggregate, bulk (including all permeable surface pores)
V_b = Volume of asphalt binder, total
V_B = Total asphalt binder content, percent by volume
V_{se} = Volume of aggregate, effective (excluding surface pores filled with asphalt)
V_a = Volume of air voids
V_a = Air void content, volume percent
V_{mm} = Volume of aggregate and asphalt
V_{mb} = Volume of specimen, total

Figure 3-3: Definition of volume terms used in volumetric analysis.

Typical asphalt concrete mixtures, as designed in the laboratory, contain about 84 to 90% aggregate, 6 to 12% asphalt binder, and about 4% air voids by volume. Asphalt concrete is mostly composed of aggregate. If the volume percentage of two of these components is known, the other can be determined by subtraction. For example, if we know that a mixture is to be designed with 4% air voids and 10% asphalt binder by volume, we can calculate the amount of aggregate required as 100 −(4 + 10) = 86% by volume.

When a sample paving mixture is prepared in the laboratory, it can be analyzed to determine its probable performance in a pavement structure. The analysis focuses on four characteristics of the mixture and the influence those characteristics are likely to have on mix behavior. They are:

- Mix density
- Air Voids
- Voids in the mineral aggregate
- Asphalt content

Mix Density

The density of the compacted mix is its unit weight or the weight of a specific volume of mix. Density is particularly important because high density of the finished pavement is essential for lasting pavement performance. In mix design testing and analysis, density of the compacted specimen is usually expressed in kilograms per cubic meter (kg/m^3). It is calculated by multiplying the bulk specific gravity of the mix by the density of water (1,000 kg/m^3).

The bulk specific gravity of a mixture refers to the specific gravity of a specimen of compacted mixture, including the volume of air voids within the mixture. It is equivalent to the mass of a given specimen in grams, divided by its total volume in cubic centimeters. The bulk specific gravity of an asphalt concrete mixture can be determined using either laboratory compacted specimens or cores or slabs cut from a pavement.

The standard procedure for determining the bulk specific gravity of compacted asphalt concrete involves weighing the specimen in air and in water. The following formula is used for calculating bulk specific gravity of a saturated surface-dry specimen:

$$G_{mb}=A/(B-C) \quad \text{……………………..} \quad \text{eq. 3.3}$$

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

The specimen density and the maximum theoretical density, both of which are determined in the laboratory, are each used as standards to determine if the density of the finished pavement meets specification requirements.

Air Voids

Air voids are small pockets of air between the coated aggregate particles in the final compacted HMA. Air void content does not include pockets of air within individual aggregate particles, or air contained in microscopic surface voids or capillaries on the surface of the aggregate. A certain percentage of air voids is necessary in the finished HMA to allow for a slight amount of compaction under traffic and a slight amount of asphalt expansion due to temperature increases. The allowable percentage of air voids in laboratory specimens is between 3 percent and 5 percent for surface and base courses, depending on the specific design.

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

In Marshall Mix design method of HMA, the allowable range for air void content in laboratory mix designs is range between 3.0 to 5.0%. However the in-place air void content of HMA pavement is often assumed to be about 7%, but recent research suggests that immediately after construction the air void content of HMA pavements typically ranges from about 6 to 11%, with a median value between 8 and 9% [25]. Cores taken from a newly constructed pavement will generally have air void contents in this range. However, once the pavement is opened to traffic, the repeated loading as trucks pass over the pavement will tend to further compact the material in the wheel paths of the pavement.

Determining air void content is one of the main purposes of volumetric analysis. Unfortunately, there is no simple direct way to determine the air void content of an asphalt concrete specimen. Air void content is determined by comparing the specific gravity (or density) of a compacted specimen with the maximum theoretical density of the mixture used to make that specimen. For example, if the compacted density of an asphalt concrete specimen is 95.3% of the theoretical maximum specific gravity, the air void content is 100 − 95.3 = 4.7%.

Density and air void content are directly related. The higher the density is the lower the void in the mix will be, and vice versa. Job specifications usually require the pavement compaction achieve an air void content of less than 8 percent and more than 3 percent. Air void content is calculated from the mixture bulk and theoretical maximum specific gravity:

$$V_a = 100\left[1 - \frac{G_{mb}}{G_{mm}}\right] \text{……………………….. eq. 3.4}$$

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

For this research Air void in the mix is one factor of comparison between limes treated and untreated conditions. Also, the moisture susceptibility test is done for 7±1% air void as stated in AASHTO T 283.

Voids in the Mineral Aggregate (VMA)

It is the inter-granular void spaces that exist between the aggregate particles in a compacted paving mixture. VMA includes air voids and spaces filled with asphalt. VMA is a volumetric measurement expressed as a percentage of the total bulk volume of a compacted mix.

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

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

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

Minimum VMA is necessary to achieve an adequate asphalt film thickness, which results in a durable asphalt pavement. Increasing the density of the gradation of the aggregate to a point where below-minimum VMA values are obtained leads to thin films of asphalt and a low-durability mix. Therefore, economizing in asphalt content by lowering VMA is actually counter-productive and detrimental to pavement quality. Table 3.4 shows specification for VMA in ERA manual.

VMA is simply the sum of the air void content and the effective asphalt binder content by volume:

$$\mathrm{VMA} = \mathrm{V_a} - \mathrm{V_{be}} \quad \text{or}$$

$$\mathbf{VMA = 100 \left(1 - \frac{G_{mb}(1-\mathit{P_b})}{\mathit{G_{sb}}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3.5}}$$

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

Binder Content

Binder content is one of the most important characteristics of asphalt concrete. Use of the proper amount of binder is essential to good performance in asphalt concrete mixtures. Too little binder will result in a dry stiff mix that is difficult to place and compact and will be prone to fatigue cracking and other durability problems. Too much binder will be uneconomical, since asphalt binder is, by far, the most expensive component of the mixture and will make the mixture susceptible to rutting and shoving. Typical asphalt binder contents range from 3.0% or less (for lean base course mixtures) to over 6.0% (for surface course mixtures and rich bottom layers), which are designed for exceptional durability and fatigue resistance [25].

Asphalt binder content can be calculated in four different ways: total binder content by weight, effective binder content by weight, total binder content by volume, and effective binder content by volume. Total asphalt content by volume is calculated as the percentage of binder by total mix mass:

$$\mathbf{P_b = 100\left(\frac{M_b}{M_s+M_b}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3.6}}$$

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

Total asphalt binder content by volume can be calculated as a percentage of total mix volume using the following formula:

$$\boldsymbol{V_b = \frac{P_b G_{mb}}{G_b}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{eq. 3.7}$$

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

The absorbed asphalt binder content by volume is also calculated as a percentage of total mix volume:

$$\mathbf{V_{ba} = G_{mb}\left[\left(\frac{P_b}{G_b}\right) + \left(\frac{P_s}{G_{sb}}\right) - \left(\frac{100}{G_{mm}}\right)\right]} \text{……………………. eq. 3.8}$$

Where
V_{ba} = Absorbed asphalt content, % by total mixture volume
G_{mb}= Bulk specific gravity of the mixture
P_b= Total asphalt binder content, % by mix mass
G_b= Specific gravity of the asphalt binder
P_s = Total aggregate content, % by mix mass
= 100 - P_b
G_{sb}= Average bulk specific gravity for the aggregate blend
G_{mm}= Maximum specific gravity of the mixture

The effective asphalt by volume is found by subtracting the absorbed asphalt content from the total asphalt content:

$$\boldsymbol{V_{be} = V_b - V_{ba}} \text{……………………. eq. 3.9}$$

Where
V_{be}= Effective asphalt content, % by total mixture volume
V_b= Total asphalt binder content, % by mixture volume
$V_{ba,}$ = Absorbed asphalt content, % by total mixture volume

The effective and absorbed asphalt binder contents can also be calculated as percentages by weight, once the volume percentage has been calculated:

$$\mathbf{P_{be} = P_b\left(\frac{V_{be}}{V_b}\right)} \text{……………………. eq. 3.10}$$

$$\mathbf{P_{ba} = P_b - P_{be}} \text{……………………. eq. 3.11}$$

Where
P_{be}= Effective asphalt binder content, % by total mass
P_b= Asphalt binder content, % by total mass (see Equation 5-5)
V_{be}= Effective asphalt binder content, % by total mixture volume (see Equation 5-8)
V_b= Asphalt binder content, % by total mixture volume (see Equation 5-6)
P_{ba}= Absorbed asphalt binder, % by total mixture mass

Voids Filled with Asphalt

Voids filled with asphalt (VFA) is the percentage of inter-granular void space between the aggregate particles (VMA) that contains or is filled with asphalt. VFA is used to ensure that the effective asphalt part of the VMA in a mix is not too little (dry, poor durability) or too great (wet, unstable). The acceptable range of VFA varies depending upon the traffic level for the facility. Higher traffic requires a lower VFA, because mixture strength and stability is more of a concern. Lower traffic facilities require a higher range of VFA to increase HMA durability. A VFA that is too high, however, will generally yield a plastic mix.

In designing asphalt concrete mixtures, VFA is closely related to both VMA and V_{be}. This is because with the design air void content constant at about 4.0%, as VMA increases, V_{be} increases and VFA also increases. Therefore, in most cases VFA should be thought of as simply an indicator of mix richness, like VMA or V_{be}. If design voids are fixed or allowed to vary only over a narrow range, there is little point in simultaneously controlling VMA, V_{be}, and/or VFA.

It is not entirely clear what aspects of performance are related to VFA that are not also strongly related to other volumetric factors, especially V_{be}. Some engineers have proposed that fatigue resistance increases with increasing VFA. However, VFA and V_{be} are strongly related.

Recent research strongly suggests that V_{be} is a somewhat better overall indicator of fatigue resistance in asphalt concrete mixtures. Therefore, in order to control or evaluate fatigue resistance, engineers and technicians should either use V_{be}, or VMA at a constant design air void content.

VFA is the effective binder content expressed as a percentage of the VMA:

$$\mathrm{VFA} = 100\left(\frac{\mathrm{V_{be}}}{\mathrm{VMA}}\right) \text{ or}$$

$$\mathbf{VFA = 100\left(\frac{VMA-V_{\mathit{a}}}{VMA}\right)\text{……………………. eq. 3.12}}$$

Where VFA is the voids filled with asphalt, as a volume percentage.

Apparent Film Thickness

"Film thickness," when applied to asphalt concrete mixtures, refers to the average thickness of binder coating aggregate particles in the mixture. Some engineers and researchers have proposed that this is an important characteristic related to several aspects of pavement performance. Mixtures with low film thickness will be brittle and prone to durability problems, while mixtures with high film thickness will have too much asphalt and may be prone to rutting and shoving.

