Investigating the Compactability of Hot Mix Asphalt Utilizing the Concept of the Locking Point

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DEDICATION

To Margarita and Estefania

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ABSTRACT

Compaction is an important process for the asphalt mixture service life. An adequately compacted mixture is crucial for long-lasting pavement. Compaction is a procedure utilized to compress and decrease the material's volume, which provides essential ingredients that influence the pavement's performance. During asphalt mix compaction, the aggregate coated with asphalt binder are compressed together, following an increase of interparticle friction and surface contact and finally interlocking to provide the resistance to deformation. At the same time, the permeability is decreased, and the durability is increased. Compactability is utilized to evaluate how much compaction energy is required to compact asphalt mixture. Locking point is an important concept in selecting a proper aggregate gradation in the asphalt mixture design. The locking point can be defined as the moment during asphalt mixture compaction at which an aggregate structure becomes stable. Beyond this point, further compaction does not contribute much to the increase in mixture density and can even damage aggregate particles. To better understand the compactability and interlocking properties of the hot mix asphalt, the overall objectives of this study are: to develop the method that permits determination of the locking point when impact compaction method is applied, acquire an understanding of the interlocking characteristics of aggregate structure through routine mix design procedure that includes different variables: mixture type, aggregate gradation and angularity, asphalt binder, mixing sequence and compaction method, establish the acceptable over-compaction for common

materials utilized in Tennessee, and to quantify the interlocking between aggregates particles by 2D and 3D image processing. The results of this study give a better understanding of the compactability and interlocking of asphalt mixtures.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

GENERAL INTRODUCTION

Problem Statement

Hot Mix Asphalt (HMA) is a composite material typically utilized in road construction. The basic components of HMA are aggregate, asphalt cement, and air. The asphalt mix design has been implemented and continuously improved since then. The mix design aims to balance aggregates, asphalt cement, and air, which would provide adequate durability, flexibility, stability, permeability, and workability. The most common mix designs achieve this balance only by judging the volumetric properties. During the twentieth century, many mix design methods were developed, which improved the knowledge about asphalt mixture behavior. Except for improving compaction methods to simulate field compaction better, there was little effort to understand the compaction process, compactability, and interlocking of aggregates.

Compaction is a procedure utilized to compress and decrease the material's volume, which provides essential ingredients that influence the pavement’s performance. During asphalt mix compaction, the aggregate coated with asphalt binder are compressed together, following an increase of interparticle friction and surface contact and finally interlocking to provide the resistance to deformation. At the same time, the permeability is decreased, and the durability is increased. In dense-graded mixtures, the decrement of air void to the designed level can guarantee a flexible pavement characterized by imperviousness. For poorly compacted dense-graded mixtures, it is typical for mixtures with connected air voids. This interconnection permits water and solvents to penetrate the asphalt layer even the entire pavement structure and causes damage or at least a shorter pavement service life by causing asphalt binder oxidation, cracking, premature aging, and stripping. If the water reaches the base course, it can decrease the strength or damage by the freeze-thaw cycle. Besides, the insufficient compaction during construction will result in further densification by the traffic. However, traffic compaction is mostly applied in the wheel paths and can result in a safety hazard, especially during rainy weather or night. Over-compaction can be defined as additional energy applied to the asphalt mixture, which might damage the newly developed aggregate skeleton (Bonnot 1997; Roberts et al. 1991).

Most mix design methods allow successful design, production, placement, and asphalt mixtures by specifying asphalt cement and aggregate quality and volumetric requirements. However, currently, there is no mix design process dedicated to the aggregate structure or the relation between aggregate structure and compactability or performance of the asphalt mixture. It is imperative to understand the compaction process and compactability of asphalt mixture to improve workability and performance.

Objectives

To better understand the compactability and interlocking properties of the hot mix asphalt, the overall objectives of the proposed study are:

- Develop the method that permits determination of the locking point when the impact compaction method is applied.

- Acquire an understanding of aggregate structure's interlocking characteristics through routine mix design procedure that includes different variables: mixture type, aggregate gradation and angularity, asphalt binder, mixing sequence, and compaction method.
- Establish the acceptable over-compaction for common materials utilized in Tennessee.
- Quantify the interlocking between aggregates particles by 2D and 3D image processing.

Research Questions

This study addresses the compaction behavior, compactability, and interlocking of asphalt mixture based on the laboratory experiments. For the research contained in this dissertation, the following research questions were asked:

- How can the impact compaction process be monitored and characterized?
- How do aggregate properties affect compactability and the locking point of the asphalt mixture?
- How does the asphalt binder affect compactability and the locking point of the asphalt mixture?
- Does the over-compaction lead to aggregate damage?
- Can image processing give insight into the internal aggregate structure at the locking point?

Organization

This work is divided into ten chapters, as follow:

- Chapter One defines the problem, research questions, objectives, and outline of this study.
- Chapter Two includes a literature review on the compaction of Hot Mix Asphalt.
- Chapter Three describes the development of the method to determine the locking point for impact compaction.
- Chapter Four describes the influence of aggregate gradation on compactability of asphalt mixture
- Chapter Five describes the influence of aggregates angularity on compactability of asphalt mixture
- Chapter Six describes the influence of asphalt binder on the compactability of asphalt mixtures
- Chapter Seven includes the analysis of the resistance of aggregate and asphalt mixture to over-compaction.
- Chapter Eight includes the characterization of aggregate interlocking in asphalt mixture by mechanistic performance tests.
- Chapter Nine includes quantification of asphalt mixture interlocking utilizing 2D and 3D image processing.
- Chapter Ten concludes the findings of this work and provides recommendations for future research.

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Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D.-Y., and Kennedy, T. W. (1991). "Hot mix asphalt materials, mixture design and construction."

CHAPTER TWO

LITERATURE REVIEW

Disclaimer: Portions of this chapter will be repeated in subsequent chapters.

History of Asphalt Mixtures

The history of asphalt mix design had started at the beginning of the twentieth century when the industry realized the importance of correct mix design. Asphalt mix design is the process of determining the optimum proportions of asphalt cement, coarse aggregates, and fine aggregates for creating well-performing and long-lasting pavements. The first method to determine optimum binder content in the asphalt mix was the pat test, which was highly imprecise based on visual appraisement. However, for asphalt mix designing pioneers, it still served as a useful tool for improving asphalt quality and performance. Based on that, the bitulithic pavement (Figure 2.1) was developed and patented by Federick Warren. This mix incorporated large stones up to three inches, allowing lower asphalt cement consumption and a lower price (Brown et al. 2009)

Another method, the Hubbard-Field test, named after the Asphalt Institute's inventors and members, was used to establish the optimum components, especially for fine-graded mixes. This method was popular in designing asphalt mixes in many states until it was replaced by the Marshall method (INSITUTE 2007; Institute 2007)

The 1930s were characterized as an important decade for asphalt mix design development. During this period, the Hveem and the Marshall mix design methods were developed and dominated the paving industry in the United States and the rest of the world for over fifty years. Invented by Francis Hveem, the

Figure 2.1. Bitulithic pavement placement process. Tampa, Florida (1920s.)

Hveem design method was based on three principles: the asphalt mix needs sufficient asphalt cement to cover each aggregate particle with optimum thickness; the asphalt mix needs enough stability to support traffic load; and finally, as the thickness of the asphalt cement film increases, its durability also increases. Hveem's method was used by 25% of States in the United States, especially on the West Coast until 1990. The Marshall method was developed by Bruce Marshall around 1939 and improved by the Corps of Engineers of the United States Army. This design method uses values of flow, stability, and density to define optimum asphalt cement content. The Marshall mix design method was the most widely used method to design asphalt mix in the United States (75% of all States utilized this method) until 1990 as it started to be gradually replaced with the Superpave method (Brown et al. 2009; Institute 2007; Institute 2014).

The Strategic Highway Research Program developed the Superpave design method with 150 million dollars from 1987 to 1992. Since all existing mix design methods were empirical methods based on observations and experiences, this new method was expected to design asphalt mixes with more predictable performance. This research program's main research topics included traffic volume and speed, long-term and short-term aging, climatic effects, including a wide range of temperatures during production, compaction, and service. The Superpave introduced two crucial innovations in the equipment: the gyratory compactor, which simulates the compacting process more efficiently than the Marshall hammer, and a new mold with a diameter of 6" compared with the

Marshall method’s 4” diameter mold (Figure 2.2). The Superpave design method has been gaining territories in the United States Since 1990, most of the States have switched to this design method (Brown et al. 2009; Fishbaugh 1920; Institute 2007).

Compaction of Asphalt Mixture

Compaction is a procedure utilized to compress and decrease the material's volume, which provides essential ingredients that influence the pavement’s performance. During asphalt mix compaction, the aggregate coated with asphalt binder are compressed together, following an increase of interparticle friction and surface contact and finally interlocking to provide the resistance to deformation. At the same time, the permeability is decreased, and the durability is increased. In dense-graded mixtures, the decrement of air void to the designed level can guarantee a flexible pavement characterized by imperviousness. For poorly compacted dense-graded mixtures, it is typical for mixtures with connected air voids. This interconnection permits water and solvents to penetrate the asphalt layer even the entire pavement structure and causes damage or at least a shorter pavement service life by causing asphalt binder oxidation, cracking, premature aging, and stripping. If the water reaches the base course, it can decrease the strength or damage by the freeze-thaw cycle. Besides, the insufficient compaction during construction will result in further densification by the traffic. However, traffic compaction is mostly applied in the wheel paths and can result in a safety hazard, especially during rainy weather or night. Over-compaction can be defined as

Figure 2.2. Superpave specimen on the left and Marshall specimen on the right

additional energy applied to the asphalt mixture, which might damage the newly developed aggregate skeleton (Bonnot 1997; Roberts et al. 1991).

Figure 2.3 presents the optimum range of air voids for field asphalt mixture compaction. The range of 4% to 8% is for dense-graded mixtures, and when the stone matrix asphalt is compacted, the target air voids content should be at least 6%. Asphalt mixture compacted to the optimum air voids range should have terminated the interconnection between air voids, and the damage due to water or solvents are limited (Roberts et al. 1991). The compaction process can be affected by many factors such as asphalt cement and aggregates properties, mix type, compaction temperature, lift thickness, base course properties, and environmental conditions. Asphalt cement properties change with temperature, which means a specific range where viscosity permits adequate compaction by providing lubrication between particles during the compaction process. Low temperature prevents aggregate particles from moving, and the required density is impossible to achieve (Bonnot 1997).

The aggregate properties substantially impact asphalt mixture performance because the aggregate is a significant portion in an asphalt mixture (around 95% by mass or between 80% and 90% by volume). Aggregate characteristics can be divided into four groups: strength, texture, shape, and angularity, as shown in Figure 2.4 (Sukhwani et al. 2006). The angularity of aggregate plays a critical role in asphalt mixture performance. It thus is one of the most important parameters in asphalt mix design, especially the Superpave Mix Design Method. Figure 2.4

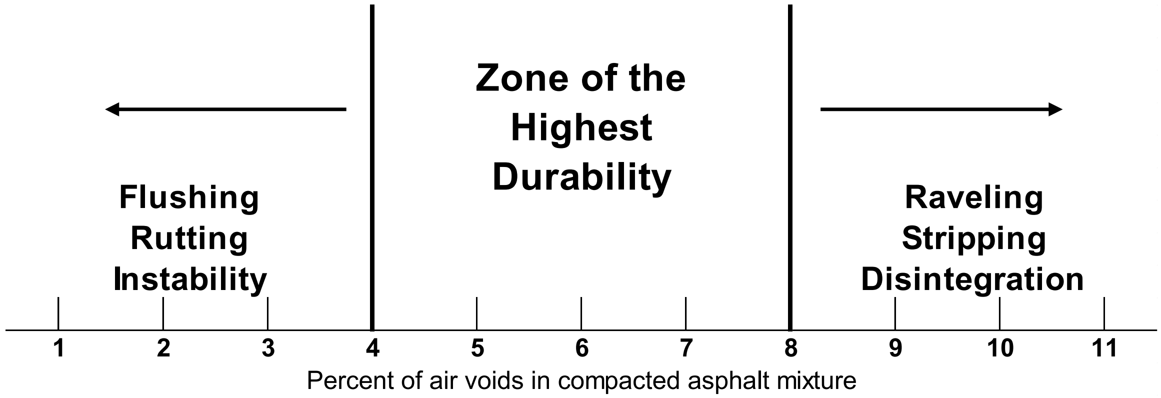

Figure 2.3. Pavement durability versus air voids

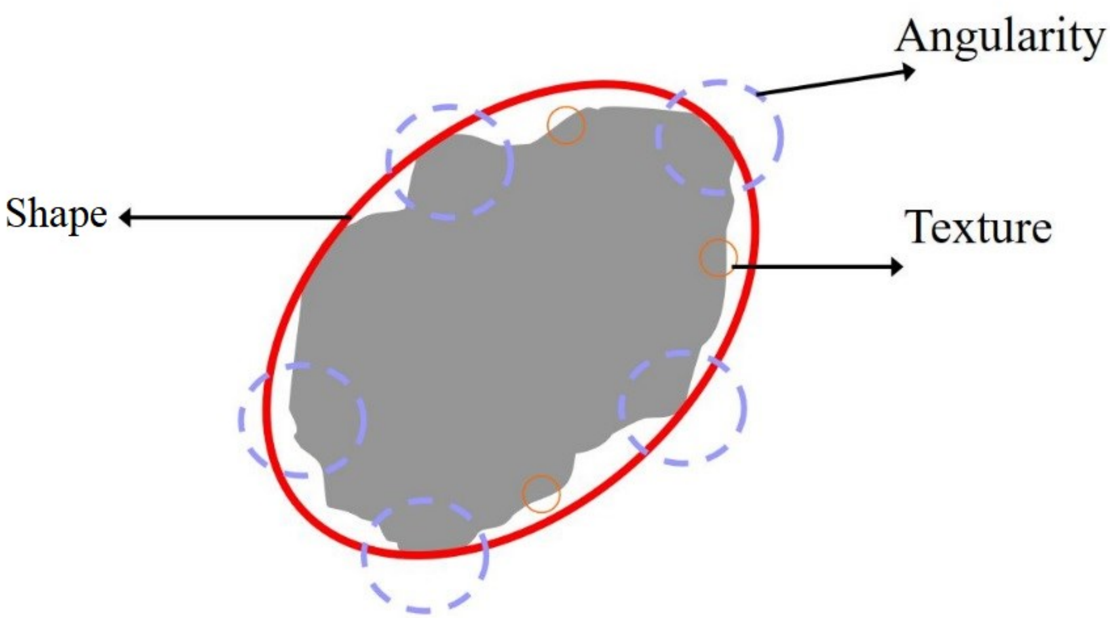

Figure 2.4. The aggregate characteristics (Sukhwani et al. 2006)

shows that aggregate angularity is defined as the sharpness of an aggregate particle (Kim and Souza 2009; Meier and Elnicky 1988).

Aggregate particles with low angularity generate fewer interparticle contact points, which improves the workability of asphalt mixtures and makes them easier to compact. However, asphalt mixture designers should look for a balance between aggregate angularity and mixture compaction because interlock is required to prevent rutting after construction. In a properly designed asphalt mixture, aggregates' composition should develop a stable aggregate skeleton for sufficient shear resistance and proper workability for adequate compaction (Huang et al. 2009).

Aggregate gradation has an important influence on asphalt mixture compactibility. Poor gradation can cause a variety of problems during production, transport, placing, and compaction. One of them is a tender mixture. These mixes are difficult to compact because of how slowly the mix develops enough strength to resist the rollers’ weight. Other problems caused by poor gradation are unstable mixtures sensitive to even a small excess of asphalt or water, harsh mixtures that tend to segregate (Brown et al. 1989; Gong et al. 2019).

Gradation is the allocation of different sizes of particles defined as the percent of total weight. Different dense-graded mixtures can be classified as coarse-graded or fine-graded. This classification is based on the maximum density line; the gradation on the coarse side is coarse-graded, and on the fine side is defined as fine-graded. Gradation is one of the most important parameters for asphalt mix design and, in most cases, the first step in the design process. Most agencies worldwide have established the permitted gradation range for each type of mixture, based on pavement structure, traffic, or climate condition. These gradation limits assure good quality of asphalt mixtures such as resistance to moisture damage, enough friction, fatigue and rutting resistance, stiffness, stability, and permeability (Jiang et al. 2019).

Asphalt binder has an important influence on the properties of asphalt mixture, even that it constitutes only around 5% of the total mass. The two most important qualities provided by asphalt binders are adhesion and lubrication. Adhesive properties of asphalt binder provide bonding between aggregates particles after compaction. Lubrication decreases friction forces and allows a more workable mixture. Friction is a force that opposes the movement of solid surfaces against each other. The surface of aggregates that are not crushed may appear plane, but there are always microscopic irregularities. When two aggregate surfaces are touching each other under pressure, these irregularities in the form of asperities or peaks make the friction force increase. These forces greatly depending on the material type utilized in the mixture (shape, texture, and angularity). The ratio of the friction force to the normal force is the coefficient of friction. This coefficient is an empirical value and must be measured for every different material. The river gravel provides less friction than a crushed material and has a lower friction coefficient. Asphalt binder decreases the coefficient of friction of aggregate during mixing and compaction, allowing the aggregate skeleton’s development and providing required volumetric properties of asphalt mixture (Al-Khateeb 2018; Leiva and West 2008; Roberts et al. 1991).

The mixing process is another important factor that influences the properties of the asphalt mixture. The inadequate mixing can impact various properties of asphalt mixes, like homogeneity, adhesion, and film thickness, that can lead to problems during compaction and later during the service period, affecting the performance of asphalt layers. Thicker asphalt film provides more flexible and durable mixes, while thinner asphalt coat yields a mix that is brittle and easy to crack. The research on bitumen and aggregates properties and their influence on characteristics of asphalt mixes have a long history. However, the mixing process had significantly less research effort. Commonly, the research assumes that the asphalt mix is a homogenous material, but only adequate mixing procedures can provide more unvarying material. The most common practice worldwide to produce asphalt mixtures is to mix the aggregates and second inject asphalt binder and permit further mixing. It is a popular and easy method favored by contractors and asphalt plant manufacturers, even that the risk of not evenly distributed film thickness and segregation is present.

The alternate method of mixing was developed in Sweden by Ohlson. The altered mixing order consists of three steps. First, the coarse aggregates are mixed with asphalt binder, which permits the largest particles’ adequate coating. Second, the filler is added to create the mastic. Third, fine aggregates are added. This alternate mixing sequence can provide more homogenous mixtures and more uniform film thickness, especially for larger aggregates (Anderson 2008; Hesami et al. 2015; Ohlson 2010).

The improvement in film thickness distribution for larger stones may positively affect the compactability of asphalt mixtures by providing additional lubrication and decreasing the compaction energy requirement. Further advantages are lowering the mixing temperature and more homogenous final product. For a more extended period, it can also bring environmental and economic benefits. The research conducted on asphalt mixtures mixed traditionally and alternatively indicated that alternative mixing provides an even air distribution through the specimen. It can indicate easier compaction (Anderson 2008; Elseifi et al. 2008; Hesami et al. 2015; Ohlson 2010).