3.8. Methods used to add lime to HMA

Hydrated lime can be added to hot mix asphalts in a variety of ways. This may range from adding dry lime to the drum mixer at the point of asphalt binder entry, to adding lime to aggregate followed by "marination" for several days. Quicklime should not be added to HMA unless it first has been completely hydrated. If quicklime remains un-hydrated in the HMA, it will change to Ca(OH)2 when it comes into contact with water during the service life of the pavement. This reaction (i.e., changing from CaO to Ca(OH)2) is expansive and will create a volume change in the HMA and losses in strength and performance.

Lime may also added by sprinkling it over the pre-wetted coarse aggregate as it passes over the conveyer belt, or it may be added in the form of slurry. However, there are problems with both techniques. When added in the dry form, the main concern is the coating of the aggregate. Also, adding the lime in a drum mix plant is ineffective as much of the lime is lost before the addition of the binder. If lime is added in a slurry form, it will increase the amount of fuel needed to heat the aggregate, and thus increase the production cost. Also, some of the other concerns regarding the addition of the lime are health hazards due to inhalation and skin exposure. As a general rule, the application rate is one percent by weight of the mix, though in cases where severe stripping is anticipated the application amount may increase. Each of the most commonly used methods of lime addition are described as follow.

3.8.1. Dry Lime on dry aggregate.

Mostly hydrated lime is added to the drum at the same time as the mineral filler. The hydrated lime comes in contact with the aggregate itself, directly improving the bond between the bitumen and the stone, while the balance enters the bitumen. The lime in the bitumen can react with the polar molecules that contribute to both stripping and oxidation, while simultaneously stiffening and toughening the mix. The dry method is the simplest and commonly used application methods.

3.8.2. Dry Lime on Moist Aggregate

This method is the one most commonly used throughout the U.S. It involves metering the lime onto a cold feed belt carrying aggregate that has been wetted to approximately 1-3% over its saturated surface dry (SSD) condition. The lime treated aggregate is then run through a pug mill to insure thorough mixing before it is fed into the plant [21].

Lime is applied to damp aggregate in order to insure more complete coverage of the stone than is achieved using the dry method. Lime that does not adhere to the stone is dispersed throughout the mix where it will contribute to the other improvements that have been described. The "dry on damp" method of adding hydrated lime to hot mix is also relatively simple, but driving off the water required by the process uses additional fuel and may slow down plant production to some degree. At least one state that uses this method requires the aggregate to be marinated in stockpile before use to provide additional time for the lime to react with the surface of the stone and further improve anti-stripping performance.

After mixing, the lime-treated aggregate is usually placed on the weigh belt in a drum mixer operation or on a charging belt for the dryer of the batch mixer. Some agencies allow the introduction of lime into the drum after the aggregate has been mostly dried and just prior to the application of the asphalt cement. This method may increase the resistance of the mixture to stripping; however, the maximum benefit of using lime will be achieved when it is mixed with the aggregate in the presence of water.

3.8.3. Slurry Method

This method utilizes a slurry mixture of lime and water that is applied at a metered rate to the aggregate, insuring superior coverage of the stone surfaces. After the slurry is applied, the aggregate can either be fed directly into the plant or marinated in stockpile for some period of time, allowing the lime to react with the aggregate. Because the lime is bound to the stone, this method results in the least dispersion of the lime throughout the rest of the mix [21].

The use of lime slurries has several advantages: improved resistance of the treated hot mix to stripping; reduced dusting associated with the addition of dry lime to the aggregate; and improved distribution of the lime on the aggregate.

Lime slurries made from hydrated lime or quicklime has also been used. Lime-slurried aggregates are conveyed directly to the drying and mixing portion of the HMA facility or placed into stockpiles for marination. However, the use of lime slurries adds more water than is typically used for conventional lime applications and can substantially increase the water content of the aggregate prior to entering the drying and mixing portions of the HMA facility.so that, it increased fuel consumption and reduced HMA production can result. The use of lime slurries also requires purchasing or renting specialized equipment to prepare the lime slurry at the site of the mixing operation.

Marinating or stockpiling treated aggregate prior to re-entry into the HMA facility is fairly common in different states of U.S like California, Nevada, and Utah. The advantages of marination include: a reduction in moisture content while the aggregate is stockpiled; the lime treatment can be performed separately from the HMA production with some economic advantage; and an improvement in the resistance to moisture can result (particularly when aggregates have clays present in their fines or have clay coatings). The treatment of aggregates followed by marination also allows for the use of the lime on only problematic or strip-prone aggregate. For example, a fine aggregate may be highly water sensitive while coarse aggregates may not be water sensitive [02].

Disadvantages of marination include: additional handling of the aggregate; additional space for both lime-treated and untreated stockpiles; and lime can be washed from the aggregate during marination. Carbonation of the lime in stockpiles of aggregate does not appear to be a major problem, as it usually occurs only on the surface of the stockpile.

Adding dry lime to the asphalt binder and storing the lime-modified binder prior to mixing with the aggregate has not been practiced in the field. However, recent research demonstrates the potential effectiveness of this approach.

In general hydrated lime has been renowned for many years as the premier asphalt modifier to correct stripping (moisture sensitivity) problems. As its use has grown, many other benefits have been identified, both in laboratory and field projects across the world. The need to produce high performance asphalt pavements increases the importance of lime as a multi-functional asphalt modifier.

3.8.4. Laboratory procedure of adding hydrated lime

The objective of this study was to evaluate HMA mixture with the addition of lime. Of the three techniques for this research two of them with and without marination were used before preparing HMA samples. The first one (Dry lime on moist aggregate) refers to a technique of adding water to dry aggregates and distributing the moisture by mixing and hydrated lime at a rate of 1.5 percent is then mixed with the moistened aggregates. The second method (lime slurry method) also resulted in 1.5 percent hydrated lime being added to the aggregates, but the lime was introduced in the form of lime-water slurry.

A 48 hour marination time was used to allow for any pozzolanic reaction that might occur between the aggregates and lime. During this time the moist aggregates and lime were sealed in a plastic container. At the end of the marination period, the aggregates were dried in preparation for mixing.

The main objective of this task is to evaluate the effectiveness of lime in reducing the moisture sensitivity of HMA mixtures and to identify the most effective method of adding lime to HMA mixtures. Therefore, to summarize, the experiment evaluated the following three methods of adding lime to HMA mixtures:

1. No lime is added.
2. Dry lime added to wet aggregate with 48 hours marination.
3. Lime slurry added to aggregate with 48 hours marination.

It is important to dry the aggregate in an oven before it adds with bitumen to prepare the HMA mix samples.

3.9. Moisture conditioning

Moisture conditioning is an important step in the evaluation of moisture damage of HMA mixtures. This research evaluates the moisture damage of HMA mixtures by comparing the various properties of the mix before and after moisture conditioning. The properties prior to moisture conditioning are typically referred to as "dry" or "unconditioned" while the properties after moisture conditioning are typically referred to as "wet" or "conditioned". The most commonly used moisture conditioning process is the one recommended by AASHTO T-283 test method entitled: "Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage."

The moisture conditioning process consists of compacting HMA samples at air-voids between 6 and 8 %, saturating half of the samples to a level between 55 and 80%, then subjecting the saturated samples to a freeze-thaw cycle consisting of freezing at 0°F for 16 hours followed by 24 hours thawing at 140°F and 2 hours at 77°F.

On this research a destructive test (a test that destroys the sample) is used to evaluate the tensile strength test of the HMA mixtures. Therefore the unconditioned and conditioned properties will have to be measured on two different sets of samples having very close air-voids.

3.9.1. Evaluation of the Moisture Sensitivity of the Mixture

The American Association of State Highway and Transportation Officials (AASHTO) Tensile Strength Ratio test (AASHTO T-283) is commonly used to evaluate improvements gained by the addition of moisture sensitivity additives. The test compares the strengths of samples both dry and after subjecting moisture conditioned samples to at least one freeze/thaw cycle. For construction purposes common specification requires a retained strength ratio after one freeze/thaw cycle to equal or exceed 75 percent.

Evaluation according to AASHTO T 283 has a major advantage to account effects of the mix physical and mechanical properties, water/traffic action, and pore pressure effects. And also have major disadvantages of these tests are the requirement of more elaborate testing equipment, longer testing times, and more laborious test procedures. Even with this disadvantage it has a better advantage that of loose mix test.

The goal of these tests on this research is to compare the properties of the lime-treated and untreated mixtures at the dry and moisture conditioned stages under single freeze-thaw cycles. Before goes to testing samples of HMA it is necessary to group the samples based on the aggregate sources.

Within this research to investigate the advantages of lime additives on moisture susceptibility, the laboratory program evaluated the Dry and Wet tensile strength after one freeze-thaw cycle for the selected optimum asphalt content.

The TS test is a destructive test which means that the sample is damaged after the conduct of the test. Therefore, the TS test cannot be conducted on the same sample before and after freeze-thaw cycling. This experiment evaluated the TS property of the HMA samples at the dry stage and after one freeze-thaw cycle. It should be noted that the dry and wet TS properties were evaluated on different sets of samples. Table 4.5 summarize the data generated from this experiment.

3.9.2. Testing procedure

At least six specimens are prepared and compacted. The compacted specimens are expected to have air void contents between six percent and eight percent. The higher percentage of air voids helps to accelerate moisture damage on the cores. Two groups for each three specimens are used.

The first group is the control group. The second group is saturated between 55 and 80percent with water and is placed in the freezer (0°F or –18°C) for 16 to 18 hours. The frozen cores then are moved to a water bath at 140°F (60°C) for 24 hours.

After conditioning, remove the specimen from the bath and place it on its side between the bearing plates of the testing machine such that the load was applied along the diameter of the specimen with a loading rate of 2 in/min.

It is recommended that steel loading strips be placed between the specimen and the bearing plates as this will simplify the calculation of the tensile strength. Apply the load to the specimen by forcing the bearing plates together at a constant rate of 50 mm per minute.

If steel loading strips are used, record the maximum load, then continue to load the specimen until it cracks. Stop the machine, remove the specimen and break it apart at the crack. Look at the inside of the specimen and estimate the percent of stripped aggregate. Record the observations.

If steel loading strips are not used, stop the machine when the maximum load is observed. Record the maximum load. Remove the specimen from the machine and measure and record the width of the flattened area on each side of the specimen. Return the specimen to the machine and continue loading until the specimen cracks. Stop the machine, remove the specimen and break it apart at the crack. Look at the inside of the specimen and estimate the percent of stripped aggregate. Record the observations.

When steel loading strips are used the load was applied at a constant rate of movement of the testing machine head of 50 mm per minute. The maximum load was recorded and placed in the equation (3-13) in order to calculate tensile strength.

$$\mathbf{St = 2000P/\ (\pi t D)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{eq. 3.13}$$

Where S_t = tensile strength (kPa),

P = Maximum load (N),

t = Specimen thickness (mm), and

D = Specimen diameter (mm).

For this research in the course of testing the tensile strength since the tensile strength machine in our laboratory is not available with steel loading strips, I used the universal testing machine. So that the steel loading strips is not functional. Consequently the following little modified equation is used to calculate the tensile strength as per recommendation of FHWA. [27]

$$S_t = S_{10} P / (44000t) \ldots\ldots\ldots\ldots \text{eq. 3.14}$$

Where:
S_t = tensile strength, Pa
S_{10} = maximum tensile stress corresponding to the width of the flattened area from table 4.5
P = maximum load, Newton
t = specimen thickness, mm

Table 3.5: Maximum tensile stress corresponding to the width of the flattened area[27]

Width of Flattened area in mm	Maximum Tensile stress, S_{10}, Kpa
0.0	11307
2.5	11232
5.0	11163
7.6	11073
10.2	10997
12.7	10832
15.2	10618
17.8	10397
20.3	10135
22.9	9915
25.4	9687

Tables 4.5 show the results of compacted asphalt specimens tested for tensile strength. The strengths for each of both the unconditioned and moisture conditioned sets along with the tensile strength ratios (TSR's)for both sources of aggregate indicated in the table. Tensile strength ratios represent the proportion of tensile strength retained between the moisture damaged and unconditioned sets of a specific additive concentration. TSR's were calculated using the following equation:

$$\text{Tensile Strength Ratio (TSR)} = S_2/S_1 \ldots\ldots\ldots\ldots \text{eq. 3.15}$$

Where:

S_2 = average tensile strength of the conditioned (moisture damaged) set (Kpa);

S_1 = average tensile strength of the unconditioned set (Kpa).

CHAPTER FOUR: LABORATORY TEST RESULTS

Table 4.1 and Table 4.2 are summarizing the mixtures properties versus Asphalt binder content evaluated in this study. Where

G_{mb}= Bulk specific gravity,
G_{mm}= Theoretical maximum specific gravity,
V_b= Percentage volume of total Asphalt,
V_{ba}= Percentage volume of absorbed asphalt,
V_{be}= Percentage volume of effective asphalt,
P_{be}=Effective asphalt content (% mass of mix),
V_a= Void in the total mix,
VMA= Voids in the mineral aggregate and
VFA = Void filled with asphalt

Table 4.1: Test Result of Marshall mixture for aggregate A

No Lime (Controlled condition)

Binder content	Stability (N)	Flow (mm)	G_{mb}	G_{mm}	V_b (%)	V_{ba} (%)	V_{be} (%)	P_{be} (%)	V_a (%)	VMA (%)	VFA (%)
4.50	7.70	-	2.225	2.464	9.82	6.68	93.32	4.20	9.70	18.86	48.56
5.00	9.45	2.73	2.281	2.452	11.18	7.91	92.09	4.60	6.97	17.26	59.64
5.50	10.55	3.55	2.309	2.436	12.45	7.83	92.17	5.07	5.23	16.70	68.69
6.00	10.67	3.85	2.328	2.425	13.69	9.06	90.94	5.46	3.99	16.44	75.73
6.50	8.37	4.43	2.331	2.402	14.86	6.91	93.09	6.05	2.94	16.77	82.48

Dry Lime – (After 48 Hour Marination)

Binder content	Stability (N)	Flow (mm)	G_{mb}	G_{mm}	V_b (%)	V_{ba} (%)	V_{be} (%)	P_{be} (%)	V_a (%)	VMA (%)	VFA (%)
4.50	7.65	2.80	-	2.469	10.00	8.46	91.54	4.12	-	-	-
5.00	9.89	3.10	2.231	2.441	10.94	4.25	95.75	4.79	8.605	19.08	54.89
5.50	11.07	3.90	2.297	2.432	12.39	6.61	93.39	5.14	5.550	17.12	67.58
6.00	10.74	4.90	2.343	2.425	13.78	9.13	90.87	5.45	3.375	15.90	78.77
6.50	8.36	6.88	2.342	2.407	14.92	8.15	91.85	5.97	2.688	16.39	83.60

Slurry Lime - (After 48 Hour Marination)

Binder content	Stability (N)	Flow (mm)	Gmb	Gmm	Vb (%)	Vba (%)	Vbe (%)	Pbe (%)	Va (%)	VMA (%)	VFA (%)
4.50	9.17	3.15	2.277	2.477	10.05	11.41	88.59	3.99	8.072	16.97	52.44
5.00	10.42	3.40	2.310	2.442	11.28	11.26	88.74	4.44	5.405	16.21	66.65
5.50	11.87	3.83	2.337	2.430	12.60	5.98	94.02	5.17	3.827	15.68	75.58
6.00	10.23	4.51	2.349	2.420	13.79	7.82	92.18	5.53	2.954	15.69	81.17
6.50	8.24	5.29	2.352	2.409	14.99	8.88	91.12	5.92	2.375	16.03	85.19

Table 4.2: Test Result of Marshall mixture for aggregate B

No Lime (Controlled condition)

Binder content	Stability (N)	Flow (mm)	Gmm	Gmb	Vb (%)	Vba (%)	Vbe (%)	Pbe (%)	Va (%)	VMA (%)	VFA (%)
4.00	9.46	2.95	2.71	2.51	9.74	2.13	7.62	3.13	7.46	15.08	50.51
4.50	10.34	3.07	2.68	2.53	11.03	1.84	9.19	3.75	5.78	14.97	61.39
5.00	11.01	2.66	2.66	2.55	12.36	1.86	10.50	4.25	4.24	14.74	71.23
5.50	9.87	3.08	2.64	2.54	13.59	1.88	11.71	4.74	3.49	15.20	77.02
6.00	7.78	3.15	2.62	2.55	14.83	2.01	12.82	5.19	2.79	15.61	82.15

Dry Lime - 48 Hour Marination

Binder content	Stability (N)	Flow (mm)	Gmm	Gmb	Vb (%)	Vba (%)	Vbe (%)	Pbe (%)	Va (%)	VMA (%)	VFA (%)
4.00	12.03	2.93	2.75	2.42	9.40	3.29	6.12	2.60	11.93	18.05	33.89
4.50	12.43	4.95	2.71	2.48	10.84	2.77	8.07	3.35	8.36	16.43	49.14
5.00	13.49	5.53	2.67	2.51	12.19	2.19	10.00	4.10	5.87	15.88	63.01
5.50	11.79	4.21	2.65	2.57	13.73	2.53	11.20	4.49	3.13	14.33	78.18
6.00	9.50	6.95	2.64	2.56	14.94	2.87	12.06	4.85	2.94	15.00	80.41

Slurry Lime - 48 Hour Marination

Binder content	Stability (N)	Flow (mm)	Gmm	Gmb	Vb (%)	Vba (%)	Vbe (%)	Pbe (%)	Va (%)	VMA (%)	VFA (%)
4.00	10.54	3.40	2.73	2.44	9.46	2.75	6.71	2.84	10.82	17.53	38.28
4.50	12.22	2.83	2.70	2.49	10.86	2.53	8.32	3.45	8.00	16.32	51.00
5.00	11.21	4.36	2.67	2.53	12.29	2.28	10.02	4.07	5.14	15.16	66.07
5.50	10.83	5.45	2.64	2.56	13.67	1.89	11.78	4.74	2.92	14.70	80.13
6.00	9.75	5.60	2.60	2.59	15.06	1.47	13.60	5.41	0.69	14.29	95.16

4.1. Optimum Asphalt Content Determination

It is common practice to design the mix using the Marshall Test (ASTM D1559) and to select the design binder content by calculating the mean value of the binder contents for (a) maximum stability, (b) maximum density, (c) the mean value for the specified range of void contents and (d) the mean value for the specified range of flow values. The following two methods are commonly used to determine the optimum asphalt content from the plots:

Method I-NAPA Procedure

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

2. Determine the following properties at this optimum asphalt content by referring to the plots:
    - Marshall stability
    - Flow
    - VMA and
    - VFA.
3. Compare each of these values against the specification values and if all are within the specification, then the preceding optimum asphalt content is satisfactory. If any of these properties is outside the specification range, the mixture should be redesigned.

Method 2-Asphalt Institute Method

1. Determine:
    (a) Asphalt content at maximum stability
    (b) Asphalt content at maximum density
    (c) Asphalt content at midpoint of specified air void range (4 percent typically)
2. Average the three asphalt contents selected above.
3. For the average asphalt content, go to the plotted curves and determine the following properties:
    - Stability;
    - Flow;
    - Air voids; and
    - VMA.
4. Compare values from Step 3 with criteria for acceptability given in Table 4.3 and Table 3.5.

Since ERA manual recommend the second method, for this research the Asphalt Institute Method is selected to determine the optimum asphalt binder. The properties of the mix design at this design binder content with recommended Marshall Criteria is then shown in Table 4.3

Table 4.3: Suggested Marshall Test Criteria (ERA Manual)

Total Traffic (10^6 ESA)	**< 1.5**	**1.5 - 10.0**	**> 10.0**
Traffic Class	T1, T2, T3	T4, T5, T6	T7, T8
Minimum Stability (KN at 60 ^{0}C)	3.5	6	7
Minimum flow (mm)	2	2	2
Compaction level (Number of blow)	2 x 50	2 x 75	2 x 75
Air void (percent)	3 - 5	3 - 5	3 - 5
VMA		Show Table 3.5	

Table 4.4 & 4.5 summarizes the selected optimum asphalt binder contents using the Marshall Mix design criteria. The selected optimum binder content (OBC) and volumetric properties of each of all mixtures are included with in the table.

Table 4.4: Optimum binder content for aggregate A

Criteria	Max result	Corresponding Bitumen cont.	OBC	Criteria	Check at OBC	Required Specification	Remark
No lime							
Stability	10.67	6.00	6.00	Stability	10.09	> 7 KN	Ok!
Bulk Sp.Gr	2.328	6.00		Air Void	3.99	5-Mar	Ok!
Air Void	4%	6.00		Flow	3.85	2 - 4mm	Ok!
Avg bitumen = 6.0				VMA	16.44	> 15 %	Ok!
				VFA	75.73	70 - 85	Ok!
Dry Lime (After 48 Hr. Marinating)							
Stability	11.07	5.50	5.79	Stability	10.88	> 7 KN	Ok!
Bulk Sp.Gr	2.34	6.00		Air Void	4.29	5-Mar	Ok!
Air Void, %	4.00	5.86		Flow	4.58	2 - 4mm	Not ok!
Avg bitumen = 5.79				VMA	16.00	> 15 %	Ok!
				VFA	74.07	70 - 85	Ok!
Lime Slurry (After 48 Hr. Marinating)							
Stability	11.87	5.50	5.65	Stability	11.38	> 7 KN	Ok!
Bulk Sp.Gr	2.35	6.00		Air Void	3.57	5-Mar	Ok!
Air Void, %	4	5.46		Flow	4.03	2 - 4mm	Fair!
Avg bitumen = 5.49				VMA	15.69	> 15 %	Ok!
				VFA	77.40	70 - 85	Ok!