Another key factor of successful compaction is mix design. The history of asphalt mix design dates to the beginning of the twentieth century when pioneers that worked with asphalt, based on their previous experiences, realized the importance of adequate dosage of mix components. Asphalt mix design determines the optimum proportions of asphalt cement, coarse aggregates, and fine aggregates, allowing for well-performing and long-lasting pavements (Roberts et al. 1991).

The first method to determine optimum binder content in the asphalt mixture was the pat test, which was highly imprecise based on visual appraisement. Still, for the earliest asphalt mix designers, it permitted high advancement in quality and performance. Around the same time, the bitulithic pavement was developed and patented by Federick Warren. This mix incorporated large stones up to three inches, allowing lower asphalt cement consumption and a lower price (Bonnot 1997).

The threshold for the asphalt industry development was Bruce Marshall's invention of a new design method. For over 50 years, Marshall Asphalt Mix Designs dominated the United States and the world paving industry. Internationally, the Marshall method is still the top choice for designers. Two generations of engineers, specialists, and experts utilized this design method without a profound understanding of the impact compaction process.

Asphalt mixtures have been used in pavement construction since the beginning of the twentieth century. Various studies have been conducted to evaluate the compactability of these mixtures when different compaction methods are applied, including refusal density, kneading, and impact compactors. The introduction of the Superpave Gyratory Compactor (SGC) in the 1990s made it possible to monitor specimen height changes during compaction and better understand the process. Most of the methods for compaction study are based on the densification curve obtained from SGC compaction. This curve represents the change in the specimen's height after each gyration, which can be later translated into a change in density or compaction (Leiva and West 2008; Mallick 1999).

Parameters to define the compactability of asphalt mixture

Before the SGC was developed by the Strategic Highway Research Program in the early 1990s, there was little effort to understand compaction processes or the compactability of asphalt mixtures. The lack of research effort can be attributed to the absence of equipment capable of providing sufficient data. The most widely used design methods in the pre-Superpave era were the Hveem and the Marshall Methods. The Hveen Method uses a kneading compactor, and the Marshall Method uses an impact hammer to prepare samples. Neither of these provides sufficient data to evaluate compactability (Roberts et al. 2002).

Various methods have been proposed to evaluate the compactability of asphalt mixtures. The Construction Densification Index (CDI) and the Transportation Densification Index (TDI) were introduced by Bahia et al. (1998). The CDI represents the effort required to compact an asphalt mix to 92%, while the TDI represents the energy required for vehicles to further compact from 92% to 98% during the service period. The CDI is the area under the densification curve limited by eight gyrations and compaction of 92%. The CDI can also be understood as the area under the densification curve with compaction in the range of 88% to 92%. The TDI is defined as the area under the densification curve with compaction in the range of 92% to 98%. In practice, the CDI represents the effort required to compact asphalt mix, while the TDI represents the compaction of an asphalt mix by traffic to 98%. Figure 2.5 shows the determination of CDI and TDI from a densification curve.

The next method, the Slope of Densification Curve, was presented by Anderson et al. (2002). The densification curve plotted logarithmically can describe the shear resistance of an aggregate's structure (Anderson et al. 2002).

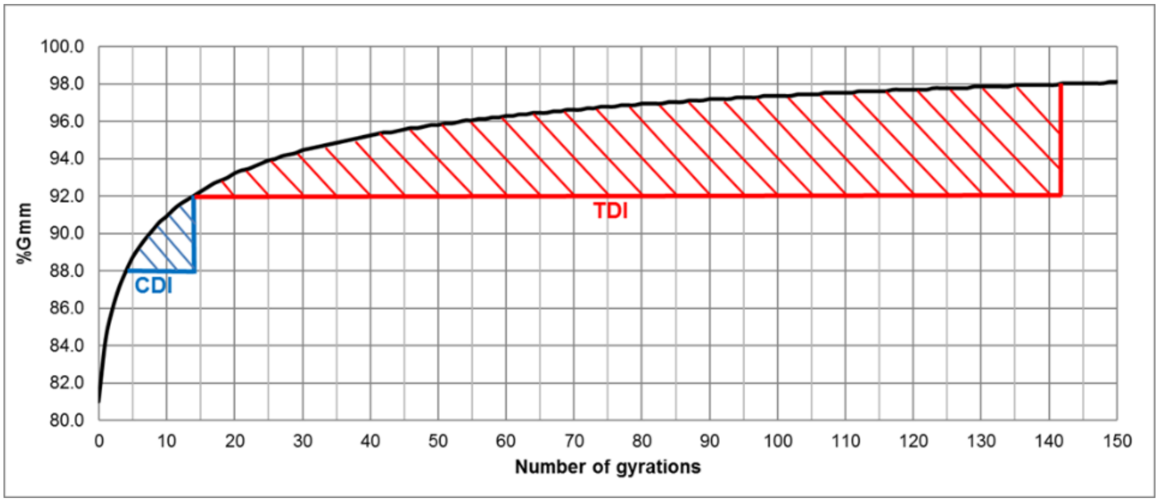

Figure 2.5. Determination of CDI and TDI from a densification curve

Another method utilized by Leiva and West 2008, is the number of gyrations to reach 92% compaction. It is widely accepted that an asphalt mix should be compacted in the field until it reaches minimum compaction of 92%. It is expected that a mix is easy to compact up to 92%, allowing contractors to utilize less energy during construction. A mix becomes harder to compact above 92%, to better resist further compaction by traffic.

An important concept found in the literature regarding compaction is the concept of the locking point. This concept will be discussed in the next section.

The Locking Point

Various methods have been proposed to evaluate the compactability of asphalt mixtures. The Construction Densification Index (CDI) and the Transportation Densification Index (TDI) were introduced by Bahia et al. (1998). The CDI represents the effort required to compact an asphalt mix to 92%, while the TDI represents the energy required for vehicles to further compact from 92% to 98% during the service period. The CDI is the area under the densification curve limited by eight gyrations and compaction of 92%. The CDI can also be understood as the area under the densification curve with compaction in the range of 88% to 92%. The TDI is defined as the area under the densification curve with compaction in the range of 92% to 98%. In practice, the CDI represents the effort required to compact asphalt mix, while the TDI represents the compaction of an asphalt mix by traffic to 98%.

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An important concept found in the literature regarding compaction is the concept of the locking point. During compaction, aggregates are brought together. A skeleton is developed made of coarse aggregates interlocked with each other—the point at which aggregates interlock is defined as the locking point. Initially, the locking point was proposed by William J. Pine, the engineer of the Illinois Department of Transportation (Vavrick et al. 2002). The locking point determines a point on the densification curve beyond which the mix skeleton starts to resist compaction. Different asphalt mixtures lock up at a different number of gyrations. It is desirable for the locking point to be close to the roller's final field compaction. Such asphalt mix permits easier field compaction by contractors and provides resistance to loads from traffic. Many ways of determining the locking point have been proposed. Mohammad and Al-Shamsi (2007) report that the Alabama Department of Transportation describes the locking point as when the sample being gyrated loses less than 0.1 mm between gyrations. The Georgia Department of Transportation describes the locking point as the number of gyrations at which the same height repeats three times. Vavrik and Carpenter (1998) introduced the most common practice, defining locking point as the first gyration in the first set of three gyrations at the same height, preceded by two sets of two gyrations at the same height. **Error! Reference source not found.** shows an example of the l ocking point determination.

Before the SGC was developed by the Strategic Highway Research Program in the early 1990s, there was little effort to understand compaction processes or the compactability of asphalt mixtures. The lack of research effort can be attributed to the absence of equipment capable of providing sufficient data. The most widely used design methods in the pre-Superpave era were the Hveem and the Marshall Methods. The Hveen Method uses a kneading compactor, and the Marshall Method uses an impact hammer to prepare samples. Neither of these provides sufficient data to evaluate compactability (Roberts et al. 2002).

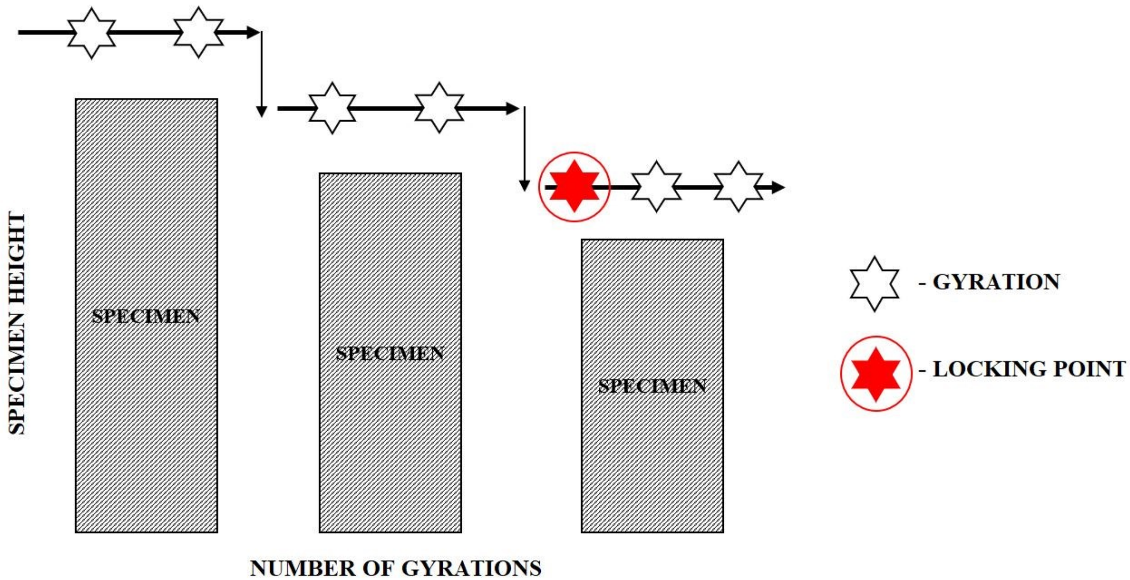

Figure 2.6. Diagram of the locking point determination

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CHAPTER THREE

DEVELOPMENT OF THE METHOD TO DETERMINE THE LOCKING POINT FOR IMPACT COMPACTION

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My contribution to this paper was performing majority of the experimental tests, data analysis, and preparing the original draft and all figures and tables.

Abstract: Locking point is an important concept in selecting a proper aggregate gradation in the asphalt mixture design. The locking point can be defined as the moment during asphalt mixture compaction at which an aggregate structure becomes stable. Beyond this point, further compaction does not contribute much to the increase in mixture density and can even damage aggregate particles. This study employed two compaction methods, a Superpave Gyratory Compactor and a Marshall Compactor, to investigate different asphalt mixtures’ locking points. For the Marshall compaction method, an accelerometer was attached to the Marshall hammer to record the asphalt mixtures' response. For the Superpave gyratory compaction, changes in the compacted samples’ height and density were utilized to determine locking points. A total of ten mixtures was designed and evaluated. All the mixtures were prepared with the same asphalt binder PG 64-22 and aggregates. The aggregates were pre-screened by different sieves to control variability in gradation. This study shows that it is feasible to determine most of the mixtures' locking points with an accelerometer. The one exception was the largest aggregate, which experienced particle breakage during compaction. The locking

point was found to be dependent on the full range of aggregate sizes of a mixture. Stone mastic asphalt (SMA) mixtures with similar gradation in fine particles showed less variability in locking points. Dense-graded mixtures with smaller maximum aggregate sizes exhibited lower locking points. These results can be attributed to their higher asphalt content, which served as a lubricant. The 101.6-mm (4-inch) Marshall mold was not adequate for determining the mixtures' locking point with particles larger than 25.4 mm (1 inch).

Introduction

Compaction is critical for asphalt mixture design, construction, and service. In asphalt mix design, compaction of asphalt mixture specimens is used to determine the mix's optimum properties. During construction, compaction is applied to achieve target density requirements. Over the service life, asphalt pavement is subjected continuously to compaction by tires of vehicles (Institute 2007).

Asphalt mixtures have been used in pavement construction since the beginning of the twentieth century. Various studies have been conducted to evaluate the compactability of these mixtures when different compaction methods are applied, including refusal density, kneading, and impact compactors. The introduction of the Superpave Gyratory Compactor (SGC) in the 1990s made it possible to monitor specimen height changes during compaction and better understand the process. Most of the methods for compaction study are based on the densification curve obtained from SGC compaction. This curve represents the change in the specimen’s height after each gyration, which can be later translated into a change in density or compaction (Leiva and West 2008; Mallick 1999).

Objective and Scope

This research aimed to evaluate the aggregate structure’s locking characteristics in asphalt mixtures through routine mixture design procedures. With this objective in mind, both the Marshall Compactor and the Superpave Gyratory Compactor were used to evaluate the impact locking point and the gyratory locking point of different asphalt mixtures. Additionally, the gyratory locking point samples were compacted in two mold sizes to evaluate sample size's effect on the compaction results. A total of ten mixtures was included in this study: seven dense-graded mixes with a maximum size of aggregate from 50.8 mm (2”) to 12.7 mm (1/2”) and three Stone Mastic Asphalt with a maximum size of aggregate from 25.4 mm (1”) to 12.7 mm (1/2”). The maximum size of an aggregate is defined as the smallest sieve opening through which the entire amount of the aggregate is required to pass (AASHTO T 2). The binder used was PG 64-22.

Laboratory Experiments

Materials

Ten hot mix asphalts were utilized in this study. First, different limestone aggregates were collected in East Tennessee, including #4 stone, #5 stone, #56 stone, #7 stone, and #10 screenings. The next step was to screen all the aggregates through the same set of sieves: 50.8 mm (2”), 38.1 mm (1.5”), 31.8 mm (1 ¼”), 25.4 mm (1”), 19.1 mm (¾”), 15.9 mm (5/8”), 12.7 mm (½”), 9.5 mm

(3/8”), No. 4, No.8, No. 30, No. 50, No. 100 and No. 200. The screening objective was to reduce aggregate variability and permit the design of a set of asphalt mixtures that possessed the same aggregate properties and compare the locking points of different mixtures with limited influence of abrasion angularity.

The same unmodified binder PG 64-22 was used for all the mixtures to eliminate binder properties’ influence. The mixing temperature for this binder was 154.4 °C (310 °F); the compaction temperature was 143.3 °C (290 °F).

Equipment

The compaction of specimens for the mix design was performed using a standard Marshall Mechanical Compactor and the 101.6-mm (4-inch) molds. The same equipment was used to compact the specimens and thus determine the impact locking point. A Data Acquisition System was used to receive acceleration data and transmit it to the software. An accelerometer with a capacity of 49050 m/s2 (5,000 g) was installed on the Marshall hammer. For the Superpave specimens, the Superpave Gyratory Compactor was utilized to compact the material into 150-mm specimens and 100-mm specimens. The setup for the accelerometer and the Marshall hammer is presented in Figure 3.1.

Specimens Preparation

Once the material retained on each of the indicated sieves was pre-screened, the mix design process started. For the seven dense-graded mixtures, the Tennessee Department of Transportation’s specifications were used to modify voids in the mineral aggregate greater than 14% (TDOT 2015). For the three Stone

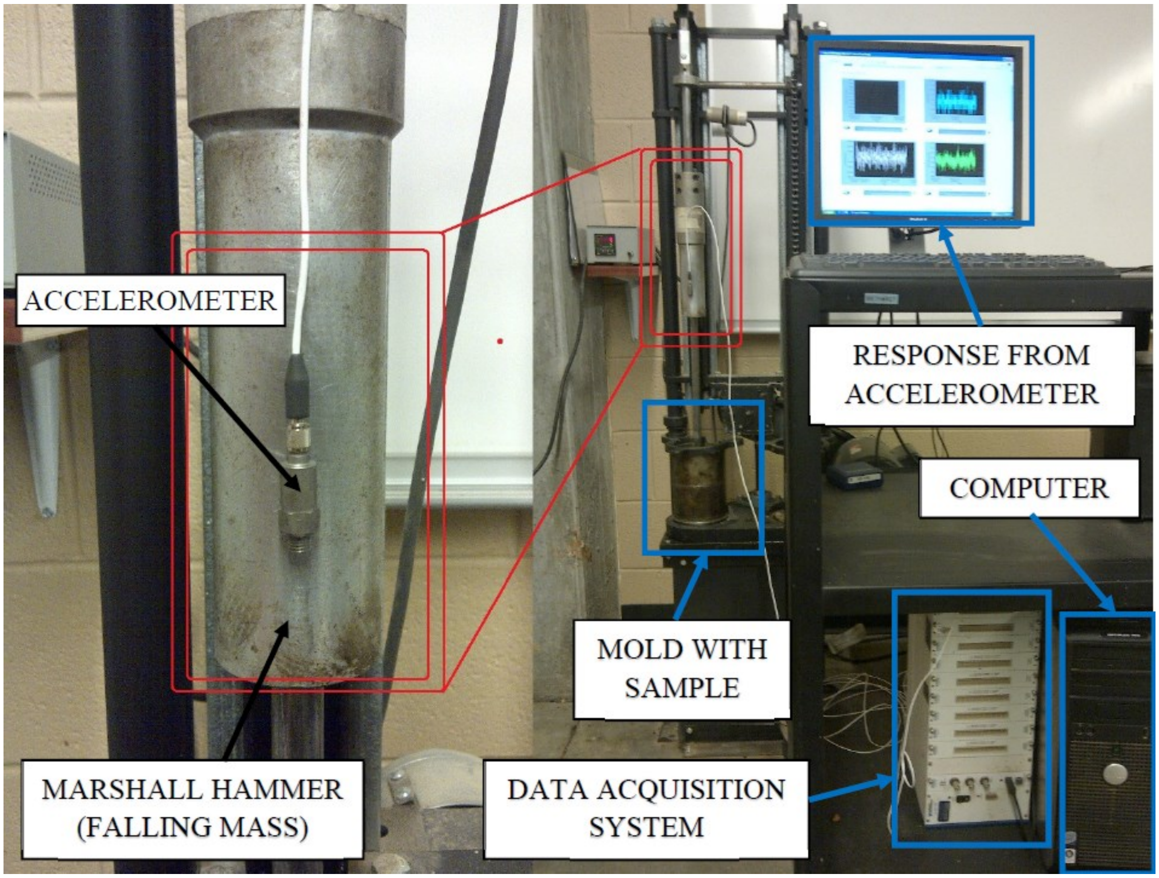

Figure 3.1. Setup of the Impact Locking Point Experiment

Mastic Asphalt mixtures, the Georgia Department of Transportation's specifications were used (GDOT 2013). Each mixture's granulometric composition was chosen as a middle point between the low and high limits provided in the specifications. A summary of the aggregates' composition is presented in Table 3.1. For each mixture, coarse and fine specific gravities were determined. Sieve No. 4 was used to sort the aggregates into coarse and fine groups. Next, four samples with different binder content were prepared for all ten mixtures. The specific gravity of each compacted specimen was tested, and the optimum binder content was determined. A summary of mix designs is presented in Table 3.2. The Marshall Mix Design was utilized to compact all the mixtures with a different number of blows depending on the mix type: dense-graded specimens received 75 blows for each side, and SMA specimens got 50 blows each side. The same 101.6-mm (4-inch) mold size was used for all specimens. After the mix designs were completed, the production of asphalt mixes started, and around 25 kg of each mixture was prepared.