Table 4.5: Optimum binder content for aggregate B

Criteria	Max result	Corresponding Bitumen cont.	OBC	Criteria	Check at OBC	Required Specification	Remark
No lime							
Stability	11.010	5.00	5.39	Stability	10.12	> 7 KN	Ok!
Bulk Sp.Gr	2.546	6.00		Air Void	3.66	3 - 5%	Ok!
Air Void, %	4.000	5.16		Flow	2.99	2 - 4 mm	Ok!
Avg bitumen = 5.39				VMA	15.10	> 15 %	Ok!
				VFA	75.75	70 - 85	Ok!
Dry Lime 48 Hr Marination							
Stability	13.490	5.00	5.28	Stability	12.54	> 7 KN	Ok!
Bulk Sp.Gr	2.571	5.50		Air Void	4.34	3 - 5%	Ok!
Air Void, %	4.000	5.34		Flow	4.79	2 - 4 mm	Not ok!
Avg bitumen = 5.28				VMA	15.01	> 15 %	Ok!
				VFA	71.51	70 - 85	Ok!
Lime Slurry 48 Hr Marination							
Stability	12.220	4.50	5.25	Stability	11.02	> 7 KN	Ok!
Bulk Sp.Gr	2.586	6.00		Air Void	4.03	3 - 5%	Ok!
Air Void, %	4.000	5.26		Flow	4.91	2 - 4 mm	Not ok!
Avg bitumen = 5.25				VMA	14.93	> 15 %	Ok!
				VFA	73.10	70 - 85	Ok!

As stated on previous topics the outputs of this research include the changes of important physical properties of HMA samples after the application of lime additives. Therefore the table stated here applies for all samples made in laboratory as crisscross indications in addition to moisture susceptibility tests.

The moisture damaged tensile strength of each lime application was also compared with the unconditioned control tensile strength shown in the last column of table 4.6 & 4.7 for each of respective aggregates.

Table: 4.6. Moisture susceptibility (Tensile Strength) test results of aggregate A

				Dry sample				Wet sample						
Additive %	OBC	Sample no	Gmm	Gmb	Air void	Dry TS Kpa	Avg. Dry TS, Kpa	Gmb	Air void	Saturation %	Wet TS Kpa	Avg. Wet TS, Kpa	TSR	TSR compared to "No lime"
No lime														
0	6	A	2.425	2.243	7.5	857.0	852.2	2.248	7.3	76.4	659.87	732.06	0.86	
		B		2.255	7.0	825.2		2.253	7.1	71.4	775.73			
		C		2.258	6.9	874.2		2.250	7.2	68.7	760.58			
Dry lime														
1.50	5.79	A	2.428	2.256	7.1	881.1	904.8	2.246	7.5	72.4	757.77	802.51	0.89	1.03
		B		2.251	7.3	928.1		2.260	6.9	78.3	825.96			
		C		2.248	7.4	905.3		2.253	7.2	71.9	823.80			
Slurry lime														
1.50	5.65	A	2.430	2.253	7.3	920.5	931.0	2.250	7.4	72.3	837.62	844.18	0.91	1.06
		B		2.255	7.2	941.9		2.265	6.8	74.5	866.50			
		C		2.250	7.4	930.8		2.248	7.5	72.3	828.42			

Table: 4.7. Moisture susceptibility (Tensile Strength) test results of aggregate B

				Unconditioned (Dry sample)				Conditioned (Wet sample)						
Additive %	OBC	Sample no	Gmm	Gmb	Air void	Dry TS Kpa	Avg. Dry TS, Kpa	Gmb	Air void	Saturation %	Wet TS Kpa	Avg. Wet TS, Kpa	TSR	TSR compared to "No lime"
No lime														
0	5.39	A	2.642	2.473	6.4	948.3	952.4	2.457	7.0	64.3	688.4	685.70	0.72	
		B		2.460	6.9	922.8		2.468	6.6	68.4	666.1			
		C		2.441	7.6	986.1		2.452	7.2	70.2	702.6			
Dry lime														
1.50	5.28	A	2.660	2.476	6.9	1064.7	998.6	2.484	6.6	64.7	864.5	858.80	0.86	1.19
		B		2.490	6.4	972.8		2.468	7.2	66.3	823.1			
		C		2.471	7.1	958.3		2.482	6.7	69.4	888.8			
Slurry lime														
1.50	5.25	A	2.645	2.452	7.3	1084.5	1051.7	2.455	7.2	65.1	954.3	936.00	0.89	1.24
		B		2.452	7.3	1021.2		2.465	6.8	68.7	895.7			
		C		2.476	6.4	1049.4		2.455	7.2	71.4	958.0			

CHAPTER FIVE

ANALYSIS AND DISCUSSION

This chapter concentrated on evaluating the impact of lime treatment on the overall physical properties and moisture sensitivity of laboratory prepared mixtures. The experiment evaluated two methods of adding lime into HMA mixtures which were produced using two sources of aggregates. This section summarizes the data developed during the laboratory evaluation. The purpose of these tests was to compare the mechanical properties of asphalt mixtures and prediction of stripping potential using AASHTO T 283 test method. For moisture sensitivity the laboratory program evaluated dry tensile strength at 25 ^{0}C and wet tensile strength at 25 ^{0}C after one freeze-thaw cycle

5.1. Analysis on physical properties of compacted HMA.

The application of hydrated lime additives on both aggregate has noticeable effects on the moisture sensitivity and important physical properties of HMA. The following section analyze and discuss the result collected with in the laboratory under control conditions.

5.1.1. Stability

Stability is generally a measure of the mass viscosity of the aggregate-asphalt cement mixture and is affected significantly by the angle of internal friction of the aggregate and the viscosity of the asphalt cement. Anything that increases the viscosity of the asphalt cement increases the Marshall stability.

In addition to that the filler effect of the lime in the asphalt reduces the potential of the asphalt to deform at high temperatures, especially during its early life when it is most susceptible to rutting. Furthermore, the lime makes the HMA less sensitive to moisture effects by improving the aggregate-asphalt bond. As the HMA ages due to oxidation, hydrated lime reduces not only the rate of oxidation but also the harm created by the products of oxidation.

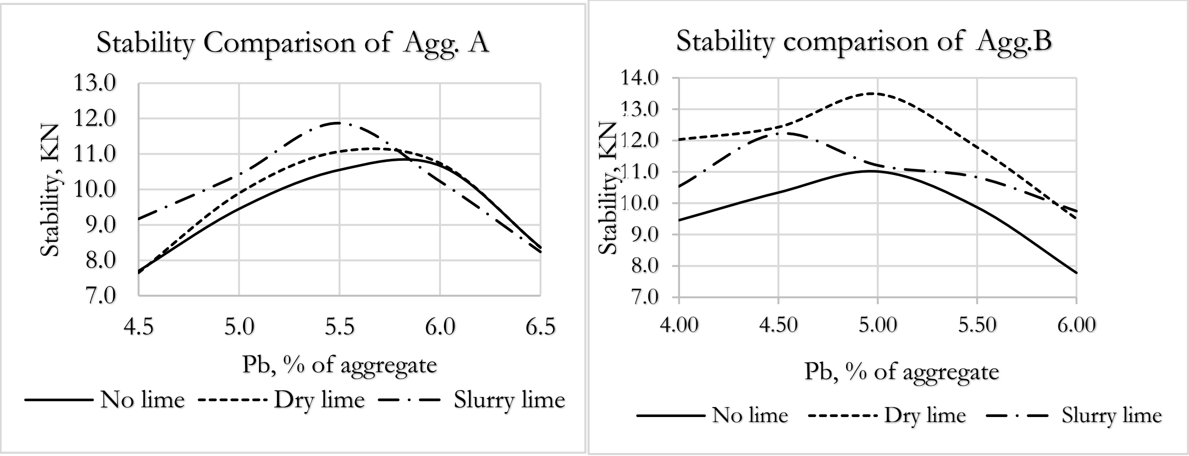


Fig 5.1: Stability comparison of lime modified and unmodified samples

The small percentage of lime additives have the effects on stability of both aggregates as shown in figure 5.1. This may be due to making the asphalt cement and dust combination act as a more viscous binder thus increasing the Marshall stability. Therefore the hydrated lime filler stiffens the asphalt film and reinforces it.

The filler properties of lime additive increases the stiffness and decreases the rut depth. This effect keeps the asphalt from hardening excessively and from becoming highly susceptible to cracking (through fatigue and low temperature or thermal cracking). So that, the filler effect of the hydrated lime dispersed in the asphalt improves fracture resistance and further improves cracking resistance.

5.1.2. Flow

Flow refers that the vertical deformation of the sample (measured from start of loading to the point at which stability begins to decrease) in 0.25mm. High flow values generally indicate a plastic mix that will experience permanent deformation under traffic, whereas low flow values may indicate a mix with higher than normal voids and insufficient asphalt for durability and one that may experience premature cracking due to mixture brittleness during the life of the pavement

The flow value has a general trend of consistently increases with increasing asphalt content. For 75-blow Marshall designs that are used on high volume roads, the flow value is usually specified to be in the range of 2 – 4 mm. Fig 5.2 shows that the lime modified samples are increases in flow compared with the unmodified samples. For both aggregate, application of hydrated lime have negative effect on the flow number. The increased flow no out of the required specification range exposed the HMA for permanent deformation during their time of service.

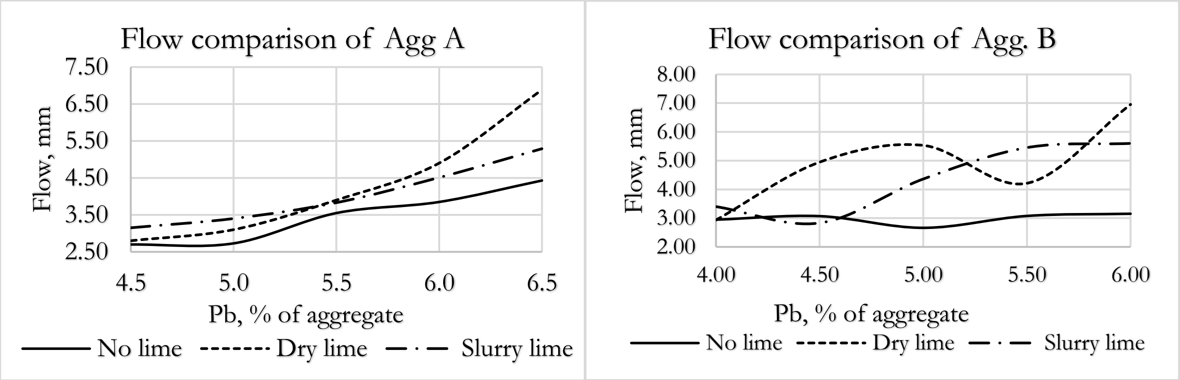


Fig 5.2: Flow comparison of lime modified and unmodified samples

5.1.3. Bulk specific gravity (Gmb)

In the Marshall Mix design procedure, the density varies with asphalt content. Density increases initially as the asphalt content increases because the hot asphalt cement lubricates the particles allowing the compacting effort to force them closer together. The density reaches a peak and then begins to decrease because the additional asphalt cement produces thicker films around the individual aggregates, thereby pushing the aggregate particles further apart and resulting in lower density. Anything that decreases the in-place air voids will increase the percent density.

Since lime has an effect as filler and some part of the in place air void is enclosed by the lime, it is expected to have the lime modified HMA samples always greater bulk specific gravity compared with no lime case. However, this is true only for aggregate A. Because as observed in figure 5.3 application of hydrated lime on aggregate A increases the bulk specific gravity under all bitumen content, on the other hand on aggregate B it is greater than no lime case starting from around the middle point of 5.0 & 5.5 percent bitumen content. Yet the bulk specific gravity of lime modified samples from aggregate B greater than no lime samples at OBC. So that, the effect of hydrated lime on increasing of the bulk specific gravity vary on the aggregate type & properties.

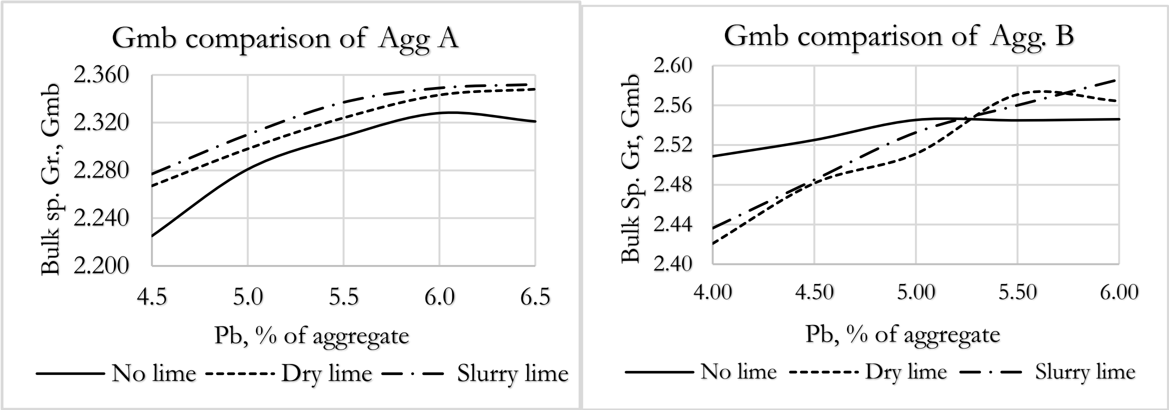


Fig 5.3: Bulk sp. Gr comparison of lime modified and unmodified samples

5.1.4. Total void in the mix (Va)

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

As observed in the figure 5.4 the lime additives have an advantage of mineral filler. The samples of aggregate A contain lime additives were always less air void compared with the normal condition. This might be due to the filler effect of hydrated lime. However the same thing is not working on aggregate B. the Va of lime modified samples on aggregate B show higher void compares with no lime samples up to it reaches on the middle point of 5.0 and 5.5 bitumen content and then after it decrease.

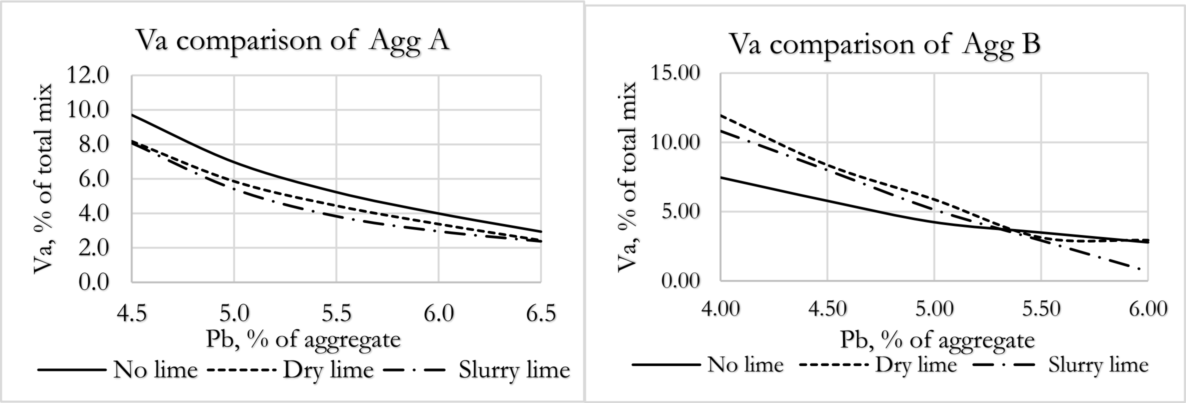


Fig 5.4: Air void comparison of lime modified and unmodified samples

5.1.5. Void in Mineral Aggregate

VMA is the total volume of voids within the mass of the compacted aggregate. This total amount of voids significantly affects the performance of a mixture because if the VMA is too small, the mix may suffer durability problems, and if the VMA is too large, the mix may show stability problems and be uneconomical to produce.

When aggregate particles are coated with asphalt binder, a portion of the asphalt binder is absorbed into the aggregate, whereas the remainder of the asphalt binder forms a film on the outside of the individual aggregate particles. Since the aggregate particles do not consolidate to form a solid mass, air pockets also appear within the asphalt-aggregate mixture. Therefore the four general components of HMA are: aggregate, absorbed asphalt, asphalt not absorbed into the aggregate (effective asphalt), and air. Air and effective asphalt, when combined, are defined as VMA.

Therefore it is not likely to hypothesize application of hydrated lime increase or decrease the VMA. Consequently, as figure 5.5 shows on aggregate A, for all bitumen content the VMA is decreases in the case of lime modified samples. In this case the resulting change in aggregate gradation due to the addition of lime modifier can contribute to a drop in VMA. Whereas on aggregate B the VMA increases for some bitumen content and decrease for another. Since the amount of variation from the control condition is not noteworthy, it has not have significant effects of durability on the overall mix.

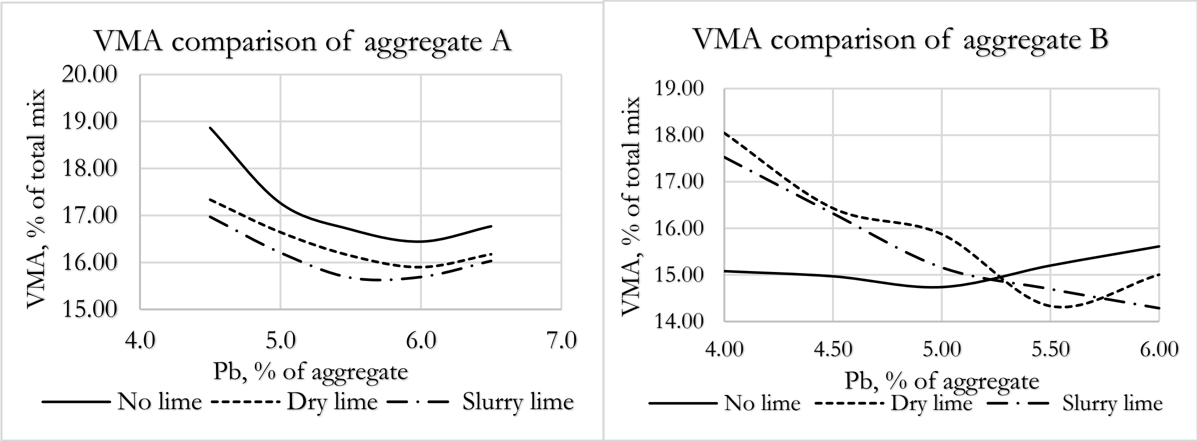


Fig 5.5: VMA comparison of lime modified and unmodified samples

5.1.6. Voids filled with Asphalt (VFA)

Voids filled with asphalt (VFA) is the percentage of inter-granular void space between the aggregate particles (VMA) that contains or is filled with asphalt. Most specifications include percent VFA requirements range from 70 - 85 percent. Since VFA depends on both VMA and V_a, the cumulative effects of these two variables are shown on Figure 5.6. The lime modified samples of aggregate A have higher VFA compared with no lime. But as in the case of VMA and Va the effect of hydrated lime on VFA of aggregate B vary with bitumen content.

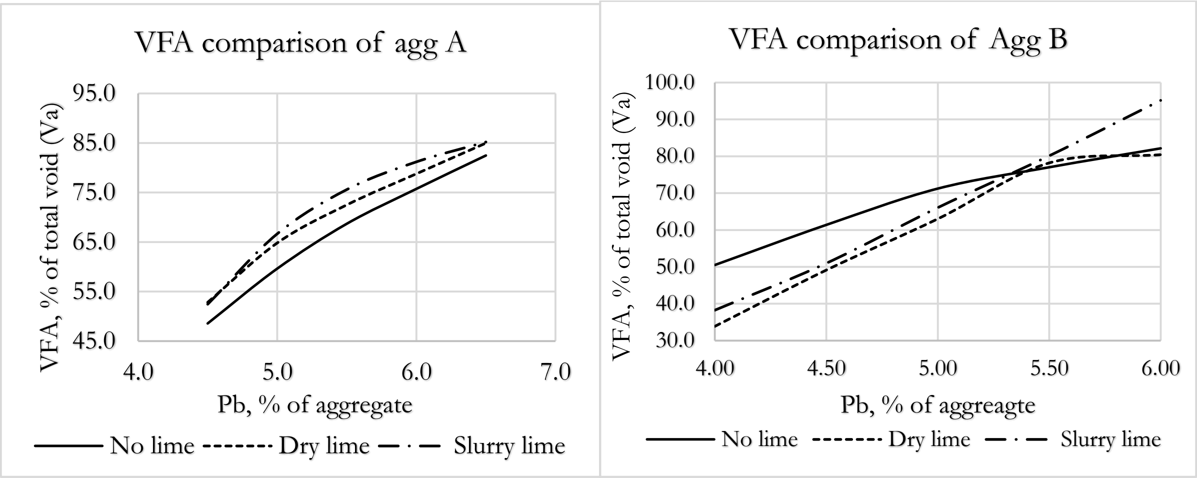


Fig 5.6: VFA comparison of lime modified and unmodified samples

5.2. Analysis of Moisture Susceptibility test results

The evaluation or comparison of this thesis consisted of laboratory testing of prepared HMA samples. This task concentrated on evaluating the impact of lime treatment on the moisture sensitivity of laboratory prepared mixtures. The experiment evaluated two methods of adding hydrated lime into HMA mixtures which were produced from each of the two sources of aggregates.