Test Procedure

The asphalt mixtures produced in the laboratory were placed in the oven for two hours for short-time aging. Each mixture consisted of eleven specimens: five specimens for the impact locking point, three specimens for the gyratory locking point compacted in a 150-mm mold, and three specimens for the gyratory locking point compacted in a 100-mm mold. The samples' weight for both the impact locking point and the gyratory locking point compacted in the 100-mm mold was

Table 3.1. Summary of Hot Mix Asphalts Granulometric Composition

Mix	1	2	3	4	5	6	7	8	9	10
Sieve	307 A	307 B	307 BM2	307 C	411 D	411 E	411 TLD	SMA 9.5	SMA 12.5	SMA 19.0
50.8 mm	100	100								
38.1 mm	90	100								
31.8 mm			100							
25.4 mm										100
19.1 mm	60	77	87	100					100	95
15.9 mm					100					
12.7 mm					97	100	100	100	93	57
9.5 mm	42	60	65	80	86	86	95	85	63	42
No. 4	30	42	48	52	65	65	65	39	24	24
No. 8	20	32	35	35	46	46	46	23	20	18
No. 30	12	16	19	18	23	23	25			
No. 50			14	11	14	14	14	13	15	15
No. 100	5	7	8	6	7	10	7			
No. 200	2.3	4.5	4.5	4.5	4.0	7.0	6.0	10.0	10.0	10.0

Table 3.2. Summary of Hot Mix Asphalt Designs

Mix		Optimum AC (%)	Air Void (%)	VMA (%)	VFA (%)	Blows
1	307A	3.5	4.0	14.0	71	75
2	307B	4.0	4.1	14.8	72	75
3	307BM2	4.4	4.0	15.2	74	75
4	307C	4.8	4.1	15.3	73	75
5	411D	5.5	4.0	15.6	74	75
6	411E	5.8	4.0	15.8	75	75
7	411TLD	5.8	4.0	15.7	75	75
8	SMA 9.5	6.8	3.6	18.2	80	50
9	SMA 12.5	6.4	3.5	17.9	80	50
10	SMA 19.0	5.9	3.5	17.2	79	50

1,230 g, while the weight of samples for a 150-mm mold was 4,000 g. The accelerometer was placed on the Marshall hammer’s falling mass and connected to the data acquisition system. The software was configurated to record the data with a frequency of 10,000 Hz. The Superpave Gyratory Compactor was set to compact the samples by applying two hundred gyrations.

The samples used to test the impact locking point and the gyratory locking point compacted in the 150-mm mold were prepared for each mixture on the same day. Because it was time-consuming to change the Superpave compactor head from 150-mm to 100-mm, the samples for the gyratory locking point compacted in the 100-mm mold were prepared the next day. All the samples prepared for testing the impact locking point were compacted, utilizing 75 blows on each side of the specimen (the samples for the SMA mix design had been compacted with 50 blows on each side). The compaction process was standardized at 75 blows to maintain the same conditions for all the specimens and compare them. Similarly, the samples compacted via the Superpave Gyratory Compactor were all under the same condition of two hundred gyrations.

Methods for Determining Locking Point

The impact locking point can be defined as the first blow of the impact hammer that produces stable peak acceleration and impact duration, which means the duration of the interaction between the hammer and the mixture. This method is based on the change of specimen stiffness during compaction. Initially, during the first blows applied to the specimen, the mixture is still loose, implying low stiffness. During this initial compaction stage, the peak acceleration is low, and the duration of impact is long. In this stage, various acceleration peaks can be observed, mostly limited to two peaks. The compaction continues with every blow; the stiffness increases, peak acceleration increases, and impact duration decrease. After the impact locking point is reached, stiffness changes become minimal, and peak acceleration and impact duration no longer see significant changes. A graphic presentation of the changes in acceleration and impact time is presented in Figure 3.2.

Figure 3.3 presents the acceleration data obtained from mixture 4 (307C) sample 1. The five graphs show the mixture response to compaction at 1, 10, 60, 129, and 150 blows. It can be observed that with every blow applied to the specimen, the peak acceleration increased, and the impact duration decreased until the locking point was reached at 129 blows. During the initial stage of compaction (blow 1 and 10), there were two acceleration peaks. The acceleration increased from 2305 m/s2 (235 g) at the first blow up to 4807 m/s2 (490 g) at the locking point. The duration of impact decreased from 0.0035 s (blow 1) to 0.0013 s (blow 129, i.e., locking point). After that, the peak acceleration varied between 4699 m/s2 (479 g) and 4817 m/s2 (491 g), and impact duration between 0.0013 s and 0.0014 s.

The impact locking point can be used to indicate a boundary that separates effortless and effortful compaction. Difficult compaction means no meaningful change in density, and further compaction can lead to aggregate damage.

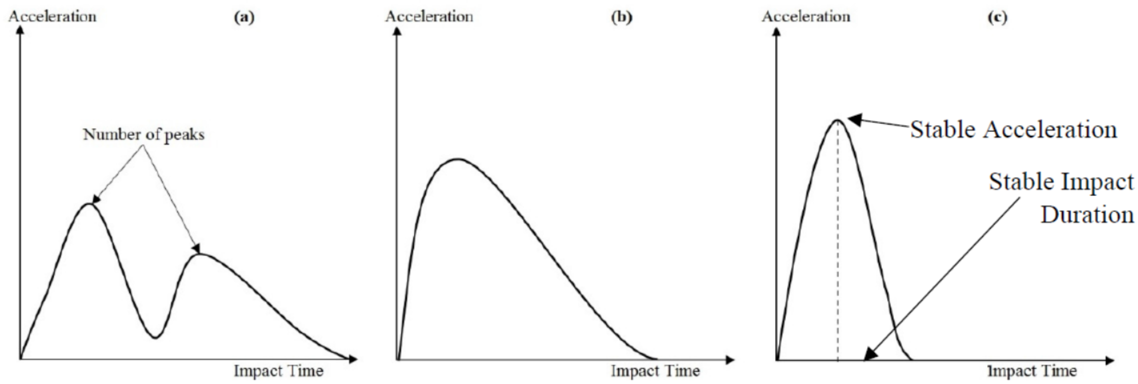

Figure 3.2. A typical response in different compaction stages: (a) initial, (b) middle, (c) at the impact locking point

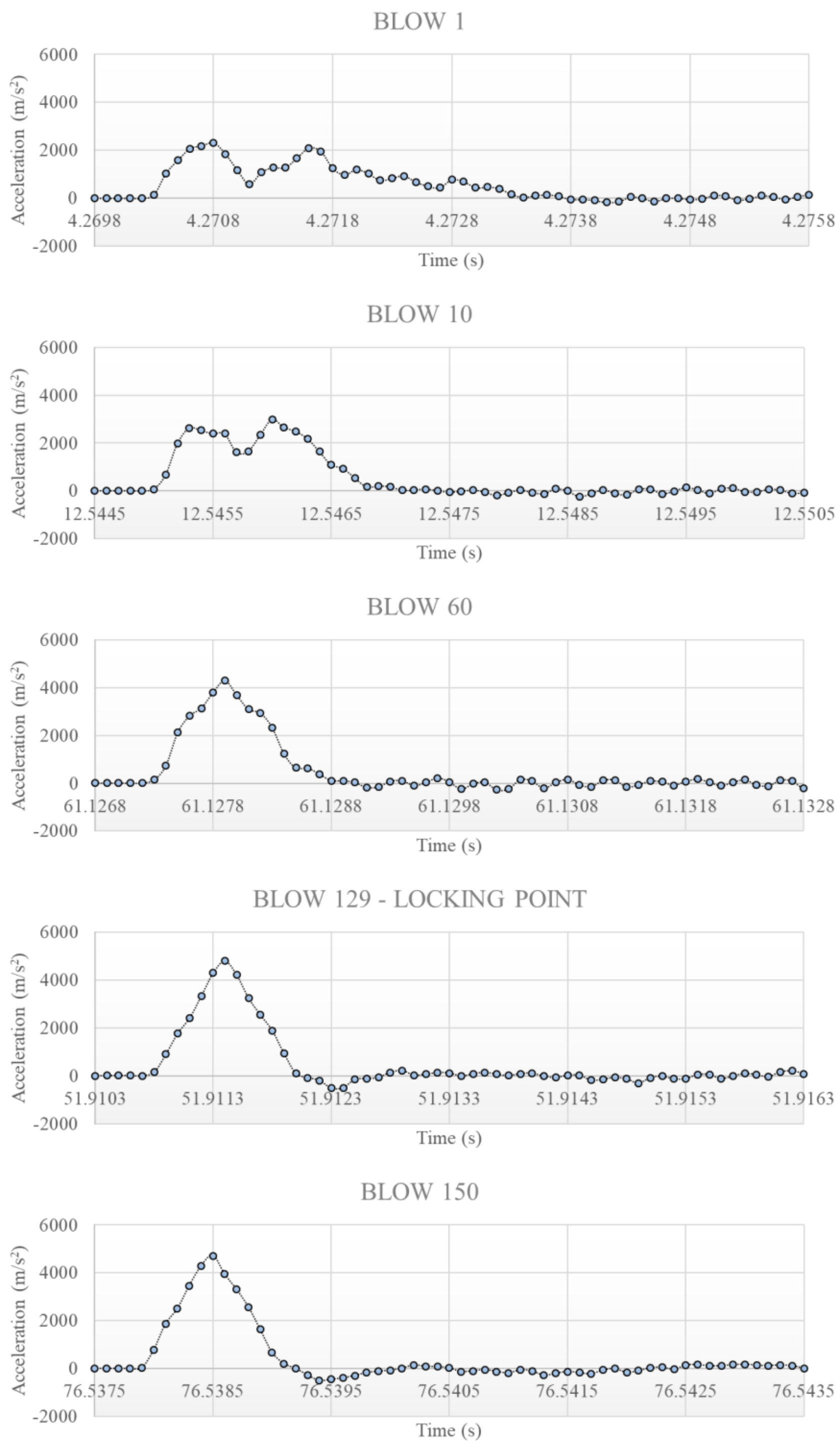

Figure 3.3. Example of the acceleration data and determination of the locking point

Polaczyk et al. 2018 measured change in density to confirm that the density change is significantly smaller after crossing the locking point than before the mixture reaches the locking point. Three samples were compacted, first at 150 blows, second at the impact locking point, and third at 15 blows below the impact locking point. On average, compacted samples at 15 blows below the locking point had air voids 1.2% higher than at the final compaction. In comparison, samples that were compacted at the locking point had air voids only 0.19% higher than at the final compaction.

The gyratory locking point was determined by following the Georgia Department of Transportation (GDOT) method, which defines the locking point as the number of gyrations at which the same height repeats three times. Initially, the method developed by Vavrik and Carpenter 1998 who introduced a commonly used definition that defines the locking point as the first gyration in the first set of three gyrations at the same height that is preceded by two sets of two gyrations at the same height, was utilized in this study. However, it was impossible to obtain the correct result for several specimens, as the sequence 2-2-3 does not necessarily appear in all densification curves.

Results and Data Analysis

Impact Locking Point

In this study, various mixtures were utilized: ten mixtures that included three SMA and seven dense-graded. A substantial improvement over previous research considered aggregates' variability by screening and producing unvarying material for each of the sieves. The materials were screened by sieves to minimize the variation of aggregates for each mixture, thereby eliminates aggregate variability as a factor in the results. Figure 3.4 presents the results of the impact locking point.

The number of samples for each mixture was fixed at five due to the availability of material. The final value of the impact locking point was calculated as the average of the five samples. It was impossible to determine the impact locking point for mixture 1 (307A) or samples three and four of the mixture 2 (307B), suggesting that these mixtures' locking point may be higher than 150 blows. However, in mixtures one and two, the failure to reach a locking point may be attributable to aggregates' breakage, especially the largest coarse aggregates. The specimens of mixture 1 (307A) and 2 (307B) are depicted in Figure 3.5.

The breakage of aggregates, caused by the impact hammer, made it impossible for the aggregates to lock down and yield steady peak acceleration and impact duration readings. Once the specimens' compaction was terminated, the samples were warmed and disintegrated to review the magnitude of damage caused by the impact hammer. To verify breakage, all sides of the aggregates that were not covered with asphalt cement were examined. Post-compaction gradation (sieve analysis) was also performed on aggregate previously washed with the solvent. The comparison of pre- and post-compaction sieve analysis is presented in Figure 3.6. The revision concluded that some of the larger particles suffered a rupture. This phenomenon was particularly visible in mixture 1, which suffered the most extensive damage. The four-inch mold may be inadequate to perform this

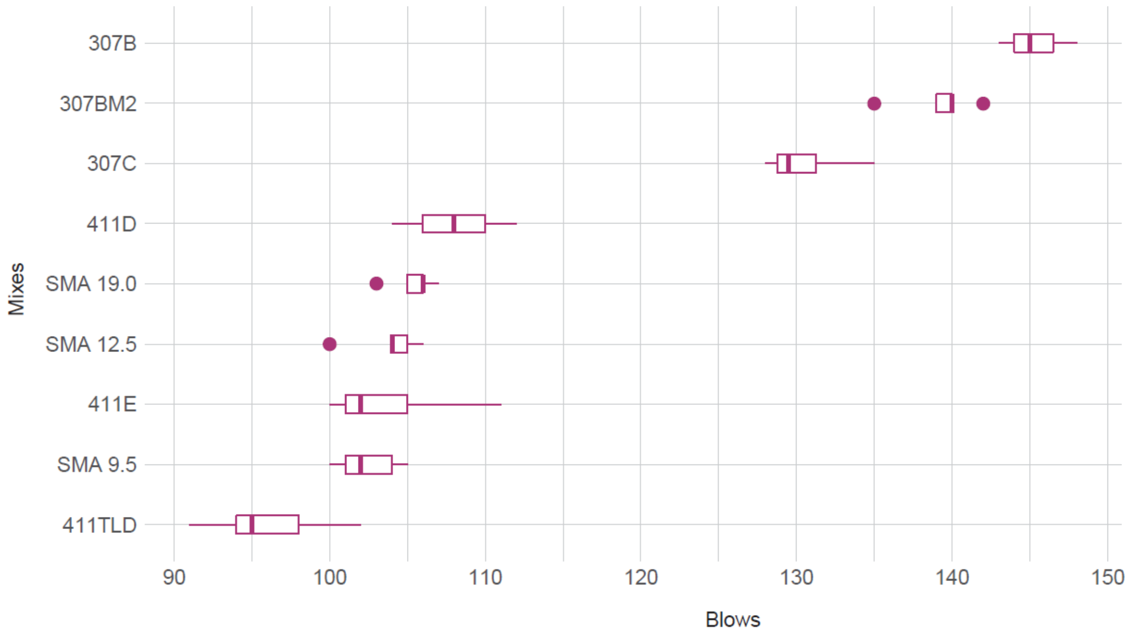

Figure 3.4. The Summary of the Impact Locking Points

Figure 3.5. Example of the Aggregates damage. (A) Mixture One (307A), (B) Mixture two (307B)

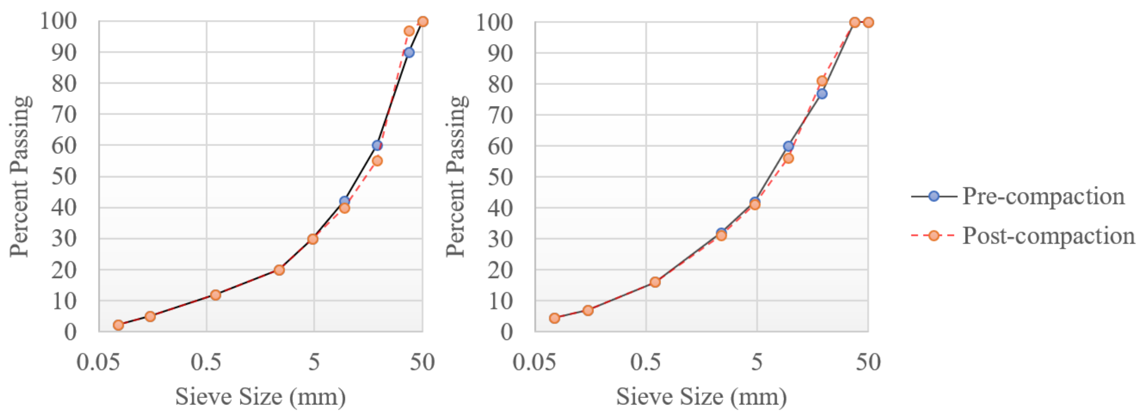

Figure 3.6. Pre- and post-compaction sieve analysis. On the left, mixture 1 (307A) sample 1. On the right, mixture 2 (307B) sample 3

experiment on mixtures with particles larger than 25.4 mm (1 inch). Also, the limestone aggregates may be too soft to prevent particle damage before compaction is terminated.

The value of the locking point for mixture 1 has not been concluded. However, for mixture 2, 3 out of 5 samples gave valid results, and the final value was calculated as the average of the three samples. Sample 4 of mixture 4 (307C) was discarded due to human error during the compaction process. It was possible for the rest of the mixtures to obtain five different samples and calculate the average.

The results show that for dense-graded asphalt mixtures, the impact locking point decreases with decreasing maximum aggregate size and range from 145 blows for mixture 2 to 96 blows for mixture 7. Also, it can be concluded that base course asphalt mixtures have a higher impact locking point, with an average of 138 blows, while surface asphalt mixtures have lower impact locking points, with an average of 103 blows. The Stone Mastic Asphalt (SMA) mixtures follow the pattern that the impact locking point increases with increasing aggregates' size utilized in the mixture. However, the impact locking point range is significantly smaller, from 102 blows for the 9.5 mm mixture to 105 for the 19.0 mm mixture.

The average result of the impact locking point for the base course indicates that it is close to the 150 blows commonly used for the Marshall Mix Design of dense-graded mixtures. The difference between the locking point and the final compaction is 12 blows, which means the mix design samples are slightly over-compacted. The result obtained for the surface asphalt mixture, 103 blows, indicates a difference of 47 blows between the impact locking point and final compaction. This difference can lead to significant over-compaction, in extreme cases, even damage to aggregates and errors in the mix design. From the results in Figure 3, it can be concluded that the average Stone Mastic Asphalt specimen, when compacted at 50 blows for each side, misses only four blows to reach the impact locking point. The results also show that the average dense-graded asphalt mixture requires higher compaction energy to achieve the impact locking point than the SMA mixture requires.