5.2.1. Tensile strength

Tensile strengths of dry and wet conditioned specimens subjected to a freeze-thaw cycle were tested for tensile strength. Both conditioned specimens were averaged and organized to produce the result on figures 5.7 to 5.14. The tensile strength results of conditioned samples have different values as compared to unconditioned specimens. For example the average tensile strength of no lime groups of both aggregate A and B dropped from 852.2 kpa to 732.02 kpa and 952.40 kpa to 685.70 kpa respectively after moisture conditioning.

The moisture susceptibility test of control groups of aggregate A have visible variation before and after moisture conditioning. After single freeze and thaw the tensile strength reduced from 852.2 to 732.06 kpa. The advantage of lime is clearly observed when comparing the tensile strength of lime modified samples with no lime (control) groups. In both cases before and after moisture conditioning the results of lime modified samples are showed some improvement over no lime samples.

Before moisture conditioning both dry lime and lime slurry groups have a value of 904.8 and 931.0 kpa respectively. Which is greater than 852.2kpa of no lime groups. Similarly after moisture conditioning dry lime groups have average tensile strength of 802.51 and lime slurry have 844.18kpa. Again both values are greater than 732.06kpa from no lime group. Just as aggregate A similar effects observed on aggregate B. In general, Figure 5.7 and 5.8 summarizes the strength gain of the three groups before and after conditioning.

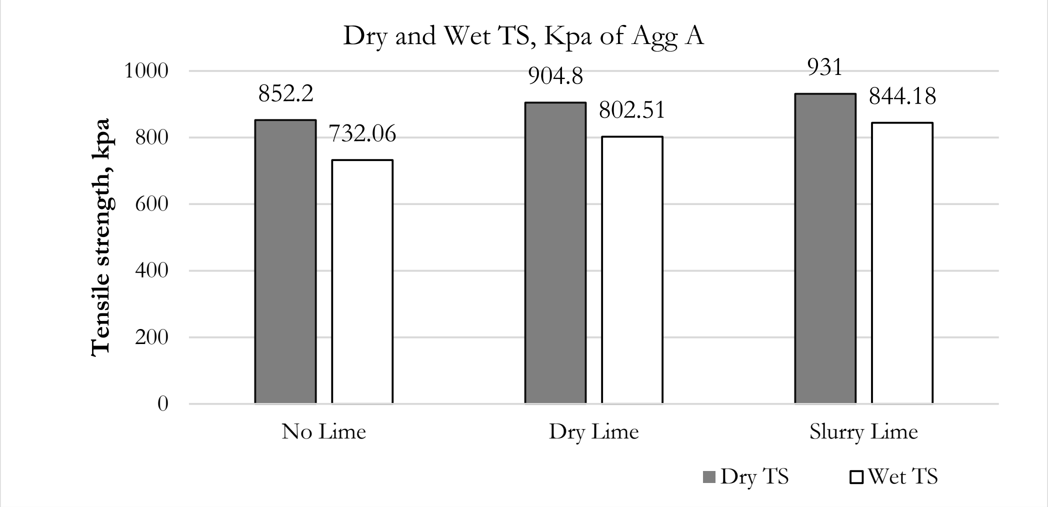


Figure 5.7: Dry and Wet tensile strength of lime modified and unmodified samples of Aggregate A before and after conditioning

From the result shown on figure 5.7 and 5.8, the lime additives that generates a higher tensile strength of the HMA mix at the dry and moisture conditioned stages will improve the long-term performance of the HMA pavement.

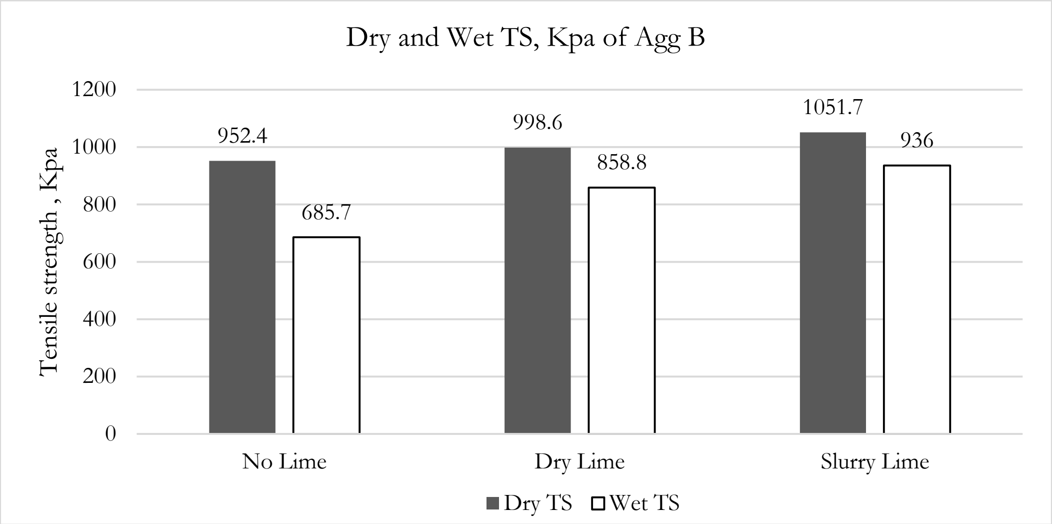


Figure 5.8: Comparison of tensile strength for different sample conditioning (lime modified and unmodified samples) of Aggregate B

The above figures explain the part of the statistical figures which compares the similar mixtures as they are subjected to different moisture conditioning processes. The other part of the statistical figures of fig 5.9 and 5.10 compares the tensile strength of the three mixtures groups as they are subjected to similar conditioning processes. For example, in figure 5.9 looking on the left comparison of the unconditioned no lime, dry lime and lime slurry mixture of aggregate A. The moisture conditioned samples also indicates on the right side of figure 5.9.

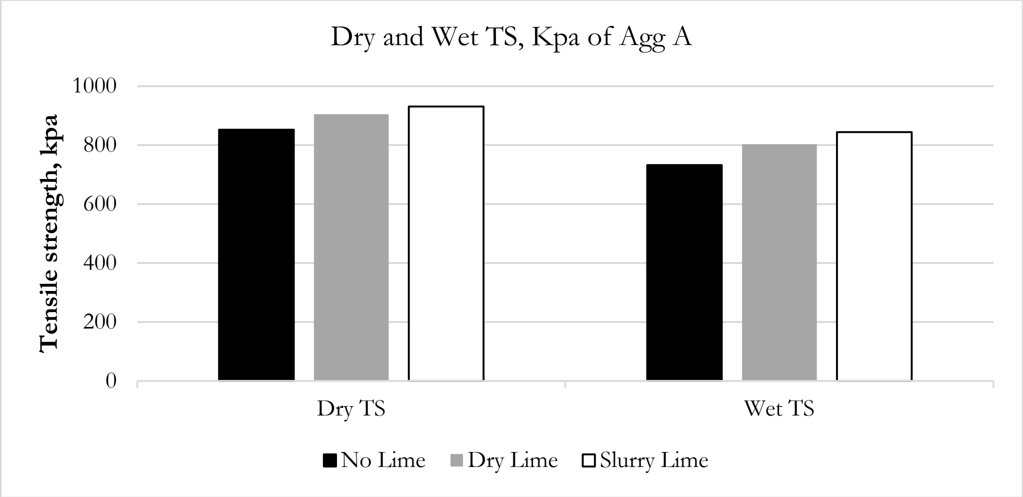


Figure 5.9: Comparison of dry and wet TS of each group of lime treatment of aggregate A

The data presenting on figures 5.9 and 5.10 provide the quick reference to evaluate the impact of lime additive and method of application on the moisture sensitivity of typical HMA mixtures. The test result indicates that in all cases (control and lime modified), both dry and wet tensile strength of lime modified samples have higher value compared with no lime or control condition. This shows the benefit of lime additives on moisture susceptibility of hot mix asphalt.

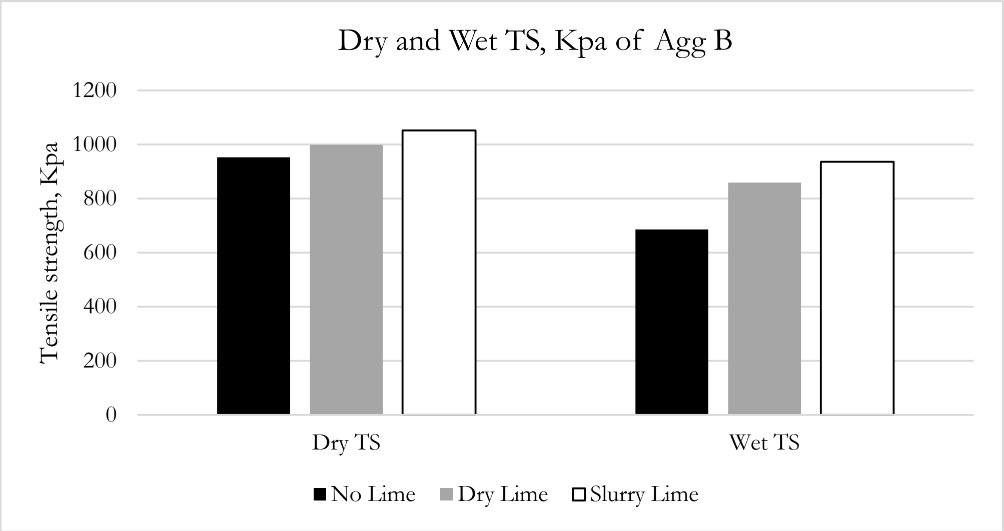


Figure 5.10: Comparison of dry and wet TS of each group of lime treatment of aggregate B

In general the tensile strength of no-lime mixture exhibits lower tensile strength than the other two groups after one freeze-thaw cycle. This is because lime enhances the bitumen-aggregate bond and improves the resistance of the bitumen itself to water-induced damage.

5.2.2. Tensile Strength Ratios (TSR)

Tensile strength ratio was another method used to analyze the indirect tensile strength data. The tensile strength ratio evaluated the amount of tensile strength retained after subjecting specimens to a freeze-thaw cycle as described in chapter 3.