Gyratory Locking Point

Figure 3.7 presents data from the 150-mm mold. Similarly to the impact hammer results, the gyratory locking point for the dense-graded asphalt mixtures increases as the maximum aggregate size increases. The base mixtures obtained a higher average gyratory locking point of 80 gyrations than the surface mixtures, which achieved an average gyratory locking point of 47 gyrations. The Stone Mastic Asphalt mixtures had an average gyratory locking point of 94. It can be shown from the gyratory locking points results that when the mixture has coarser aggregates, then the gyratory locking point is higher. The difference between the SMA mixture’s locking points is not as pronounced as for the dense-graded mixtures, where the difference is around one gyration for two blows. Interestingly, the gyratory locking point of the SMA is much higher than that of the dense-graded mixture. Also, for the SMA, the compaction effort required to achieve both locking

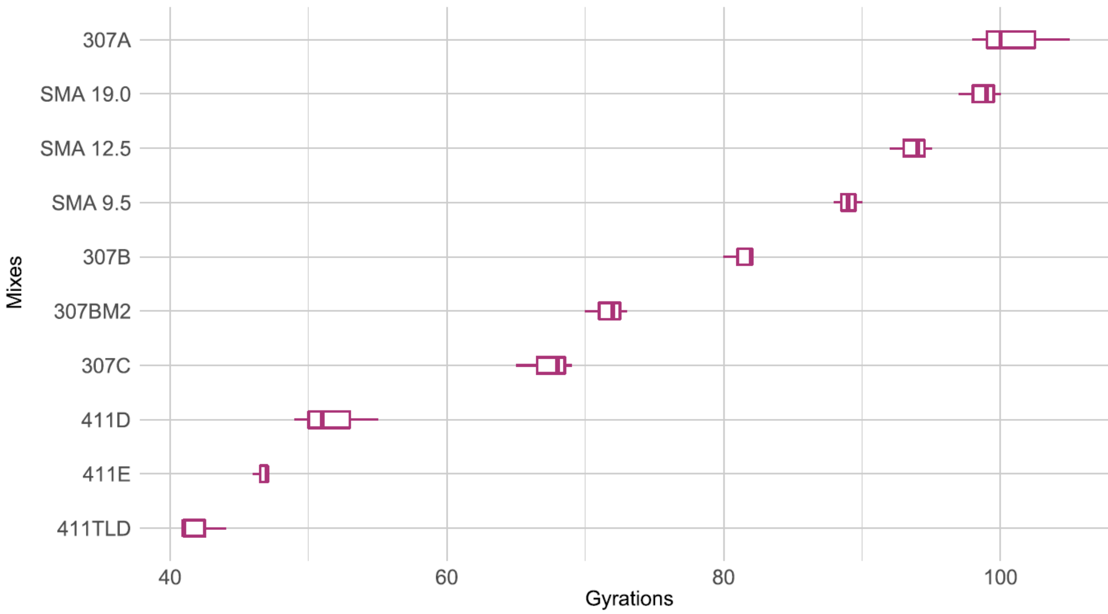

Figure 3.7. The Summary of the Gyratory Locking Points (Mold 150-mm)

points are similar, 94 gyrations for the gyratory locking point or 103 blows for the impact locking point.

Figure 3.8 presents the gyratory locking points obtained from the 100-mm diameter mold. The objective of utilizing different mold sizes was to analyze how mold size influences the locking points results. Previous research efforts focused on investigating whether mold size differences affect the asphalt mixture's compaction and properties. Hall et al. 1996 investigated how the sample size affects compaction and volumetric properties of asphalt mixtures. The study utilized the same 150 mm mold for all the samples, and the weight of the samples varied from 2000 g to 6500 g. Hall concluded that compaction characteristics and volumetric properties change with the size of the sample. McGennis et al. 1996 presented the hypothesis that the resulting compaction should be the same for both molds for the same mixture and the same number of gyrations. Two 12.7 mm (½") and five 19.1 mm (¾") nominal maximum size aggregate mixtures were tested. Specimens were prepared at the optimum asphalt content in the 150-mm and the 100-mm gyratory molds. Specimens specific gravities from the two mold sizes were compared. More than half of the results rejected this hypothesis. Jackson and Czor 2003 evaluated using the 100-mm mold to prepare test samples in the laboratory by collecting different mixes and comparing relative density obtained with the 100-mm mold and the 150-mm mold. This work found the significant statistical differences between results obtained from two sizes of molds. Nonetheless, the recorded differences were smaller than could be measured given

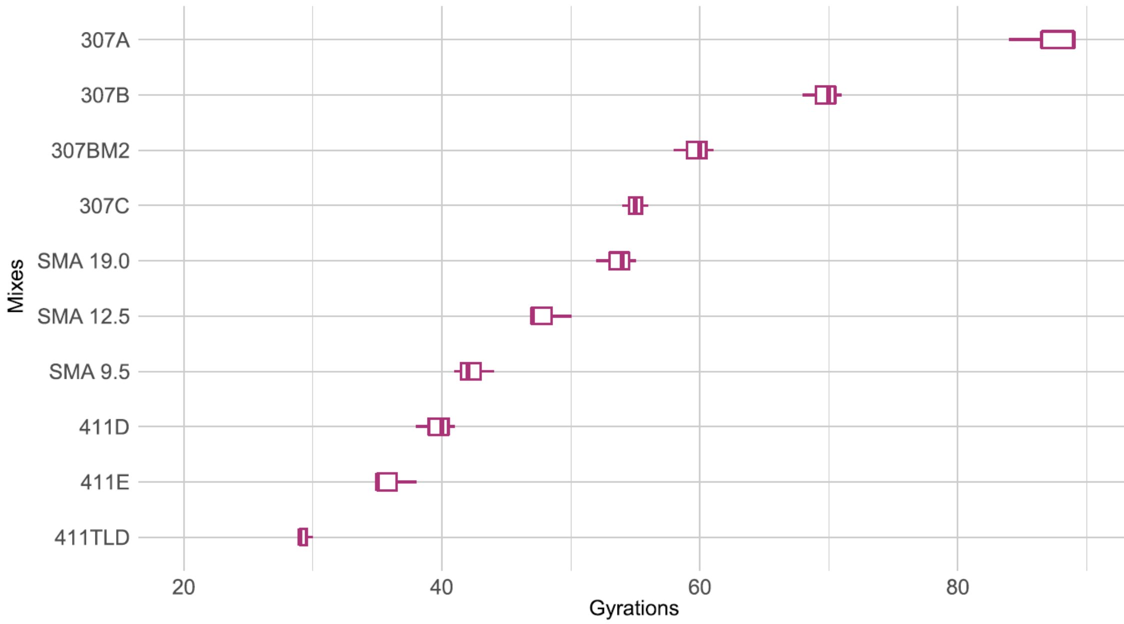

Figure 3.8. The Summary of the Gyratory Locking Points (Mold 100-mm)

the laboratory test methods' precision. The researchers concluded that there is no significant difference from an engineering point of view.

In the current study, the specimens compacted in 100-mm mold had the same aggregate and binder properties as samples compacted with the Marshall hammer and 150 mm SGC molds. As Figure 3.8 shows, the gyratory locking point for the 150-mm specimens was significantly higher than that of the 100-mm specimens, which means more compaction effort is required to achieve skeleton structure in asphalt mixture if larger molds are used for specimen compaction. However, even with this significant difference in gyratory locking points' values, the results indicated that the rankings of mixtures for the two different mold sizes were identical. These rankings support the conclusion that the concept of locking point can discriminate the compaction properties of one mixture from another no matter which mold size is used.

Figure 3.9 presents a summary of all the locking points obtained during this research. It can be observed that the gyrations are more efficient in achieving the locking point than impact regardless of the mold used. However, the difference is higher for dense-graded mixtures. The ranking of locking points was maintained for all the mixtures, but again for dense-graded mixtures, the difference was more significant than for SMA. The small difference in SMA locking points may be attributed to these mixtures' granulometric composition, where the finer sieves do not vary. These results may indicate that the finer particles of granulometric

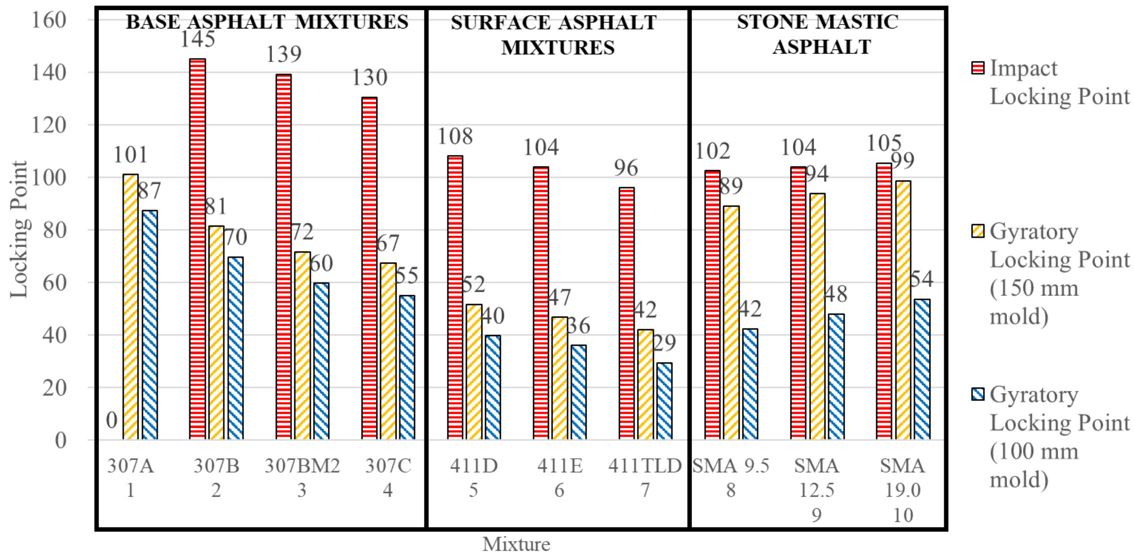

Figure 3.9. The Summary of the Locking Points

composition have a more significant influence on the locking point than courser aggregates.

Conclusions

In this study, two compaction methods, the SGC and Marshall Compactor, were used to investigate the locking points of asphalt mixtures. Ten different asphalt mixtures were produced with the same aggregates pre-screened with sieves to eliminate the influence of aggregate gradation. The specimens were compacted utilizing a Marshall Hammer with an accelerometer attached to the falling mass and then with the SGC. The response of specimens obtained by the accelerometer and the change in specimen height in the SGC compaction was measured to determine the impact and gyratory locking points for each mixture. The following conclusions were drawn based on the results of this study:

- The impact locking point can be determined with an accelerometer attached to the Marshall hammer. For researchers, it can be used to evaluate the compactability of the asphalt mixture. It can provide an easy way for contractors to determine the effort required to compact asphalt mixture in the field.
- The locking point is related to the full gradation of the blend consisting of coarse and fine aggregates. Dense-graded mixtures show a broader range in locking points than SMA mixtures. This difference may be attributed to granulometric variation. Dense-graded mixtures vary in both coarse and fine aggregates, whereas SMA mixtures vary mostly in coarse aggregate. In this study, the range of optimum asphalt content for dense-graded mixtures was 2.3%, while

for SMA, the range is 0.9%. Thus, variation in asphalt content can affect the locking point.

- In this study, dense-graded mixtures with smaller maximum aggregate size had a lower locking point. This finding may be attributed to the fact that these mixtures generally contain more asphalt binders, which serve as a lubricant and make compaction easier and faster. In this study, one type of asphalt binder was used. Further research is needed to determine the asphalt binder's influence on the locking point, especially the difference between modified and unmodified binders.
- The locking point of base mixtures was slightly under 150 blows, the standard number of blows in the Marshall Mix Design. The SMA had the impact locking point just above 100 blows, again the mix design's typical number. In contrast, surface mixtures showed an impact locking point far below 150 blows. This finding indicates that surface mixtures may suffer over-compaction and aggregate breakage when 150 blows are used for mix design. Further study is needed, including performance comparison between mixtures compacted traditionally and at the locking point.
- The samples that contained particles larger than 25.4 mm (1 inch) were damaged during compaction. The 101.6 mm (4-inch) Marshall mold may not be adequately large for determining the impact locking point for mixtures with the aggregate particles larger than 25.4 mm (1 inch).

- The gyratory locking points for the 150-mm specimens were significantly higher than those for 100-mm specimens, but the ranking is maintained regardless of mold size. This finding allows comparing the locking points for different mixtures if the mold's same size is utilized. In the current study, all comparisons were made with samples of the same weight. Further study is needed to determine if the specimen's weight (height) influences the locking point.
- The scope of this research was limited to evaluate the locking point of various types of asphalt mixtures. Further work is needed to correlate the locking point with performance tests and mix design parameters.

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CHAPTER FOUR

INFLUENCE OF AGGREGATE GRADATION ON COMPACTABILITY OF ASPHALT MIXTURE

A version of this chapter was accepted as Polaczyk, P., Han, B., Gong, H., Ma, Y., Xiao, R., Hu, W., and Huang, B. "Influence of Aggregate Gradation on the Compactability of Asphalt Mixtures Utilizing Locking Point" to be published in ASCE, *Journal of Materials in Civil Engineering*.

My contribution to this paper was performing majority of the experimental tests, data analysis, and preparing the original draft and all figures and tables.

Abstract: Aggregate gradation is crucial for the performance of asphalt mixtures. However, a good mix design must include a compromise between performance and workability. This study used two compaction methods: the impact (Marshall hammer) and gyratory (Superpave gyratory compactor), to investigate the influence of aggregate gradation on the compaction of asphalt mixture utilizing the concept of the locking point. For the impact compaction, an accelerometer was placed on the Marshall hammer's falling mass to record the asphalt mix response, with which the impact locking point was defined. For the gyratory compaction, the densification curves were utilized to define the locking point. Twelve mixes, three for each mixture type (base, intermediate, and surface), were designed and prepared in the laboratory. The asphalt mixes were tested for their locking points concerning their type and gradation. Results indicated that the locking point could be determined for most of the mixtures compacted by both the impact and gyration methods, except for the mixture of the bigger stone and coarser gradation. The locking point of the asphalt mixture was strongly dependent on its gradation. A

coarser mix resulted in a higher locking point. Thus, the maximum aggregate size was not the only factor determining the locking point but the whole gradation.

Introduction

The compaction of a Hot Mix Asphalt (HMA) is a process that reduces the volume of air by applying external energy in the form of rollers for the field compaction or different types of compactors for laboratory compaction (Roberts et al. 1991). The decreased air voids increase the density of the asphalt mixture. Compaction should provide an optimum amount of air voids, as too low amount of air voids can lead to damage of the mixture because of the asphalt binder volume changes caused by temperature (Xiao et al. 2012). The adequate amount of air voids limits permeability and provides long-lasting performance. Too high air-void content can lead to a permeable asphalt mixture layer, accelerate the asphalt binder's oxidation, and rutting. For efficient compaction, the load applied by the roller or laboratory compactor must be higher than forces that resist compaction provided by the mixture (Roberts et al. 1991).

Polaczyk et al. (2019) indicated that both aggregates and asphalt binder play the role during the compaction process. The higher participation of crushed (more angular) aggregates, the more difficult it is to compact the mixture. However, at the same time, these crushed materials develop a stable and robust skeleton that resists traffic. Asphalt cement provides bonding and lubrication during compaction, allowing aggregate particles to roll against each other, thereby providing higher density. Garcia et al. (2020) investigated the effect of aggregate gradation on asphalt mixtures' performance. They indicated that the mixture is more sensitive to change in gradation in the fine part than it is in the coarse part. The research concluded that using volumetric parameters as the unique indicator of mix quality might be insufficient. Ma et al. (2020) indicated that the inclusion of recycled materials without rejuvenation additives lead to stiffer, less durable mixtures, which would produce poor workability.

On the other hand, Polaczyk et al. (2018) indicated that the mixture is over-compacted; it might damage the aggregate and compromise the excellent performance and long service life. Al Shamsi and Mohammad (2010) concluded that it requires more energy to compact coarse asphalt mixtures than intermediate or fine mixes. As the gradation becomes coarser, the compactability of the asphalt mix typically worsen. Prowell and Brown (2007) determined and evaluated different definitions of the locking point and compared it to the field results. The conclusions indicated that the LP2-2-3 definition had the best relationship with the field compaction.

Vavrik (2000) concluded that the optimum aggregate composition's goal is to provide the maximum possible density for dense-graded mixtures. If a mixture is to be filled with stone and a structural capacity is needed, the best theoretical strength would be obtained with a single piece of stone placed as an asphalt mix layer. The asphalt mixture must deal with smaller pieces of stone, that no matter how well packed, do not reach the strength of the solid piece of stone. However, smaller stone pieces allow better workability and permit the asphalt mixture to work as a flexible pavement layer. Dense-graded mixes need to achieve the highest possible packing that would be as close as possible to the maximum density line to reach the maximum strength, but always considering that there has to be enough air void to allow sufficient space asphalt binder to avoid asphalt bleeding.

In the 1960s, the Federal Highway Administration presented an aggregate gradation chart that utilizes 0.45 exponent for sieve size. This chart provides an easy and convenient way to determine the maximum density composition for a mix of various aggregates. In most cases, the maximum density gradation does not yield enough voids to accommodate sufficient asphalt binder and must be modified to reach the minimum voids in mineral aggregate (Roberts et al. 1991). In most cases, the required gradation line and maximum density line cross at the nominal maximum size and differ by some intermediate sieves (Jia et al. 2019). Different state agencies have a variety of specifications for different types of asphalt mixtures. Even though Superpave Mix Design introduced standardized control points for gradation, most agencies modify them to include their accumulated field experience (Roberts et al. 1991).

Aggregate gradation has an important influence on asphalt mixture compactability. Poor gradation can cause a variety of problems during production, transport, placing, and compaction. One of them is a tender mixture (Gong et al. 2019). These mixes are difficult to compact because of how slowly the mix develops enough strength to resist the rollers' weight. Other problems caused by poor gradation are unstable mixtures sensitive to even a small excess of asphalt or water, harsh mixtures that tend to segregate (Brown et al. 1989).

Gradation is the allocation of different sizes of particles defined as the percent of total weight. Different dense-graded mixtures can be classified as coarse-graded or fine-graded. This classification is based on the maximum density line; the gradation on the coarse side is coarse-graded, and on the fine side is defined as fine-graded (Jiang et al. 2019). Gradation is one of the most important parameters for asphalt mix design and, in most cases, the first step in the design process. Most agencies worldwide have established the permitted gradation range for each type of mixture, based on pavement structure, traffic, or climate condition. These gradation limits assure good quality of asphalt mixtures such as resistance to moisture damage, enough friction, fatigue and rutting resistance, stiffness, stability, and permeability (Polaczyk et al. 2019).

Objectives and Scope

This study's objective was to investigate the influence of aggregate gradation of the different mixture types on the locking point while compacted using the impact and the gyration method. A total of four asphalt mixtures types (B-mix, BM2-mix, C-mix, and D-mix) were chosen, each with different maximum aggregates size following the Tennessee Department of Transportation (TDOT) Standard Specifications (TDOT 2015). B-mix is classified as a base mixture with 38.1 mm (1½") maximum aggregate size, BM2-mix is an intermediate (binder) mix with 31.8 mm (1¼") maximum aggregate size, C-mix is a binder or surface mix for low traffic or slow traffic roads with 25.4 mm (1”) maximum aggregate size, and D-mix is a surface mixture with 12.7 mm (½”) maximum aggregate size. The aggregates used in this study were various sizes of limestone. The mix designs were prepared using Marshall Design Method. The compaction evaluation samples were compacted in the 101.6-mm (4-inch) Marshall mold and 100-mm and 150-mm Superpave molds. One type of binder, PG 64-22, was used in all asphalt mixtures.

Laboratory Experiments

Materials

The different sizes of crushed limestone were utilized in this study. The important task was to limit possible variability in materials, so the aggregates were screened through the same set of sieves: 38.1 mm (1 ½”), 31.8 mm (1 ¼”), 25.4 mm (1”), 19.0 mm (¾”), 15.9 mm (5/8”), 12.7 mm (½”), 9.5 mm (3/8”), No. 4, No.8, No. 30, No. 50, No. 100 and No. 200. For all the mixtures, the same unmodified binder PG 64-22 was used. The mixing temperature was 154.4 °C (310 °F), and the compaction temperature for this asphalt cement was 148.9 °C (300 °F).

Equipment

The compaction for the mix design was achieved by using a Marshall Compactor with 4-inch molds. The falling mass's weight was 4.53 kg (10 lb.), and the fall height was 45.72 cm (18 in). The speed of compaction was approximately one blow per second. The same compactor was used to prepare samples used to determine the locking point using the impact compaction method. A 49050 m/s2

(5000 g) accelerometer was fixed on the Marshall Compactor's falling mass. A Superpave Gyratory Compactor (SGC) was utilized to determine the locking point compacted in 100-mm molds and 150-mm molds. The pressure applied on the specimens was 600 kPa, the rotation was 30 gyration per minute, and the compaction angle was 1.25º.

Specimen Preparations

Four types of dense-graded mixtures were used. The pre-screened material was dried and weighted to prepare specimens for mix design. For all the mixtures, the Tennessee Department of Transportation specifications were utilized. The Marshall mix design method was used to design all the mixes. First, each mix's gradation was chosen as a middle point between the low and high limits provided in the specification (Group 2). Second and third gradations were chosen as a low (Group 1) and high limit (Group 3). A summary of the gradations is shown in Figure 4.1.

For each mixture, coarse (ASTMC127 2015) and fine (ASTMC128 2015) specific gravities were determined with the division on sieve No. 4. Next, mix designs were prepared for all 12 mixtures (ASTMD1252 2017; ASTMD2041 2011). A summary of mix designs is presented in Table 4.1. Each mix design consisted of four samples with different asphalt content. Each specimen received 75 blows (each side). The 101.6-mm (4-inch) mold size was utilized for testing the locking point when the sample was compacted with an impact hammer. The samples were compacted using 100-mm and 150-mm molds and the Superpave Gyratory

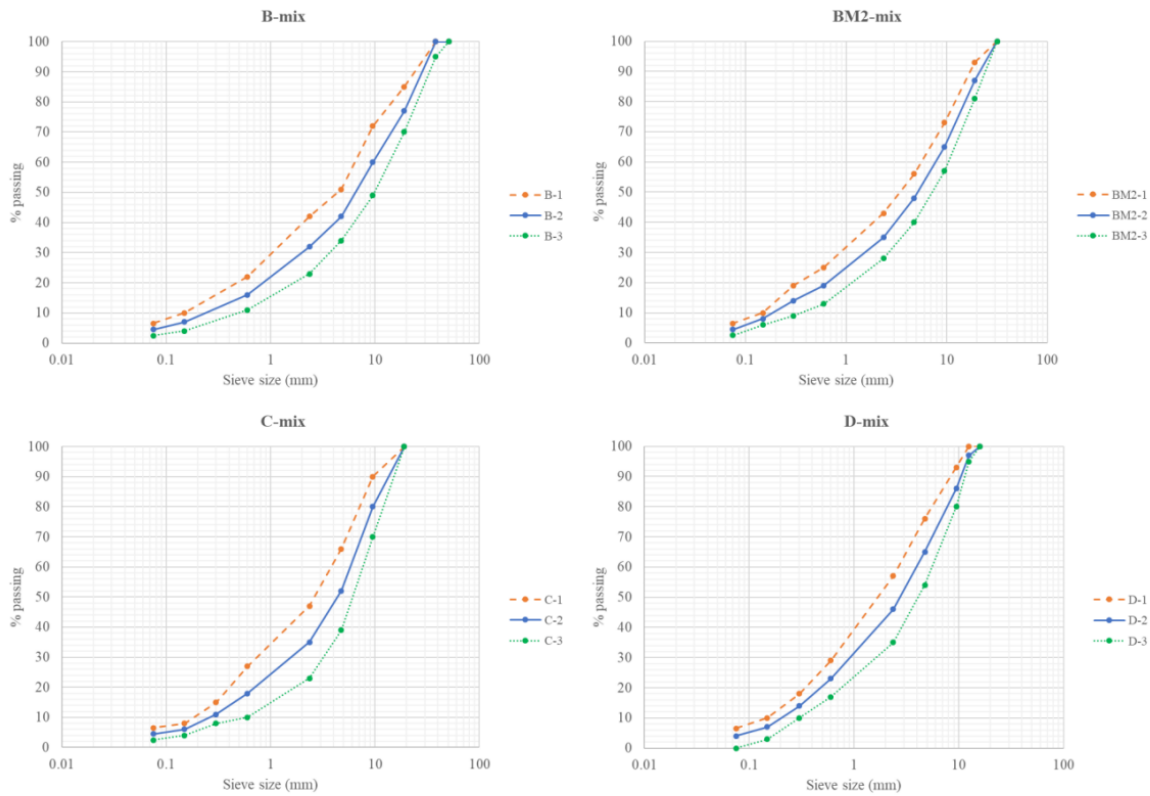

Figure 4.1. The summary of asphalt mixtures granulometric composition

Table 4.1. Results of the Marshall Mix Designs

Mix	Optimum AC (%)	Air Void (%)	VMA (%)	VFA (%)
B-1	3.4	4	11.5	65
B-2	4.0	4	11.9	66
B-3	4.9	4	12.5	68
BM2-1	3.5	4	12.3	67
BM2-2	4.4	4	13.2	70
BM2-3	5.1	4	14.8	73
C-1	3.6	4	12.7	69
C-2	4.8	4	13.5	70
C-3	5.5	4	15.4	74
D-1	3.9	4	14.8	73
D-2	5.5	4	15.6	74
D-3	7.2	4	18.1	78

Compactor for a gyratory locking point. The number of samples was limited to three for each mixture, each compaction method, and mold size due to the high amount of material required.

Testing Procedure

Samples for the impact locking point test were prepared in the following way. The short-term aged (2 hours) specimen was placed in a pre-heated 101.6-mm (4-inch) Marshall mold and compacted by applying 75 blows at each side of the sample. Each sample weighed 1,200 grams. The locking point data were acquired with an accelerometer attached to the falling mass of the Marshall hammer. The data were sent to the data acquisition system and then stored in the computer. The 49050 m/s^2 (5000 g) accelerometer was enough to obtain uninterrupted acceleration data during the entire compaction process. The set-up for this experiment was similar to proposed by Polaczyk et al. 2018. The raw acceleration data was filtered and smoothed, utilizing the moving 5-points average method. The filtered data were then plotted in the time domain, and acceleration at each hammer blow was determined. The impact locking point was defined as the first blow during the impact compaction, after which the duration of the impact and the peak acceleration does not change significantly (±5%) (Polaczyk et al. 2019a).

Samples for the gyratory locking point test were prepared in the following way. The short-term aged specimen was placed in a pre-heated 100-mm and 150-mm Superpave molds and compacted by applying 150 gyrations for each sample.

The samples were compacted in a 100-mm mold weighing 1,200 grams. The samples compacted in a 150-mm mold weighed 4,800 grams (four times the smaller samples). The gyratory locking point was obtained following the method proposed by Vavrik and Carpenter 1998, which describes one of the most common definition that states the locking point as the first gyration in the first set of three gyrations at the same height preceded by two sets of two gyrations at the same height.

Results and Discussion

Gyratory Compaction Method

Mixtures with a larger maximum aggregate size have higher the locking point for all three groups. Table 4.2 shows the locking point data obtained from the mixtures compacted in 150-mm mold. For group 1, which represented gradation at the lower limit, the locking points ranged from 109 gyrations for B-mix down to 56 gyrations for D-mix. For group 2, which is in the middle between lower and upper gradation limit and proximity to the maximum density curve, the results ranged from 81 gyrations for B-mix to 52 gyrations for D-mix. Group 3 represents the mixes with gradation composition at the upper limit, and the locking point for this group ranged from 72 gyrations for B-mix to 43 gyrations for D-mix.

For the same type of mixture, the locking point is higher for the mixture with coarser aggregates, and it can be attributed to lower asphalt content. Asphalt cement provides lubrication between aggregates particles and facilitates its movement and interlocking. For all the base mixtures, the lowest statistical results

Table 4.2. Summary of the gyratory locking point results for 150-mm mold

Mix	Sample 1	Sample 2	Sample 3	**Mean**	Standard Deviation	Difference (MAX-MIN)	Variance
B-1	102	110	116	**109**	7.0	14	32.89
B-2	82	80	82	**81**	1.2	2	0.89
B-3	75	72	70	**72**	2.5	5	4.22
BM2-1	95	91	97	**94**	3.1	6	6.22
BM2-2	70	72	73	**72**	1.5	3	1.56
BM2-3	63	60	65	**63**	2.5	5	4.22
C-1	79	73	75	**76**	3.1	6	6.22
C-2	68	65	69	**67**	2.1	4	2.89
C-3	54	55	59	**56**	2.6	5	4.67
D-1	53	56	58	**56**	2.5	5	4.22
D-2	51	49	55	**52**	3.1	6	6.22
D-3	37	34	32	**34**	2.5	5	4.22

were obtained for mixtures from group 2. The standard deviation for this group ranged from 1.2 for B-mix to 2.1 for C-mix, and the variance ranged from 0.89 for B-mix to 2.89 for C-mix. It can be observed that for the base mixtures, there is a higher difference in the locking point between lower limit mixtures from group 1 and group 2 than between group 2 and group 3. This difference is more prominent for mixtures with a larger maximum aggregate size. For the surface mixture, the results are similar to base mixtures. However, statistical data do not follow the same trend. For all three mixtures in this group, the standard deviation is 2.5, and the variance is 4.22.

Contrary to base mixtures, the difference in locking point is more significant between group 2 and 3. The difference between group 1 and group 2 is only five gyrations. It can be attributed to a smaller range between upper and lower limits for surface mix than for base mixtures.

It can be noticed from previous research that the maximum aggregate size is not the only factor that affects the gyratory locking point (Polaczyk et al. 2019), and the whole gradation defines the locking point. The BM2-mix that belonged to group 1 has a higher locking point than the base mixture from group 2 and group 3 as well as another base C-mix from group 1 has a higher locking point than BM2-mixes from group 2 and group 3, and even the higher than the B-mix from group 3. Surface mix has not followed this pattern, and the locking point for group 2 and 3 are lower than for base mixtures, except for D-mix from group 1, which has the same locking point as base C-mix from group 3.

Table 4.3 shows the locking point data obtained from the mixtures compacted in 100-mm mold. Compared with the results from different samples, the smaller mold was used to clarify how it affects the locking point. Previous research in compaction with different molds showed that volumetric data and compaction processes differ from different molds (Hall et al. 1996; Leiva and West 2008; McGennis et al. 1996). The locking point decreases if the mixtures were compacted in different mold sizes with different nominal maximum aggregate sizes.

The results indicated that the locking points followed the same pattern when the mixtures were compacted in the smaller mold. For all the mixtures in the same group, the locking point decreased as the maximum aggregate size decreased. However, the results are lower than for the samples compacted in the bigger mold. It can be attributed to the lower energy required to compact and interlock a smaller sample.

For group 1, the locking points ranged from 85 gyrations for B-mix down to 46 gyrations for D-mix. These results represent 24 gyrations decrease for B-mix, and ten gyrations decrease for D-mix compared to the bigger mold. Group 2 gave the results ranged from 70 gyrations for B-mix to 41 gyrations for D-mix. This case represents the same decrease in the locking point of 11 gyrations for B-mix and D-mix. For group 3, the locking point ranged from 62 gyrations for B-mix to 22 gyrations for D-mix. For this last group, the locking point decreases ten gyrations for B-mix and 12 gyrations for D-mix. For the same type of mixture, the locking

Table 4.3. Summary of the gyratory locking point results for 100-mm mold

Mix	Sample 1	Sample 2	Sample 3	**Mean**	Standard Deviation	Difference (MAX-MIN)	Variance
B-1	82	85	87	**85**	2.5	5	4.22
B-2	71	68	70	**70**	1.5	3	1.56
B-3	60	64	62	**62**	2.0	4	2.67
BM2-1	74	72	77	**74**	2.5	5	4.22
BM2-2	58	60	61	**60**	1.5	3	1.56
BM2-3	51	48	48	**49**	1.7	3	2.00
C-1	60	63	59	**61**	2.1	4	2.89
C-2	55	54	56	**55**	1.0	2	0.67
C-3	49	47	50	**49**	1.5	3	1.56
D-1	46	48	44	**46**	2.0	4	2.67
D-2	40	38	41	**40**	1.5	3	1.56
D-3	19	25	23	**22**	3.1	6	6.22

point is higher for the mixture with coarser aggregates as it occurred in the bigger mold.

However, the difference between the locking points is smaller for base mixtures and slightly bigger for surface mixtures. Again, similar to the bigger mold, all the base mixtures got the lowest statistical results for mixtures from group 2. The standard deviation for this group ranged from 1.0 for C-mix to 1.5 for B-mix and BM2-mix. The variance ranged from 0.67 for C-mix to 1.56. For B-mix and BM2-mix. It can be observed that for the base mixtures compacted in 100-mm mold, there is not an as high difference as the locking point between lower limit mixtures from group 1 and group 2 and between group 2 and group 3. There is no visible pattern in these differences as it was visible for 150-mm mold. For the surface mixture, the statistical data followed the same trend as base mixtures. The lower standard deviation of 1.5 was obtained for the mixture from group 2. Contrary to the base mixture, the higher standard deviation was recorded for mixtures from group 3. Similarly, the samples compacted in 150-mm mold, there is a higher difference in the locking point between the mixes from groups 2 and 3 than between the mixes from groups 1 and 2.

Impact Compaction Method

Table 4.4 summarizes the locking point data obtained from the mixtures compacted by the 4” mold impact. As for the gyratory data, the locking point was taken as the three samples' mean value. For the samples marked with “X,” the locking point could not be established during 150 blows (75 blows on each side).

Table 4.4. Summary of the impact locking point results for 4” mold

Mix	Sample 1	Sample 2	Sample 3	**Mean**	Standard Deviation	Difference (MAX-MIN)	Variance
B-1	X	X	X	**X**	X	X	X
B-2	145	148	143	**145**	2.5	5	4.22
B-3	139	142	140	**140**	1.5	3	1.56
BM2-1	X	X	145*	**X**	X	X	X
BM2-2	140	139	135	**138**	2.6	5	4.67
BM2-3	125	129	126	**127**	2.1	4	2.89
C-1	141	146	142	**143**	2.6	5	4.67
C-2	129	130	135	**131**	3.2	6	6.89
C-3	125	122	124	**124**	1.5	3	1.56
D-1	128	121	125	**125**	3.5	7	8.22
D-2	110	112	104	**109**	4.2	8	11.56
D-3	105	109	108	**107**	2.1	4	2.89

For the B-mix of group 1, additional samples were compacted with 200 blows (100 on each side), and the locking point was established at around 165 blows. However, these results were not included in this study because of the different compaction patterns and the aggregates' breakage. After the samples' visual evaluation, the post-compaction gradation was performed, and the damage in courser aggregates was observed. For BM2-mix of group 1, no additional samples were compacted, and it was assumed that the locking point was higher than 150 blows. Only one sample from this group reached the locking point before 150 blows and was marked with an asterisk.

For the rest of the mixtures, the impact locking point was calculated as the mean value of the three samples. The same pattern was observed for the gyrator compactor's data as the locking point's value decreased with decreasing maximum aggregate size. There are only two mixtures in group 1, and the locking point decreased from 143 blows for C-mix to 125 blows for D-mix. For group 2, the locking point decrease from 145 blows for B-mix to 109 blows for D-mix. D-mix results are much lower than for base mixtures, as they ranged from 145 blows to 131 blows. The mixes from group 3 ranged from 140 blows for B-mix to 107 blows for D-mix. The base mixtures have a closer range from 140 blows for B-mix to 124 blows for C-mix. The locking point's close results for the surface mixture for group 2 and group 3, 109 blows, and 107 blows, respectively. It can indicate that the fine aggregate mixture combined with high asphalt content can be unstable and requires more energy to develop a stable skeleton. Further study is required to explore the influence of the asphalt binder on the compactability of the asphalt mixtures.

The statistical results were also evaluated for the data obtained from impact compaction; however, for the mixtures with higher maximum aggregate size (B-mix and BM2-mix), it was impossible to get sufficient data to conduct the statistical analysis. The lowest statistical data were obtained for mixtures from group 3, while for gyratory compaction, the lowest values were obtained for group 2. The standard deviation for group 3 ranged from 1.5 for B-mix and C-mix to 2.1 for BM2-mix and D-mix. The variance for group 3 ranged from 1.56 for B-mix and C-mix to 2.89 for BM2-mix and D-mix. It can be observed that the statistical results are in a closer range than for gyratory compaction; however, as was mentioned previously, some of the mixtures had insufficient data to conduct statistical analysis. For the surface mixture, the results are slightly bigger than for the base mixtures. Statistical data follow the same trend, but the values are higher for the surface mixtures than for the base mixtures.

Figure 4.2 presents the locking point results comparison obtained in this study. As can be seen, the locking point decreases with the sample size for gyratory compaction, but the mixtures' ranking is maintained. The impact compaction compared to gyration compaction is less effective per blow. Generally, for every gyration in 150-mm mold, another two blows must reach the locking point. For 100-mm mold, this difference is even higher. The results of the locking points obtained in this study followed the pattern from previous studies. As the aggregate

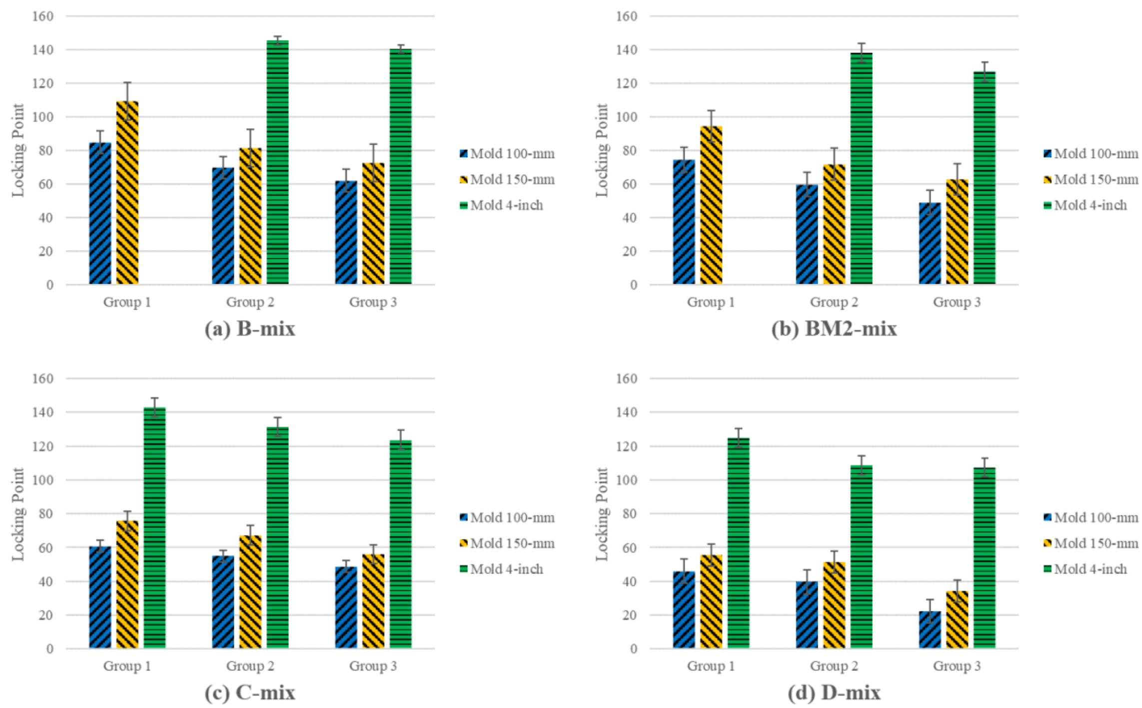

Figure 4.2. Summary of the locking point results for different types of mixtures compacted in different molds: (a) B-mix, (b) BM2-mix, (c) C-mix, and (d) D-mix

size decreased, the locking point also decreased. The higher asphalt content returned a lower locking point, which was similar to previous research works.