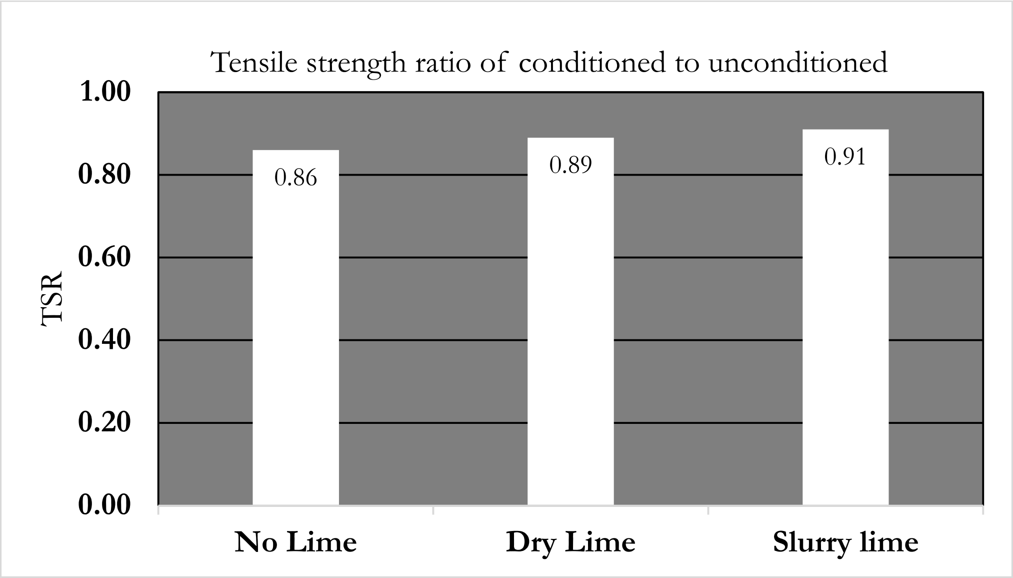


Figure 5.11: Tensile strength ratio of each cases on aggregate A

The TSR of all discrete specimens prepared for moisture susceptibility tests used in this research are shown in table 4.6 & 4.7. The result are indicated that TSR of HMA samples made from both aggregate treated with hydrated lime showed increase in all cases compared with no lime (control) conditions. The average TSR of lime treated with dry lime and lime slurry of aggregate A have a value of 0.89 and 0.91, which are greater than 0.86 of no lime (control conditions) result. Likewise on aggregate B the average TSR of lime treated with dry lime and lime slurry have value of 0.86 & 0.89. Which is also greater than no lime too. In addition to that between the two application methods little change is existing as shown in Figures 5.11 to 5.12.

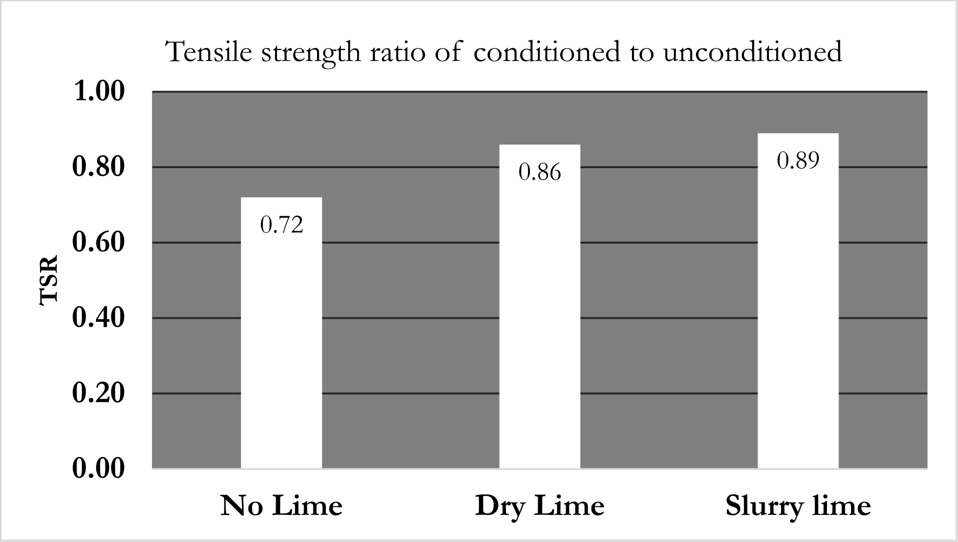


Figure 5.12: Tensile strength ratio of each cases on aggregate B

Comparing the percentage of TSR strength attainment of lime modified samples with unmodified (control) using TSR, it is obviously verify that the TSR of modified samples have always superiority on unmodified samples. The figure 4.13 and 4.14 shows the ratios of the average TSR of modified samples with unmodified

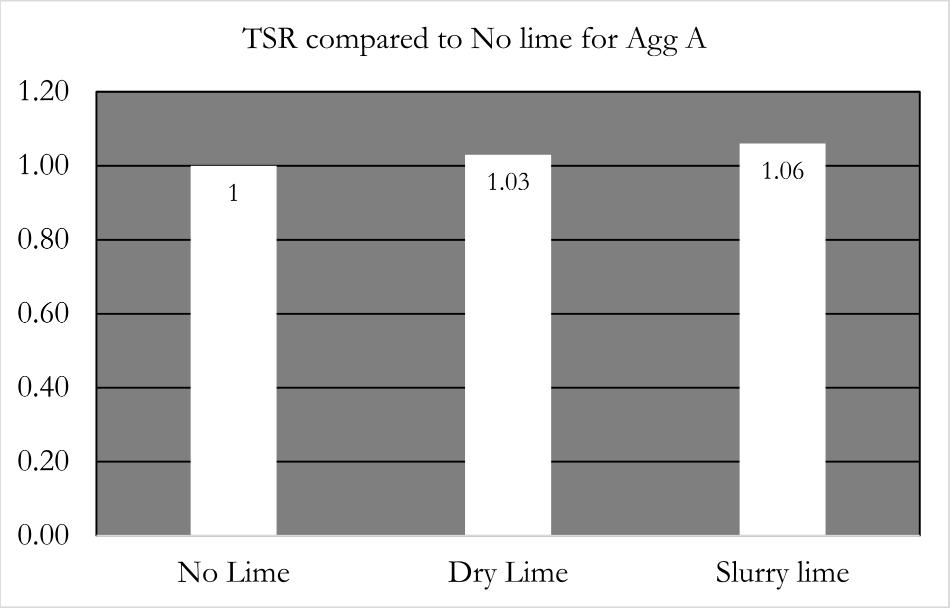


Figure 5.13: TSR compared with Control condition of aggregate A (No lime)

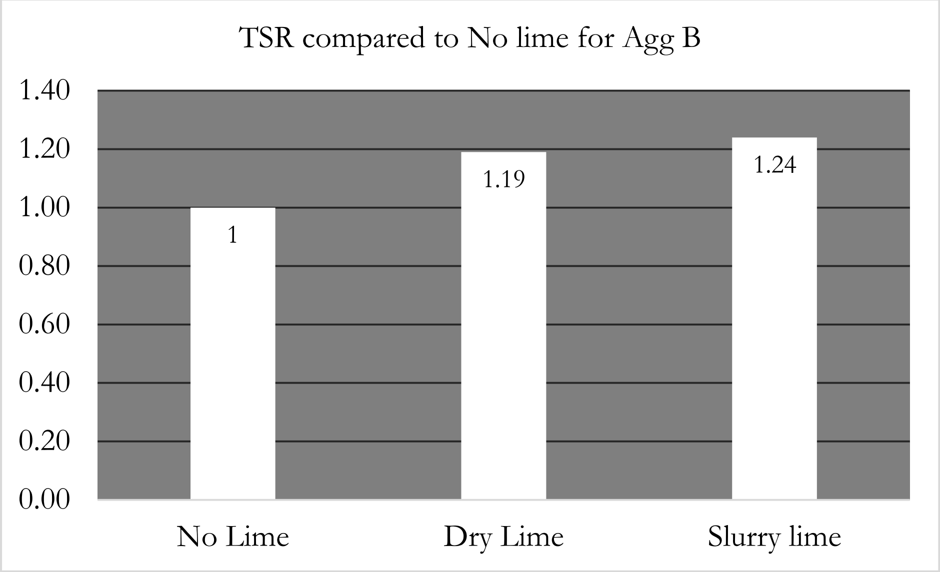


Figure 5.14: TSR compared with Control condition of aggregate B (No lime)

5.3. Statistical Analysis of Tensile Strength Using ANOVA

Following the laboratory procedures and data collection described in the previous topics, to evaluate the significance of hydrated lime additive, a statistical analysis was performed on tensile strength results performed using an Analysis of Variance (ANOVA).

A one-way ANOVA in terms of partitioning the total variation of all sample scores used in to between group and within group variation. The three groups of independent variables (no lime, dry lime and lime slurry) are considered. An individual result of the group on the dependent variable can be expressed in terms of three additive components. Therefore for this analysis the statistical model was:

$$Y_{ik} = \mu + \alpha_k + e_{ik}$$

Where
Y_{ik}= i^{th}score in thek^{th}group
μ = Grand mean of the population.
$\alpha_k = \mu_k - \mu$ = effect of belonging to group k
e_{ik}= Random error associated with this group

This linear model is an estimation of the component of one score in the population.

Testing the null hypothesis

On this research the analysis of ANOVA consists of three random samples from each of three independent groups. And the null hypothesis (H_o) is that the three methods of lime treatment (one is 'no lime') are equally effective. This refer that, there are no differences in the average performance of tensile strengths with in the three group of treatment. Therefore the null hypothesis can be set as:

$$H_o: \mu_1 = \mu_1 = \mu_2 \ldots = \mu_k$$

$$H_a: \mu_1 \neq \mu_k \text{ for some i, k}$$

In terms of the linear model, the null hypothesis could also be written

$$H_o: \alpha_1 = \alpha_1 = \alpha_2 \ldots = \alpha_k = 0$$

$$H_a: \mu_k - \mu \neq 0 \text{ for some i, k}$$

That is, there is no group effect. The null hypothesis is not rejected if the difference between the mean tensile strength of each group is attributable only to random sampling fluctuation. Using this analysis testing of the hypothesis is done at 0.05 level of significance.

The test statistics for one way ANOVA is the F ratio. Which is defined as the ratio of between group variance and within group variance (MSB/MSW). For each of the two aggregates there are three groups of lime treatment (including no lime group) and comparing of these three groups of lime treatment on individual aggregates, to use F test the collected data has 3 - 1 = 2 degree of freedom associated with MSB and 9 – 3 = 6 degree of freedom associated with MSW.