Conclusions

A laboratory study has been conducted to investigate the influence of aggregate gradation of the different asphalt mixture types on compactability by utilizing the locking point concept. A total of four types of hot mix asphalt were utilized in this study. Each type of mixture was designed with three different gradations and the same PG 64-22 asphalt binder. Two different compaction methods were applied, the impact and the gyration. The impact locking point data were acquired with the accelerometer attached to the Marshall hammer's falling mass. The impact locking point was defined as the first blow during the impact compaction, after which the duration of the impact and the peak acceleration does not change significantly (±5%). The gyratory locking point was obtained from densification curves as the first gyration in the first set of three gyrations at the same height preceded by two sets of two gyrations at the same height. Based on the results obtained in this study, the following conclusions were reached:

- Overall, the gyratory locking point could be established for all the samples utilized for this study. For the impact locking point, it was possible to obtain the locking point for most mixtures, except for coarse base mixtures. The coarse mixtures with a large stone and low asphalt content have a locking point above 150 blows, commonly used in Marshall mix design. The results obtained from different compaction methods follow the same ranking.

- The different gradation inside each type of asphalt mixture strongly influences the locking point, regardless of the compaction method. The binder type mixtures that belonged to group 1 had a higher locking point than base type mixture from group 2 and group 3 as well as binder/surface type mixture from group 1 has a higher locking point than binder type mixture from group 2 and group 3, and even higher than base mixture from group 3. The surface type mix does not follow this pattern, and the locking point for groups 2 and 3 is lower than for base type mixtures, except for mix from group 1, which has the same locking point as intermediate/surface type mix from group 3.
- The fine aggregate mixture combined with high asphalt content can be unstable and requires more energy to develop a stable skeleton. For the surface mixture, the difference between group 2 and group 3 is only two blows. Further study is required to explore the influence of asphalt binder on the compactibility of the asphalt mixtures.
- The gyratory locking point for the 150-mm specimens was higher than those compacted in 100-mm mold, but the ranking is maintained regardless of the mold size. The ranking permits comparing the locking points for various asphalt mixture when the same size of the mold is used.
- Except for the surface type mixture, coarsest mixtures inside the same type of mixture recorded the highest variance in different samples' results. The coarsest base type mixture had a variance of 32.89, while the intermediate mix

had a variance of 0.89. For surface type mixtures, the gradation difference might not have that strong influence on variance in results.

- The gyratory compactor provided higher compaction effort per gyration than the impact compactor per blow. The number of blows to reach the locking point is higher than the number of gyrations. It is especially visible for finer mixtures.

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CHAPTER FIVE

INFLUENCE OF AGGREGATES ANGULARITY ON COMPACTABILITY OF ASPHALT MIXTURES

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My contribution to this paper was performing majority of the experimental tests, data analysis, and preparing the original draft and all figures and tables.

Abstract: Aggregate angularity plays a critical role in the performance of asphalt mixtures. Current asphalt mix design methods do not specify compaction effort according to aggregate angularity or locking points. This study utilized two compaction methods, gyratory (Superpave Gyratory Compactor) and impact (Marshall Hammer), to investigate the influence of aggregate angularity on the locking point of asphalt mixtures. For gyratory compaction, densification curves were used to determine the gyratory locking point. For impact compaction, an accelerometer was connected to the Marshall hammer to register asphalt response, by which the impact locking point was determined. Five mixtures were designed and produced in the laboratory with different aggregate angularities. The mixtures were tested for their locking points and then related to aggregate angularities. Results show that the locking point could be determined for most of the study's mixtures by the gyration and impact methods, except for the mixture composed of uncrushed, round aggregates compacted with the Marshall hammer. The locking point of asphalt mixtures was highly related to aggregate angularity. A higher aggregate angularity resulted in a lower locking point. Mixtures produced

with only crushed aggregates showed locking points much lower than mixtures made with crushed and uncrushed aggregates. In contrast, mixtures made with only uncrushed aggregates had much higher locking points than those made with both aggregates. This study's findings indicate that compaction effort in asphalt mix design should be specified according to the mixtures' locking point.

Introduction

The aggregate properties substantially impact asphalt mixture performance because the aggregate is a significant portion in an asphalt mixture (around 95% by mass or between 80% and 90% by volume). Aggregate characteristics can be divided into four groups: strength, texture, shape, and angularity. The angularity of aggregate plays a critical role in asphalt mixture performance. It thus is one of the most important parameters in asphalt mix design, especially the Superpave Mix Design Method. (Kim and Souza 2009; Meier and Elnicky 1988).

Aggregate particles with low angularity generate fewer interparticle contact points, which improves the workability of asphalt mixtures and makes them easier to compact. However, asphalt mixture designers should look for a balance between aggregate angularity and mixture compaction because interlock is required to prevent rutting after construction. In a properly designed asphalt mixture, aggregates' composition should develop a stable aggregate skeleton for sufficient shear resistance and proper workability for adequate compaction (Huang et al. 2009).

Many studies have been conducted to investigate the influence of aggregate angularity on asphalt mixture properties. Wedding and Gaynor (1961) concluded that crushed gravel in asphalt mixtures could significantly increase stability compared to uncrushed aggregates. Prowell et al. (2005) indicated that asphalt mixtures with higher percentages of fractured faces could increase rut resistance.

The compaction effort in mix design is represented by a specific number of gyrations (N_{design}) for Superpave or by a specific number of blows for Marshall mix design. Both gyrations and blows simulate energy applied to the asphalt layer in the field by rollers during construction and secondary compaction applied by a few years of transit. The compaction effort is primarily based on the expected traffic and does not consider the angularity of aggregates.

Since angularity is one of the most important properties of asphalt mix aggregates, the locking point should largely depend on this property. The compaction effort should be closely related to the locking point. If there is no sufficient compaction effort to reach the locking point, the asphalt mixture might have inadequate rutting performance. Contrarily, if the mixture's energy is beyond the locking point, the fracturing of aggregates can occur and compromise the asphalt mix's performance.

Objective and Scope

This study's objective was to evaluate the influence of aggregate angularity on the locking point of asphalt mixtures compacted with the impact and the gyration method. Aggregates with high and low angularities were chosen and used in this study. Five asphalt mixtures were prepared with different aggregate angularities following the Tennessee Department of Transportation (TDOT) Standard Specifications (TDOT 2015). Aggregates with a low angularity were uncrushed river stone and natural sand from Tennessee, and those with a high angularity were crushed limestone from Tennessee. The samples were compacted in 101.6-mm (4-inch) Marshall mold and 100-mm and 150-mm Superpave molds. One type of binder, PG 64-22 (according to the Superpave performance grade), was used in all asphalt mixtures.

Laboratory Experiments

Materials

A total of six aggregates were utilized in this study: three aggregates with a low angularity (uncrushed river stone 19mm (3/4"), uncrushed river stone 9.5mm (3/8"), and natural sand), three aggregates with a high angularity (crushed limestone 19mm (3/4"), crushed limestone 9.5mm (3/8"), and crushed limestone (#10 screenings)). Figure 5.1 shows all six aggregates.

Aggregate angularity was tested following ASTMD5821 (2017) for coarse aggregates and ASTMD1252 (2017) for fine aggregates. Coarse aggregate angularity was determined for material retained on sieve No. 4 (4.75-mm). The sample mass depends on the maximum size of material particles. The sample was washed in sieve No. 4 (4.75-mm), dried, and weighed. The sample was placed on the flat surface, and each particle was evaluated to verify if a particle meets the

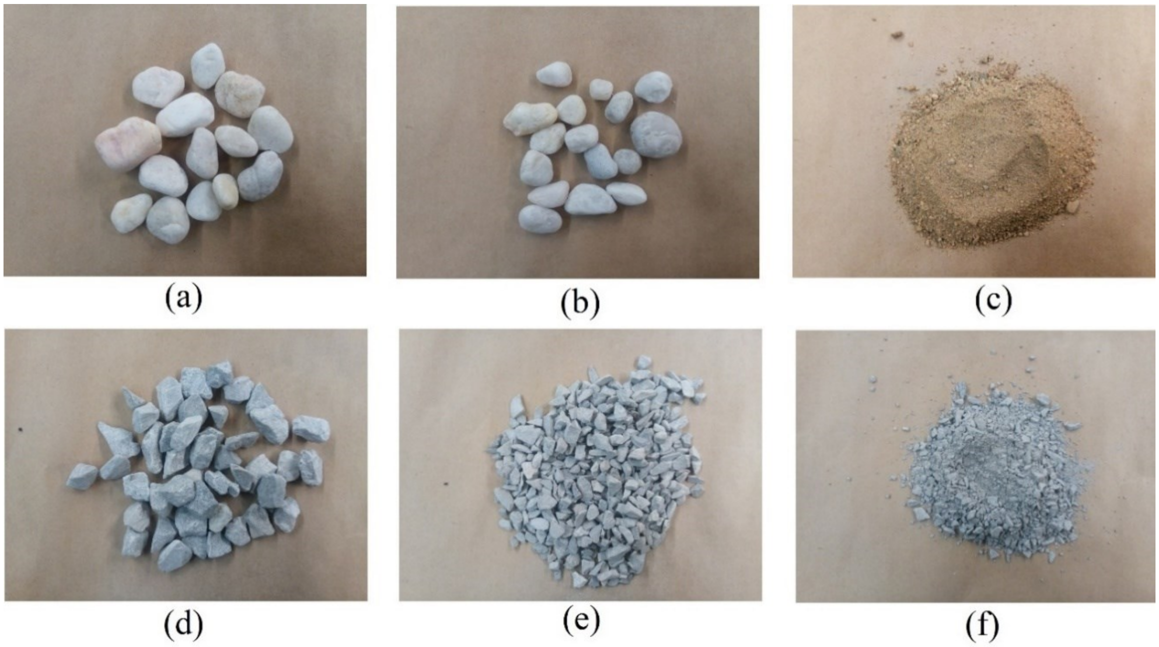

Figure 5.1. (a) Uncrushed gravel 19mm (3/4”), (b) Uncrushed gravel 9.5mm (3/8”), (c) Natural Sand, (d) Crushed Limestone 19mm (3/4”), (e) Crushed Limestone 9.5mm (3/8”), (f) Crushed Limestone (#10)

fracture criteria. Particles were separated into two categories: particles that did not meet fracture criteria and particles with a specific number of fractured faces (in this study, one face). The result was calculated as the percentage of particles with one fractured face. The uncompacted void content determined fine aggregate angularity. A calibrated measure was filled with aggregate flowing through the funnel at a specific height. The result was calculated as the relation of the void in the material that filled the measure to measure the volume. The angularity test results are presented in Table 5.1. Aggregate angularity results. The results for coarse aggregate angularity are provided for one fractured face.

Aggregates were screened by a set of sieves as follows: 25.4mm (1"), 19mm (¾"), 9.5mm (3/8"), No. 4, No.8, No. 30, No. 50, No. 100 and No. 200. Screened uncrushed material (gravel 19mm (¾"), gravel 9.5mm (3/8"), natural sand) retained on each sieve was mixed, as well as material obtained from crushed materials (limestone 19mm (¾"), 9.5mm (3/8") and #10). The aggregates were then mixed by weight to produce mixtures with different angularities following TDOT specification for 307 B base course mixture. The first mixture was composed of the low angularity materials: uncrushed river stones and natural sand. For the second mixture, 25% of crushed aggregates were added to increase angularity. The third mixture was composed of 50% crushed and 50% uncrushed aggregates. The fourth mixture was prepared with 25% uncrushed and 75% crushed materials. Finally, the fifth mixture was made with crushed aggregates. Table 5.2 presents a summary of the aggregate blends' compositions.

Table 5.1. Aggregate angularity results

Aggregate	**CAA (%)**	**FAA (%)**
Uncrushed gravel (3/4")	13	---
Uncrushed gravel (3/8")	17	---
Natural Sand	---	37.1
Crushed Limestone (3/4	100	---
Crushed Limestone (3/8")	100	---
Crushed Limestone (#10)	---	48.6

Table 5.2. Summary of the compositions of aggregate blends

SIEVE	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5
3/4"	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
3/8"	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
No. 4	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
No. 8	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
No. 30	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
No. 50	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
No. 100	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed
No. 200	100% Uncrushed	75% Uncrushed 25% Crushed	50% Uncrushed 50% Crushed	25% Uncrushed 75% Crushed	100% Crushed

For the five mixtures utilized in this study, an unmodified binder PG 64-22 was utilized to minimize binder influence. The mixing temperature for asphalt mixtures was 148.9°C (300°F), and the compaction temperature was 135°C (275°F).

Equipment

The mixture design's specimens' compaction was made using a standard Marshall mechanical compactor and 101.6mm (4-inch) molds. The same compactor was utilized to evaluate the locking point utilizing the impact compaction method. An accelerometer with a capacity of 49033 m/s2 (5000g) was placed on the falling mass of the Marshall hammer. A Superpave Gyratory Compactor (SGC) was used to obtain the locking point compacted in 100-mm molds and 150-mm molds.

Specimen Preparations

Aggregates previously screened by a specific set of sieves were blended to produce five asphalt mixtures with the different percentages of crushed and uncrushed materials. The percentage of each material was determined at each sieve level, not for the whole aggregate mix. Figure 5.2 shows the aggregate gradation of five mixtures in this study. The aggregate gradation was designed to be a mid-point between the upper and lower limits of TDOT specifications for the 307C base course mixture. The gradation of each mix was maintained equal to eliminate the influence of different gradations on the locking point. Initially, an effort was made to use the same aggregate type, such as crushed and uncrushed gravel

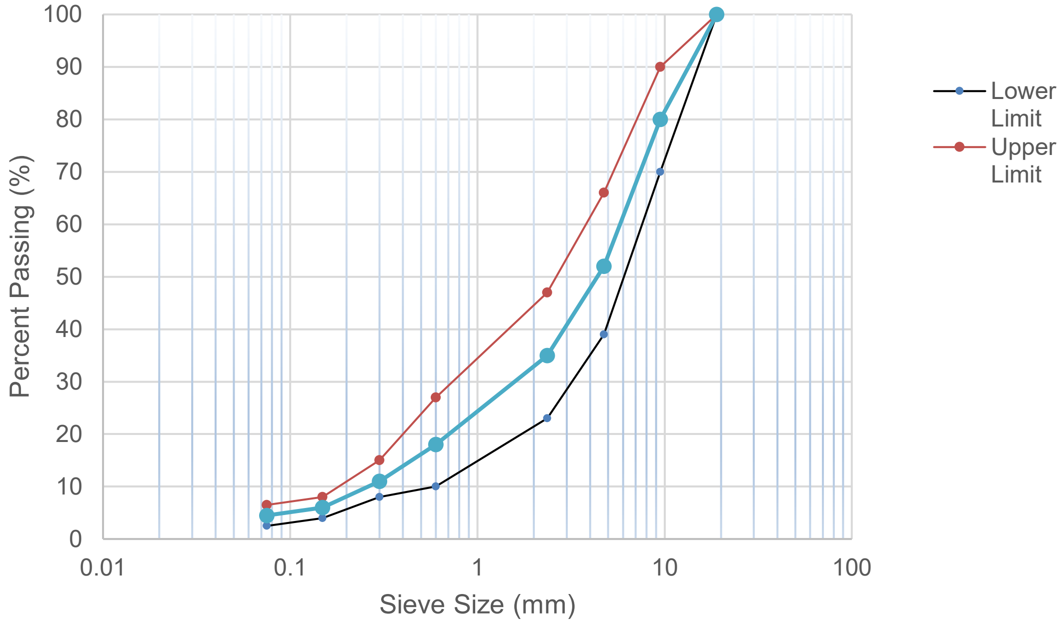

Figure 5.2. Aggregate gradation of five mixtures

and sand, to minimize the aggregate type's influence on the locking point. However, it was difficult to obtain adequate materials with a significant difference in angularities. The Los Angeles abrasion test indicated close results for gravel and limestone materials (27% for gravel vs. 34% for limestone).

Additionally, the limestone result can be affected by many asperities that increase the abrasion test's value because asperities in the crushed material can be easily damaged. Abrasion is one of the factors that can affect the locking point results. As abrasion increases, so makes the locking point. This increase might be attributed to the fact that aggregates with a high abrasion also easily break. The breakage of particles can lead to additional compaction effort, thus increasing the locking point. A similar level of abrasion could minimize the abrasion effect on the locking point results.

Asphalt cement is another factor that can affect the locking point of asphalt mixtures. Asphalt cement serves as a lubricant during the compaction of asphalt mixtures and potentially affects the locking point. Different asphalt contents and types provide different lubricating effects, thus resulting in different locking points. It was decided that in this study, the optimum asphalt content should be used for each of the mixtures. Although the influence of asphalt cement content could not be eliminated, it could be minimized using optimum asphalt content, the same mixing temperature, and the same compaction temperature. The same unmodified asphalt binder PG 64-22 was utilized to produce all the mixtures. The same mixing and compacting temperatures were used to prepare the samples. To eliminate the influence of short-time aging, all the samples were exposed to the same aging process and the same amount of aging time.

For all five aggregate mixtures, specific gravities were determined, according to ASTMC127 (2015) and ASTMC128 (2015). Specific gravity tests were performed on the aggregate blends and not on individual aggregates. The Marshall mix design was used to prepare five asphalt mixes according to the Tennessee Department of Transportation (TDOT) specifications. For each mixture, four sets of three samples with different asphalt contents were compacted by applying seventy-five blows to each side. Two samples were tested for theoretical maximum specific gravity (ASTMD2041 2011). The target air void content was set to 4%. The samples were mixed in a mechanical mixer at 148.9°C (300°F) and compacted at 135°C (275°F). Before compaction, the loose mixtures were subjected to a short-time aging process of two hours at 135°C (275°F). Since these mix designs' primary objective was to find the optimum asphalt content with specific aggregate angularity and established air voids, some of the other parameters might be out of specifications. **Error! Reference source not found.**summarizes the Marshall mix designs.

Testing Procedure

To determine the locking point with the gyratory compactor, the samples of each asphalt mixture were prepared with an optimum asphalt content and placed in pre-heated 100-mm and 150-mm Superpave Gyratory Compactor molds. The samples were compacted to 100 gyrations, and the height of every specimen was recorded after each gyration. Once compacted, the samples were left to cool down overnight. The densification curves were then obtained to determine the locking points.

In this study, the definition of the locking point proposed by Vavrik and Carpenter (1998) was utilized. This definition describes the locking point as the first gyration in the first set of three gyrations at the same height preceded by two sets of two gyrations at the same height (commonly presented as LP2-2-3). The locking point's determination was based on the relationship between cored samples and samples compacted in a 150-mm mold related to air void level.

For the locking point obtained with the impact compaction method, a 5,000g accelerometer was connected to the 10-lb—Marshall hammer mass. Data provided by the accelerometer were received by a data acquisition system and sent to a computer. The accelerometer allowed the continuous recording of the acceleration data, which were stored in the computer. The acceleration data were filtered by applying a five-points moving average and plotted in the time domain for analysis. The locking point was determined to be the first blow, after which the peak acceleration and duration of impact did not change significantly. In the authors' previous studies (Polaczyk et al. 2018).

Laboratory Experiments

Gyratory Compaction Method

Table 5.3 presents the results obtained from the samples compacted in the 150-mm mold. It was initially expected that asphalt mixtures with more angular

Table 5.3. Summary of the locking point results for 150-mm mold

Mix	Uncrushed (%)	Crushed (%)	S1	S2	S3	S4	S5	S6	S7	S8	Mean	SD	Range	Variance
1	100	0	65	75	76	64	75	70	79	69	72	5.4	15	26.0
2	75	25	58	52	60	51	60	61	62	55	57	4.2	11	15.5
3	50	50	50	55	49	49	46	58	55	50	52	4.0	12	14.3
4	25	75	51	48	50	54	47	55	53	50	51	2.8	8	7.0
5	0	100	40	46	43	47	41	43	40	45	43	2.7	7	6.4

aggregates would show a higher locking point since these mixtures are more difficult to compact. However, it was observed that more angular aggregates resulted in a lower locking point. This lower locking point can be attributed to the fact that although these mixtures were more difficult to compact, the angular particles in them were also more likely to interlock with each other at an earlier stage and result in a lower locking point.

The five mixtures' locking points ranged from 72 gyrations for mixtures with a low aggregate angularity to 43 gyrations for mixtures with a high aggregate angularity. It was observed that as aggregate angularity increased, the range and variance of locking points decreased. Mixture #1, which was produced with only uncrushed aggregates, the locking points ranged from 64 gyrations to 79 gyrations. Round aggregates generated fewer interparticle contacts. These round aggregate particles were in constant movement during compaction. This effect can be compared to compacting sand on the beach, which would hardly be successful. Mixture #1 was washed with Trichloroethylene, and sieve analysis was performed to determine if there was any aggregate breakage. The results showed that there was little aggregate breakage during compaction.

Samples of the mixtures with a higher percentage of crushed aggregates exhibited a lower locking point and a lower standard deviation, and lower variance of the range of locking points. As mentioned earlier, the average locking point results for all five mixtures ranged from 72 gyrations for uncrushed materials to 43 gyrations for crushed aggregates. The mixtures with a percentage of both crushed and uncrushed materials had a narrower range from 51 gyrations to 57 gyrations, resulting in a range of only six gyrations. In comparison, the range between the locking points for all five mixtures was 29 gyrations.

Mixture #5 consisted of only crushed materials and obtained the most consistent results of all the individual samples and the lowest locking point. The locking point range was from 40 gyrations to 47 gyrations, resulting in a range of 7 gyrations. Its standard deviation and variance were 2.7 and 6.4, respectively, resulting in the lowest value from all the mixtures. Similarly, after mixture #5 was washed with Trichloroethylene and post-compaction sieve analysis was performed, the gradation results showed no significant changes in the percentage passing each sieve, indicating that no significant aggregate breakage occurred during compaction.

Table 5.4 summarizes the gyratory locking point results using a 100-mm mold. Similarly to the locking points using 150-mm mold, the mixture produced with uncrushed aggregates showed the highest locking point of 61 gyrations. In comparison, the mixture made with crushed material had a much lower locking point of 29 gyrations.

Comparing results from the 150-mm mold with those from 100-mm mold, the ranking of mixtures' locking points is the same. However, the locking point for each mixture was lower than those from a 150-mm mold. The difference in locking point can be attributed to differences in mold size and the amount of material required to prepare each sample. The amount of material required to prepare a

Table 5.4. Summary of the gyratory locking point results for 100-mm mold

Mix	Uncrushed (%)	Crushed (%)	S1	S2	S3	S4	S5	S6	S7	S8	Mean	SD	Range	Variance
1	100	0	61	58	54	63	60	65	66	60	61	3.9	12	13.1
2	75	25	54	51	48	46	50	48	45	49	49	2.9	9	7.1
3	50	50	50	45	45	43	49	51	44	43	46	3.2	8	9.2
4	25	75	44	40	42	44	38	37	40	39	41	2.6	7	6.0
5	0	100	29	25	31	31	30	28	30	29	29	2.0	6	3.4

150-mm sample is almost four times that of a 100-mm sample. The space to accommodate aggregate movement and the compaction effort required to generate aggregate interlocking aggregate is lower for the smaller mold, explaining the lower locking points. The samples compacted in the 100-mm mold also had lower standard deviation values, variance, and range than those compacted in 150-mm mold. The locking points range was from 61 gyrations for asphalt mixture with uncrushed materials to 29 gyrations for mixtures with crushed aggregates. Similarly, the data obtained from the bigger mold shows that mixtures prepared with a combination of crushed and uncrushed material had a narrower range from 41 gyrations to 49 gyrations (a difference of 8 gyrations) than samples prepared with either crushed or uncrushed material (a difference of 32 gyrations).

For mixture #1 compacted in the 100-mm mold, the range of the results obtained from eight samples was from 54 gyrations to 66 gyrations, the standard deviation was 3.9, and the variance was 13.1. These results were lower than those for the samples compacted in 150-mm mold. Mixtures #2, #3, and #4 had a similar range, standard deviation, and variance. For the samples compacted in the more extensive mold, mixture 3 showed the highest standard deviation. Mixture #5, composed of crushed aggregates, had the lowest locking point, standard deviation, variance, and range. These lower parameters might be attributed to its highest interlocking ability with crushed aggregates and a lower compaction effort required because of its smaller size.

Table 5.5 summarizes the locking point results obtained from the samples compacted with the impact hammer. It is worth noting that similar to the gyratory compactor's locking points, when the percentage of crushed particles in the asphalt mixtures increased, the locking point decreased. However, the results of range, standard deviation, and variance did not show a clear trend as it was observed with data obtained for the gyratory compactor. Mixture #5 showed the highest standard deviation, variance, and range, followed by mixture #3, mixture #2, and mixture #4.

It was not possible to determine the locking point for mixture #1. Its results were marked as >150 blows, as found in previous works, which means that the locking point was higher than 150. The difficulty in determining the locking point for this mixture can be attributed to the simple lack of interlocking between uncrushed aggregate particles and their continuous movement. One additional sample of mixture #1 was compacted by applying 150 blows on each specimen's side. However, it was impossible to detect the locking point because of continuous variation in the peak acceleration and impact duration.

Mixtures #2, #3, and #4 showed a similar locking point pattern as the same mixtures compacted with the gyratory compactor. The pattern was characterized by a decreasing locking point and a close range of the results. The range was from 144 blows for mixture #2 to 134 blows for mixture #4. However, the standard deviation and range did not follow the pattern seen in the gyratory compactor (150-mm mold) in that process; the highest standard deviation and range of the results

Table 5.5. Summary of the locking point results for impact compaction in 101.6mm (4-in) mold.

Mix	Uncrushed (%)	Crushed (%)	S1	S2	S3	Mean	SD	Range	Variance
1	100	0	>150	>150	>150	---	---	---	---
2	75	25	142	147	143	144	2.6	5	4.7
3	50	50	140	137	134	137	3.0	6	6.0
4	25	75	135	131	135	134	2.3	4	3.6
5	0	100	102	113	107	107	5.5	11	20.2

were for mixture #3. But for the gyratory compactor, the highest values were for mixture #2. Similar to the results obtained with the gyratory compactor, mixture #5 had the lowest locking point. For gyratory compaction, mixture #5 had the most consistent results among the samples. Still, the results were less consistent for impact compaction, with a range of 11 blows, a standard deviation of 5.5, and a variance of 20.2. All three samples were washed with Trichloroethylene, and post-compaction sieve analysis was performed to evaluate possible aggregate breakage. The results showed that sample #2 suffered particle breakage in the coarse portion of the aggregate gradation curve, while samples #1 and #3 did not show significant aggregate breakage. Even with one sample affected by aggregate breakage, mixture #5 still showed the lowest locking point, consistent with its gyratory locking points.

The locking point results from both gyratory and impact compaction indicate that an increase in aggregate angularity results in a decrease in locking point. A higher angularity also requires a higher optimum asphalt content, which increases the lubricating effect of asphalt binder, thereby affecting the locking point of asphalt mixtures.

Angularity affects the locking point considerably, and the locking point that is not a part of the design and the field compaction effort can affect the performance of the asphalt mixture. The high range of locking points produced by different aggregates angularities can result in performance issues. The value of Ndesign for Superpave and the number of blows for Marshall do not consider aggregate angularities or the locking point. In this study, the locking point results for the impact compaction ranged from 107 to 144 blows. The mixture with the locking point of 107 blows is heavily over compacted when standard 75 blows per side are applied, and the skeleton of this mixture can be damaged. The locking point for gyratory compaction obtained from 150-mm mold ranges from 43 to 72 gyrations and 100-mold from 23 to 61 gyrations. These high ranges compared to the single value of Ndesign can produce under or over compacted asphalt mixture. It is advisable to utilize the locking point as the complementary factor when mix design is performed. It can be utilized as a fast indicator of possible performance issues before more complicated and time-consuming performance tests are conducted.

Conclusions

The compaction effort required in an asphalt mix design to achieve a stable and robust aggregate skeleton might be specified according to the mixture's locking point. Unnecessary further compaction causes the breakage of aggregate particles and damages the aggregate skeleton of the mixture. This study evaluated the influence of aggregate angularity on the locking point of asphalt mixtures. Based on the laboratory test results, the following conclusions can be drawn:

- Aggregate angularity had a significant influence on the locking point of asphalt mixtures. As aggregate angularity increased, the locking point of asphalt mixtures decreased. More angular aggregates not only made asphalt mixtures more challenging to compact but also increased the possibility for aggregate particles to interlock with each other at the early stage of compaction, resulting in a lower locking point.

- The locking point could not be determined for the mixture with only uncrushed aggregates (mixture #1 in this study) compacted by the impact, even with an increased number of blows. The reason can be attributed to the lack of interlocking between spherical aggregates.
- Mixtures with high participation of crushed aggregates may suffer a significant aggregate breakage during impact compaction. Aggregate breakage required additional compaction effort, resulting in a higher locking point. Additionally, aggregates breakage creates more surface area that is not covered with asphalt binder. This uncoated area may permit the water to infiltrate the asphalt layer and decrease performance and life period.
- Mixtures made with a combination of crushed and uncrushed aggregates showed a closer range of locking points in comparison to mixes with only uncrushed or crushed aggregate.
- Impact compaction and gyratory compaction (in 100mm and 150mm molds) gave a similar ranking of the locking points. However, for the same mixture, using a small size mold (100-mm gyratory mold) resulted in a lower locking point than the use of a large mold (150-mm mold). Smaller samples required lower energy to interlock.
- Compaction effort in two current asphalt design methods, Superpave (N_{design}) and Marshall (blows) does not include aggregate angularity as a design factor.

This study showed that different aggregate angularities need different compaction efforts to develop a stable aggregate skeleton and reach their locking points. Additional compaction beyond the locking point may cause aggregate breakage. It is recommended that aggregate angularity be considered in an asphalt mix design, and a mixture should not be compacted beyond its locking point to avoid potential aggregate breakage.

- The optimum asphalt content was used for each mixture to determine their locking points in this study. However, it is not clear about the effects of asphalt content on the locking point. A higher aggregate angularity usually requires a higher optimum asphalt content, which provides increased lubrication and affects locking point results. Further studies are needed to explore the effects of asphalt content on the locking point.

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CHAPTER SIX

INFLUENCE OF ASPHALT BINDER ON COMPACTABILITY OF ASPHALT MIXTURES

A version of this chapter was accepted as Polaczyk, P., Hu, W., Han. B., Gong, H., Ma, Y., and Huang. B. “Influence of Asphalt Binder on the Compactability of Asphalt Mixtures Using Locking Point” and will be published in the *Journal of the Association of Asphalt Paving Technologists*, Volume 89.

My contribution to this paper was performing majority of the experimental tests, data analysis, and preparing the original draft and all figures.

Abstract: Compaction is an important process for the asphalt mixture service life. An adequately compacted mixture is crucial for long-lasting pavement. This study's objective was to evaluate the influence of asphalt binders on the compactability of the asphalt mixtures by utilizing the concept of the locking point. Two compaction methods (impact and gyration), different temperatures, and asphalt content, and two mixing methods (traditional and alternative) were used to achieve this objective. Asphalt binder has significantly influenced asphalt mixtures' properties, even though it constitutes only around 5% of the total mass. Two important qualities provided by asphalt binders are adhesion and lubrication. Adhesive properties of asphalt binder provide bonding between aggregates particles after compaction. Lubrication decreases friction forces and allows a more workable mixture. In this study, the locking point concept was utilized to evaluate the lab compactability of mixtures. The gyratory locking point was defined by analyzing the change of the specimen’s height, and the impact locking point was captured by utilizing an accelerometer. The results indicate that the mixing sequence significantly influences the asphalt mixtures' lab compactability regardless of the

compaction method. The alternative mixing alters traditional mixing and permits an improvement in coarse aggregates' film thickness, affecting the asphalt mixture's homogeneity. The mixing sequence influences the mixtures with larger stones since it is more challenging to get an adequate coating on the largest particles, and the mixing sequence affects mixing efficiency. On average, alternative mixing permitted around 50% faster coating of aggregate particles than traditional blending. The lubricative properties of asphalt binder increase with decreasing viscosity, and the lab compactability of the asphalt mixture is improved by higher asphalt content.

Introduction

Asphalt binder significantly affects asphalt mixtures' properties, even though it constitutes only around 5% of the total mass. Two important qualities provided by asphalt binders are adhesion and lubrication. The adhesive properties of the asphalt binder provide bonding between aggregates particles after compaction. Lubrication decreases friction forces and allows more workable mixtures. Friction is a force that opposes the movement of solid surfaces against each other. The surface of aggregates that are not crushed may appear plane, but there are always microscopic irregularities. When two aggregate surfaces touch each other under pressure, these irregularities make the friction force increase in asperities or peaks. These forces greatly depend on the material type utilized in the mixture (shape, texture, and angularity). The ratio of the friction force to the normal force is the coefficient of friction. This coefficient is an empirical value and must be measured for every different material. River gravel provides less friction than a crushed material and has a lower coefficient of friction. Asphalt binder decreases the friction coefficient during mixing and compaction, allowing the aggregate skeleton's development and providing the required volumetric properties (Al-Khateeb 2018; Baumgardner et al. 2012; Gong et al. 2019; Roberts et al. 1991).

During compaction, aggregates coated with asphalt binder interlock and created a stable structure that provides resistance to rutting and, at the same time, decreases permeability and increases durability. Several elements influence the compactability of asphalt mixes, such as asphalt mix properties, base course material and properties, the thickness, environmental condition, and type and number of rollers. The content and temperature of the asphalt binder also impact the compactability of the mixture. When asphalt content increases, the film thickness that covers aggregate particles increases and improves interparticle lubrication. Asphalt binder is a viscoelastic material whose properties change with changing temperature. The increasing temperature increases the lubricative properties of the asphalt binder (Anderson et al. 1994; Anderson 2002; Jia et al. 2019; McGennis et al. 1996; Polaczyk et al. 2019).

The mixing process is another important factor that influences the properties of the asphalt mixture. Inadequate mixing can impact various properties of asphalt mixes, like homogeneity, adhesion, and film thickness, which can lead to problems during compaction and later during the service period, affecting the performance of asphalt layers. A thicker asphalt film provides more flexible and durable mixes, while a thinner asphalt coat yields brittle and easily cracked mixes. The research on bitumen and aggregates properties and their influence on characteristics of asphalt mixes have a long history. However, the mixing process has received significantly less research effort. Commonly, the research assumes that the asphalt mix is a homogenous material, but only adequate mixing procedures can provide more unvarying material. The most common practice worldwide to produce asphalt mixtures is to mix the aggregates and second inject asphalt binder and permit further mixing. It is the primary method utilized by asphalt plant manufacturers, but there is a risk of unevenly distributed film thickness and potential segregation.

An alternate method of mixing was developed in Sweden by Ohlson. The altered lab mixing order consists of three steps. First, coarse aggregates are mixed with asphalt binder, which permits adequate coating of the largest particles. Second, the filler is added to create the mastic. Third, fine aggregates are added. This alternate mixing sequence can provide more homogenous mixtures and more uniform film thickness, especially for larger aggregates (Anderson 2008; Hesami et al. 2015; Ohlson 2010).

Improvements in film thickness distribution for larger stones may positively affect the compactability of asphalt mixtures by providing additional lubrication and decreasing the compaction energy requirement. Further advantages are the lower mixing temperatures and a more homogenous final product. Over the long run, improvements in film thickness can also bring environmental and economic benefits. Previous research conducted on asphalt mixtures mixed traditionally, and alternative ways indicate that alternative mixing provides an even air distribution through the specimen and easier compaction (Anderson 2008; Elseifi et al. 2008; Hesami et al. 2015; Ohlson 2010).

Objective and Scope

This study's objective was to evaluate how asphalt binders affect asphalt mixtures' lab compactability by utilizing the locking point concept. Two compaction methods (impact and gyration), different temperatures and asphalt content, and two mixing methods (traditional and alternative) were used in this study. Three types of asphalt mixtures (A, BM2, and D) were prepared following the Tennessee Department of Transportation Standard Specifications (TDOT 2015). The mixtures utilized limestone, natural sand, and the asphalt binder PG 64-22.

Laboratory Experiments

Materials

A total of three types (A, BM2, and D) of hot mix asphalt were utilized in this study. The A-mix is a base mixture with 2” maximum aggregate size. The BM2 is a leveling mixture with 1” maximum aggregate size. The D is a surface mixture with ½” maximum aggregate size. Each type of mixture was composed of crushed limestone and natural sand. The limestone and the natural sand were collected in different parts of East Tennessee. To reduce variability in materials, the aggregates were separated through a set of sieves: 2”, 1 ½”, 1”, ¾”, 5/8”, ½”, 3/8”, No. 4, No.8, No. 30, No. 50, No. 100 and No. 200. The aggregate was screened into single sizes to control variability. For all the mixtures, unmodified binder PG 64-22 was used. The compaction temperature for this asphalt binder was 305°F, and the mixing temperature was 315°F.

Equipment

A Superpave Gyratory Compactor (SGC) and 150-mm molds were utilized to determine the locking point. Compaction for the mix design was achieved by a Marshall compactor and 4-inch molds. The same hammer was used to compact specimens utilized to determine the locking point using the impact compaction. A 5000g accelerometer was fixed on the falling mass of the Marshall hammer.