Table 5.1 to 5.4 shows the ANOVA results of aggregate A and aggregate B of three lime treatments before and after moisture conditioning of single freeze – thaw cycle.

Table 5.1: Statistical analysis of unconditioned tensile strength of aggregate A using ANOVA

Method of treatment

	NL	DL	LS	
	856.98	881.13	920.46	
	825.24	928.05	941.85	
	874.23	905.28	930.81	
n_k	3.00	3.00	3.00	N = 9.00

T_k	2556.45	2714.46	2793.12	T = 8064.03	$\frac{T^2}{N}$ = 7,225,397.7
$\overline{X_k}$	852.15	904.82	931.04	$\bar{x}$ = 896.00	
$\sum_{i=1}^{n_k} x_{ik}^2$	2,179,713.87	2,457,198.76	2,600,735.29	$\sum_{k=1}^{3}\sum_{i=1}^{3} x_{ik}^2$ = 7,237,647.92	
T_k^2/n_k	2,178,478.87	2,456,097.70	2,600,506.44	$\sum_{k=1}^{3}\frac{T_k^2}{n_k}$ = 7,235,083.01	

Calculation of sum of squares in ANOVA, one-way classification

SSB = $\frac{(2556.45)^2}{3}+\frac{(2714.46)^2}{3}+\frac{(2793.12)^2}{3}-\frac{(8064.03)^2}{9}$

= 7,235,083.01 – 7,225,397.76

= 9,685.25

SSW = 7,237,647.92 – 7,235,083.01 = 2564.91

SST= 7,237,647.92 – 7,225,397.76 =12250.16

Summary of ANOVA

Source	SS	df	MS	F	F_{cv} (for a=0.05)
Between	9,685.25	2	4,842.62	11.33	5.99
With in	2,564.91	6	427.48		
Total	12,250.16	8			

Table 5.2: Statistical analysis of tensile strength (after conditioning) of aggregate A using ANOVA

Method of treatment

	NL	DL	LS		
	699.87	787.77	837.62		
	755.73	815.96	866.50		
	740.58	803.80	828.42		
n_k	3.00	3.00	3.00	N = 9.00	
T_k	2,196.18	2,407.54	2,532.54	T = 7,136.26	$\frac{T^2}{N}$ = 5,658,469.17
$\overline{X_k}$	732.06	802.51	844.18	$\bar{x}$ = 792.92	
$\sum_{i=1}^{n_k} x_{ik}^2$	1,609,404.52	1,932,481.79	2,138,711.82	$\sum_{k=1}^{3}\sum_{i=1}^{3} x_{ik}^2$ = 5,680,598.14	
T_k^2/n_k	1,607,735.97	1,932,081.83	2,137,922.15	$\sum_{k=1}^{3}\frac{T_k^2}{n_k}$ = 5,677,739.95	

Calculation of sum of squares in ANOVA, one-way classification

SSB = $\frac{(2196.18)^2}{3}+\frac{(2407.54)^2}{3}+\frac{(2532.54)^2}{3}-\frac{(7136.26)^2}{9}$

= 5,677,738.10 – 5,658,467.42

= 19,270.68

SSW = 5,680,598.14 – 5,677,739.95 = 2,858.19

SST = 5,680,598.14 – 5,658,469.17=22,128.97

Summary of ANOVA

Source	SS	df	MS	F	F_{cv} (for a=0.05)
Between	19,270.68	2	9,635.39	20.23	5.99
With in	2,858.19	6	476.37		
Total	22,128.97	8			

Table 5.3: Statistical analysis of unconditioned tensile strength of aggregate B using ANOVA

Method of treatment

	NL	DL	LS		
	948.30	1064.70	1084.50		
	922.80	972.80	1021.20		
	986.10	958.30	1049.40		
n_k	3.00	3.00	3.00	N = 9.00	
T_k	2857.20	2995.80	3155.10	T = 9008.10	$\frac{T^2}{N}$ = 9016207.29
$\overline{X_k}$	952.40	998.60	1051.70	$\bar{x}$ = 1000.90	
$\sum_{i=1}^{n_k} x_{ik}^2$	2723225.94	2998264.82	3320230.05	$\sum_{k=1}^{3}\sum_{i=1}^{3} x_{ik}^2$ = 9041720.8100	
T_k^2/n_k	2721197.28	2991605.88	3318218.67	$\sum_{k=1}^{3}\frac{T_k^2}{n_k}$ = 9031021.8300	

Calculation of sum of squares in ANOVA, one-way classification

SSB =	$\frac{(2857.20)^2}{3}+\frac{(2995.80)^2}{3}+\frac{(3155.10)^2}{3}-\frac{(9008.10)^2}{9}$
=	9031021.83 – 9016207.29
=	14814.54
SSW =	9041720.8100 – 9031021.8300 = 10698.98
SST=	9041720.8100 – 9016207.29= 25513.52

Summary of ANOVA

Source	SS	df	MS	F	F_{cv} (for a=0.05)
Between	14814.54	2.00	7407.27	4.15	5.99
With in	10698.98	6.00	1783.16		
Total	25513.52	8.00			

Table 5.4: Statistical analysis of tensile strength (after conditioning) of aggregate B using ANOVA

Method of treatment

	NL	DL	LS		
	688.40	864.50	954.30		
	666.10	823.10	895.70		
	702.60	888.80	958.00		
n_k	3.00	3.00	3.00	N = 9.00	
T_k	2057.10	2576.40	2808.00	T = 7441.50	$\frac{T^2}{N}$ = 6152880.25
$\overline{X_k}$	685.70	858.80	936.00	$\bar{x}$ = 826.83	
$\sum_{i=1}^{n_k} x_{ik}^2$	1411230.53	2214819.30	2630730.98	$\sum_{k=1}^{3}\sum_{i=1}^{3} x_{ik}^2$ = 6256780.8100	
T_k^2/n_k	1410553.47	2212612.32	2628288.00	$\sum_{k=1}^{3}\frac{T_k^2}{n_k}$ = 6251453.7900	

Calculation of sum of squares in ANOVA, one-way classification

SSB =	$\frac{(2057.10)^2}{3}+\frac{(2576.40)^2}{3}+\frac{(2808.00)^2}{3}-\frac{(7441.50)^2}{9}$
=	6251453.79 – 6152880.25
=	98573.54
SSW =	6256780.8100 – 6251453.7900= 5327.02
SST=	6256780.8100 – 6152880.25 = 103900.56

Summary of ANOVA

Source	SS	df	MS	F	F_{cv} (for a=0.05)
Between	98573.54	2.00	49286.77	55.51	5.99
With in	5327.02	6.00	887.84		
Total	103900.56	8.00			

The decision to accept or reject the null hypothesis (H_o) is made by comparing the test statistics (computed F ratio) with critical value from the table. If the computed F ratio is exceeds the critical value, the hypothesis is rejected; if not, the hypothesis is not rejected.

The ANOVA result of tensile strength data collected in laboratory on both aggregates before and after conditioning indicates that, on all cases except the unconditioned F value of aggregate B the observed value of the test statistics, the F ratio exceeds the critical value at 0.05 level of significance, and therefore the null hypothesis is rejected. Hence this research accepted that lime additive on HMA have an effects on the moisture susceptibility of HMA.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the use of lime additive to improve the resistance of HMA against moisture-induced damage and important physical properties of HMA. Using standardized testing procedures, aggregate was tested for all the necessary quality tests including specific gravity, absorption, abrasion resistance, void content, and gradation. Similarly important quality tests of bitumen were conducted in a laboratory and all the results were pass the necessary specifications.

The scope of this thesis was a bit large in terms of the number of tests conducted on lime additive. For each of the two aggregate 3 mix designs were prepared to select the optimum bitumen content. Then after for the selected optimum bitumen content the moisture susceptibility test of specimens were complete for modified and unmodified samples.

The goal of this research analysis was to assess the impact of adding lime on the tensile strength properties of the HMA mixtures regardless of the method of application. This analysis will try to answer the question of whether lime is effective in increasing the performance and reducing the moisture sensitivity of the HMA mixtures irrespective of which application method is used. On the basis of test results and analysis obtained in a controlled laboratory, the following conclusions and recommendations are presented:

6.1. Conclusions

1. In all study comparisons with in the controlled laboratory, moisture conditioned lime treated mixes had an improved ability to retain the mechanical property of tensile strength and the untreated mixtures to some extent lower than the properties of the lime-treated mixtures. Therefore based on these data, it can be concluded that for selected aggregate the lime treatment was effective in reducing the moisture sensitivity of hot mixtures asphalt irrespective of which application method is used.
2. The result of stability on this research has exhibited that hydrated lime improve the resistance of the HMA to permanent deformation damage at high temperatures, especially during its early life when it is most susceptible to rutting. This is due to filler effect of the lime with in the asphalt and it gives extra power to improve an advantage on rut resistance.
3. Both dry and slurry lime treated samples had higher stability than control or no lime methods. In addition to that, tensile strength ratios of both dry lime and slurry lime were higher than those for the control for all variations. However, comparing the application of dry lime and lime slurry, the result on both groups have not large deviation to each other, therefore it is not conclusive evidence weather dry lime or lime slurry marinated for 48 hours, as a superior technique for the introduction of hydrated lime into a HMA mix.
4. In general from this research there is an indication that, hydrated lime is an additive that increases pavement life and performance through multiple mechanisms.

6.2. Recommendation

Asphalt pavements are a crucial part of our nation's strategy for building a high performance transportation network for the future. Asphalt construction is fast and relatively simple, it is economical and the materials to make it are widely available. Based on this important assets of HMA the following recommendation are given for further research.

- The advantage of hydrated lime conducted on this research evaluate the additive based solely on short term retained strengths following moisture conditioning (AASHTO T 283). This does not represent long term performance of an asphalt, which is influenced by factors other than reduced moisture sensitivity such as resistance to load induced fatigue cracking or low temperature cracking. There is a pressing need for a simple and repeatable test that can evaluate the effects of hydrated lime additives on the pavement performance.
- Hydrated lime may be added in the HMA production process in several ways. Many different methods have been used successfully. Even though the result finding on this research shows that adding lime as dry lime on moist aggregate or slurry lime on dry aggregate have good result it is more preferable to use slurry lime. This is because of all aggregate surface have a chance to coat uniformly. But it shouldn't forget that it needs high energy to dry the aggregate and special equipment for preparation of the slurry.
- In general, the researcher believes that modifying hot mix asphalt with hydrated lime will add years to pavement life. However, this advantages of hydrated lime additive is not well understood and used in our country. Therefore highway engineers and contractors all other concerned bodies should consider hydrated lime's role in improving the long-term performance and durability of pavements.
- Further research should be performed to study effectiveness of the hydrated lime especially on the moisture related failures of HMA mixtures and the effect in durability, rutting and etc...

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