The mix designs were prepared using a standard Marshall Compactor and 4-inch molds (ASTMC127 2015; ASTMC128 2015; ASTMD2041 2011; ASTMD2726 2017). The gradation of the mixtures is presented in Figure 6.1. For each mixture type (one surface mixture and two base mixtures), four samples with different asphalt content were mixed, compacted, and tested, and the optimum asphalt contents were defined. The summary data of mix design is presented in Table 6.1.

First, the samples with different asphalt content and different compaction temperature were prepared. A Superpave Gyratory Compactor and 150-mm molds were utilized to capture the gyratory locking points. Each mixture was compacted at six different temperatures ranging from 190°F to 340°F and at the six different asphalt contents (three below and three above the optimum asphalt content) after

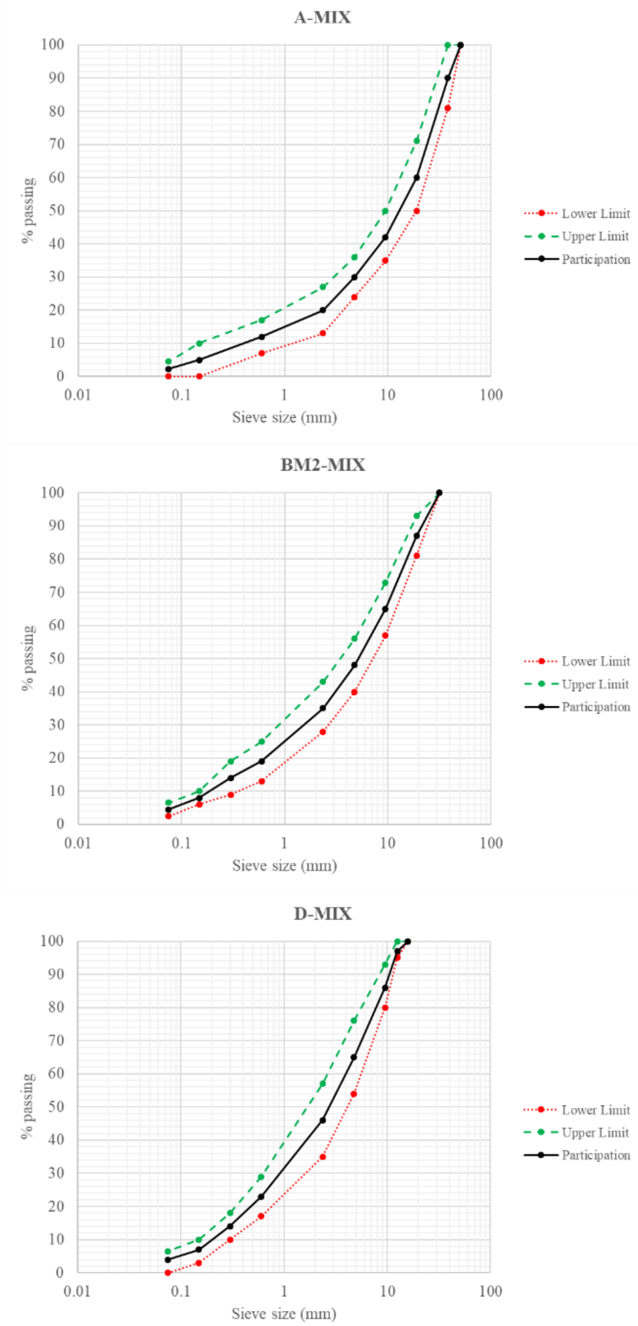

Figure 6.1. Gradation of the A, BM2, and D asphalt mixtures

Table 6.1. The summary data of asphalt mix designs

Mix	Optimum AC (%)	Air Void (%)	VMA (%)	VFA (%)	Blows
A	3.4	4.0	11.7	66	75
BM2	4.5	4.0	13.1	70	75
D	5.6	4.0	14.2	72	75

completion of 2 hours short term aging. The 4800 grams samples were compacted with 150 gyrations. The number of gyrations was chosen based on experience to obtain a complete densification curve and, at the same time, not to over-compact the specimen and get the more precise density. The gyratory locking point was acquired by following the method suggested by Vavrik and Carpenter (1998), which defines the locking point as the first gyration in the first set of three gyrations at the same height preceded by two sets of two gyrations at the same height (LP2-2-3). To determine the impact locking point, the short-term aged (2 hours) samples (1200 grams) were placed in a pre-heated 4-inch Marshall mold and compacted by 75 blows of Marshall hammer on each side of the specimen. Like the gyratory compaction, each mixture was compacted at six different temperatures ranging from 190°F to 340°F and six different asphalt contents (three below and three above the optimum asphalt content). Hammer acceleration data were obtained with an accelerometer placed on the falling mass of the Marshall hammer. The acquired data were transferred through the data acquisition system to a computer. The set-up for this experiment followed the one proposed by Polaczyk et al. 2018.

Next, the samples with the alternate mixing sequence were prepared. A separate set of specimens was prepared and compacted to evaluate the influence of mixing sequence on the compactability of asphalt mixtures. The same gradation and optimum asphalt content were used as in previous specimens. The mixing sequence utilized was proposed by Ohlson (2010) with minor adjustments. The aggregates were separated by size: coarse (retained on sieve No. 4), fine (passing sieve No. 4 and retained on sieve No. 200), filler (passing No. 200). In the original method, the boundary between coarse and fine aggregates was set on 4 mm. This study facilitates the aggregate separation, sieve No. 4, which represents 4.75 mm, was utilized. Previous studies on alternative mixing sequences indicate that it provides improved homogeneity and improves workability and compactability. First, coarse aggregate is placed in the mixer, followed by an asphalt binder. Second, the filler is added to facilitate mastic creation and obtain even distribution over the coarse aggregate. Finally, the fine aggregate is placed in the mixer. This mixing sequence offers a more uniform distribution of the filler and asphalt binder in the mixture and prevents the filler from creating clusters due to high surface area. Also, the surface of the coarse aggregates gets increased film thickness of the asphalt binder. Once the mixtures were prepared, the same compaction and testing of the locking point procedure were applied in previous samples.

Results and Discussion

Influence of asphalt binder temperature change on the locking point

To investigate the influence of asphalt binder temperature on the compactability of asphalt mixtures, a series of tests were performed using specimens of three types of mixtures. Samples were mixed at the temperature recommended by the asphalt binder supplier. Each type of mixture was compacted utilizing the same aggregate gradation but changing the asphalt binder's temperature. It was expected that increasing temperature and decreasing viscosity would facilitate the compaction and reduce the number of blows/gyrations required to achieve interlock, i.e., reduce the locking point. This section presents the results obtained from gyration and impact compaction. As it may sound ambiguous during the result discussion, the locking point increases are referred to as a higher number of blows or gyrations required to reach interlocking.

Table 6.2 presents a summary of the results for the gyratory locking point. The value of the locking point was determined as the average of three samples. As predicted, the locking point increases with decreasing temperature for all the mixtures included in this study. For A-mix, the locking point decreased by 37 gyrations when the temperature was increased by 150°F, from 190°F to 340°F. The mixtures with smaller aggregate increased the locking point when temperature decreased. However, the locking point decrease was smaller for mixtures with smaller maximum aggregate size. For BM2-mix resulted in 35 gyrations, when for D-mix, the difference was 26 gyrations. These results indicate that the lubricative properties of asphalt binder increase with decreasing viscosity. In the temperature range for typical asphalt mixture compaction between ~250°F and ~310°F, the locking point fell by 14 gyrations for A-mix, 16 gyrations BM2-mix, and 8 gyrations for D-mix. As the asphalt binder's viscosity decreased, the standard deviation and variance between the same mixture samples decreased. For A-mix, the standard deviation decreases from 4.6 to 1.0 when compacted at 190°F and 340°F, respectively. For the same mixture, the variance decreased from 14.0 to 0.7. A similar pattern can be noticed for the rest of the mixes. For BM2-mix, the standard deviation and variance decreased from 3.6 and 8.7 to 1.2 and 0.9. For D-mix, the

Table 6.2. Summary of the results for gyratory locking point versus change in asphalt binder temperature

Temperature °F (°C)	Sample 1	Sample 2	Sample 3	**Average Gyrations**	Standard Deviation	Variance
A-Mix						
190 (88)	104	95	98	**99**	4.6	14.0
220 (104)	91	88	85	**88**	3.0	6.0
250 (121)	79	83	81	**81**	2.0	2.7
280 (138)	77	74	74	**75**	1.7	2.0
310 (154)	66	67	69	**67**	1.5	1.6
340 (171)	63	61	62	**62**	1.0	0.7
BM2-Mix						
190 (88)	83	88	90	**87**	3.6	8.7
220 (104)	80	76	81	**79**	2.6	4.7
250 (121)	73	76	78	**76**	2.5	4.2
280 (138)	69	71	73	**71**	2.0	2.7
310 (154)	60	62	59	**60**	1.5	1.6
340 (171)	51	53	53	**52**	1.2	0.9
D-Mix						
190 (88)	73	80	74	**76**	3.8	9.6
220 (104)	68	73	71	**71**	2.5	4.2
250 (121)	67	63	64	**65**	2.1	2.9
280 (138)	59	63	61	**61**	2.0	2.7
310 (154)	58	55	58	**57**	1.7	2.0
340 (171)	49	51	50	**50**	1.0	0.7

values decreased from 3.8 and 9.6 to 1.0 and 0.7. Figure 6.2 presents a comparison between the gyratory locking points of the different types of mixtures. A linear relation can be seen with high values of R^2, 0.98 for A-mix, 0.97 for BM2-mix, and 0.99 for D-mix.

It was expected that at some point, the decreasing viscosity would lose its lubricant properties, and it would have less influence on the compactability of the mixtures. However, in this study's temperature range, from 190°F to 340°F, the increasing temperature decreased the locking point linearly. A higher maximum temperature, being impractical, was not considered. A lower minimum temperature would not provide adequate workability to prepare and compact the samples.

Table 6.3 shows a summary of the results for the impact locking point. The final value was the average of two samples. The number of samples was limited to two due to time-consuming data analysis, and the standard deviation and variance were not calculated. For three samples of A-mix, compacted at 190°F, 220°F, and 250°F, it was impossible to get the locking point with 150 blows applied to the specimens. It was concluded that these samples have the locking point above 150 blows and were marked as “>150”. The same procedure was applied to the BM2-mix sample compacted at 190°F. It was possible for the rest of the samples to obtain a locking point between 120 and 150 blows.

Similar to the gyratory locking point, the temperature change had a significant influence on the locking point. However, the range cannot be calculated

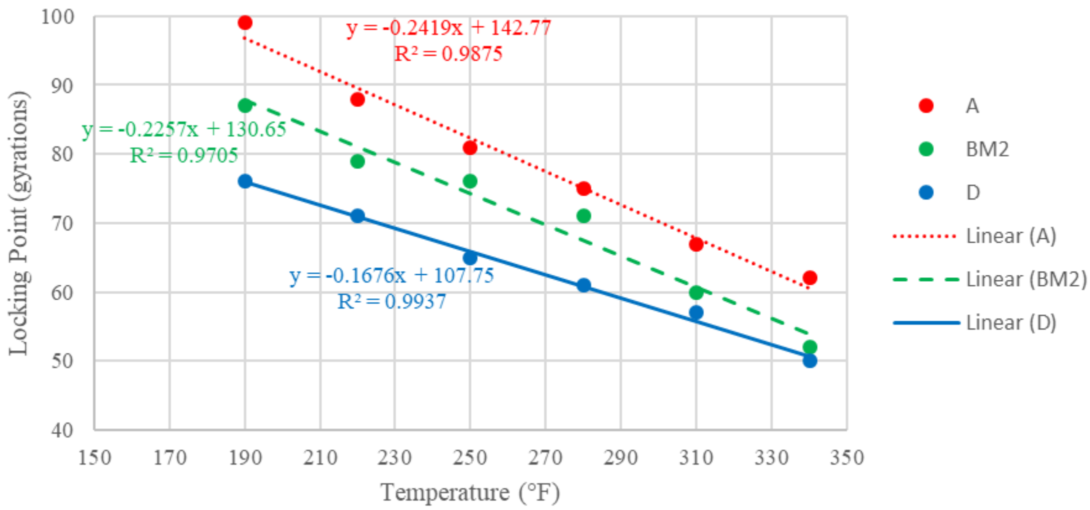

Figure 6.2. Comparison of gyratory locking points at different temperatures.

Table 6.3. Summary of the results for the impact locking point versus change in asphalt binder temperature

Temperature °F (°C)	Sample 1	Sample 2	**Average Blows**
A-Mix			
190 (88)	>150	>150	**>150**
220 (104)	>150	>150	**>150**
250 (121)	>150	>150	**>150**
280 (138)	148	149	**149**
310 (154)	144	145	**145**
340 (171)	143	143	**143**
BM2-Mix			
190 (88)	>150	>150	**>150**
220 (104)	147	149	**148**
250 (121)	142	145	**144**
280 (138)	137	138	**138**
310 (154)	130	133	**132**
340 (171)	128	133	**131**
D-Mix			
190 (88)	146	148	**147**
220 (104)	140	140	**140**
250 (121)	135	133	**134**
280 (138)	126	129	**128**
310 (154)	121	124	**123**
340 (171)	120	122	**121**

precisely, except for the D-mix. For the A-mix, the locking point range between 190°F and 340°F was more than 7 blows. For BM2-mix, the range is more than 19 blows, and for D-mix, the range is precisely 26 blows.

Different from the gyratory compaction, there is a less linear relationship between temperature and the locking point. At the higher temperature, it seems like the lubricant properties of asphalt binders do not increase anymore. Figure 6.3 presents comparative curves showing the relation between the temperature and the impact locking point. It can be noticed that between 310°F and 340°F, there is a visible decrease in the slope of the curve for the BM-2 and D-mix. The A-mix trend cannot be drawn because it was possible to obtain only three points, and the trend is not possible to establish.

The locking points obtained for BM2-mix and D-mix were best fitted with four order polynomials. The R^2 for these mixtures was 1 and 0.99, respectively. The mixture compaction behavior at different temperatures may be attributed to how the energy is applied when the specimen is gyrated and when the impact is applied. The higher temperature was not applied because it is uncommon for unmodified binders to use higher compaction temperature and damage to the asphalt binder. For gyratory compaction, it was visible that the slope of the curve decreases with decreasing aggregate size. It indicates that the compactability of asphalt mixtures with the smaller maximum aggregate size is less susceptible to changes in temperature. There is no such indication for impact compaction.

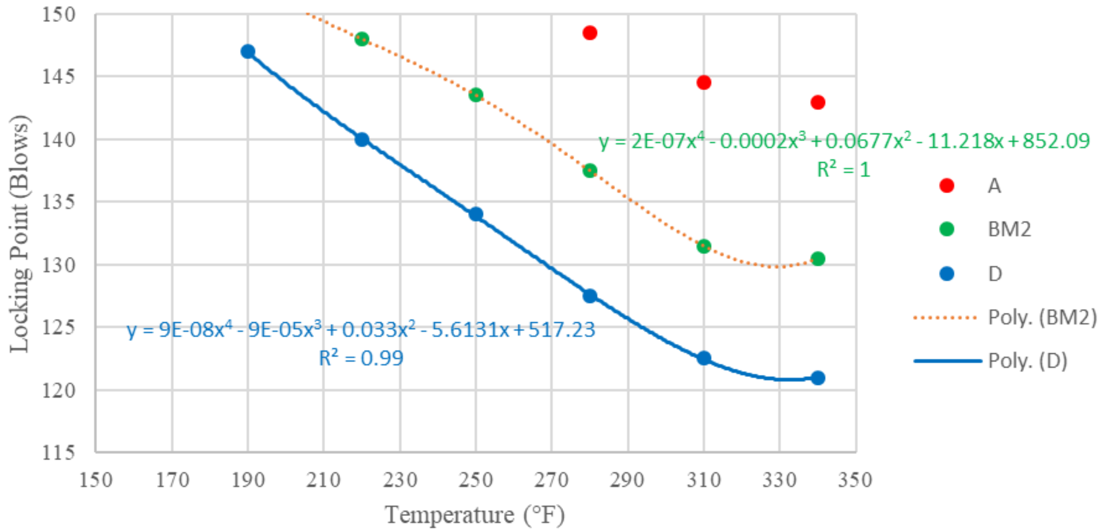

Figure 6.3. Comparison of the impact locking points at different temperatures

Comparing the results, it can be concluded that the slopes of BM2 and D-mix are similar.

Influence of asphalt binder content change on the locking point

To investigate the influence of asphalt binder content on the compactability of asphalt mixtures, a series of tests were conducted using specimens of three types of mixtures. Each type of mixture was compacted utilizing the same aggregate gradation and only changing the asphalt binder's content. It was expected that increasing asphalt content would improve compactability and decrease the locking point. In this section, the results obtained from gyration and impact will be presented.

Table 6.4 presents a summary of the results obtained from the gyratory compaction. The value of the locking point was determined as the average of three samples. As predicted, the locking point decreased with increasing asphalt binder content for all the mixtures in this study. Each type of mixture had a different set of asphalt contents that depended on the optimum asphalt content. For each mixture, six binder contents, which are close to optimum asphalt content, were tested. Further increasing or decreasing asphalt content would move air voids too far from the optimum 4%.

For A-mix, the asphalt content ranged from 2% to 4.5%. This mix's locking point decreased from 92 gyrations to 58 gyrations, respectively (decrease of 34 gyrations). For BM2-mix, the asphalt content ranged from 3% to 5.5%, and the locking point decreased from 81 gyrations to 55 gyrations (decrease of 26

Table 6.4. Summary of the results for gyratory locking point versus change in asphalt binder content

Asphalt Content (%)	Sample 1	Sample 2	Sample 3	**Average Gyrations**	Standard Deviation	Variance
A-Mix (3.4% optimum asphalt content)						
2.0	89	95	92	**92**	3.0	6.0
2.5	80	85	81	**82**	2.6	4.7
3.0	79	76	82	**79**	3.0	6.0
3.5	75	70	72	**72**	2.5	4.2
4.0	63	65	66	**65**	1.5	1.6
4.5	59	58	57	**58**	1.0	0.7
BM2-Mix (4.5% optimum asphalt content)						
3.0	85	78	79	**81**	3.8	9.6
3.5	73	77	75	**75**	2.0	2.7
4.0	72	70	74	**72**	2.0	2.7
4.5	67	70	69	**69**	1.5	1.6
5.0	59	61	62	**61**	1.5	1.6
5.5	55	56	54	**55**	1.0	0.7
D-Mix (5.6 % optimum asphalt content)						
4.0	72	78	77	**76**	3.2	6.9
4.5	72	67	72	**70**	2.9	5.6
5.0	69	66	65	**67**	2.1	2.9
5.5	63	66	63	**64**	1.7	2.0
6.0	61	58	59	**59**	1.5	1.6
6.5	54	52	54	**53**	1.2	0.9

gyrations). For D-mix, the asphalt content ranged from 4% to 6.5%, and the locking point decreased from 76 gyrations to 53 gyrations (decrease of 23 gyrations). From the results, a mix composed of larger stone generally has a higher locking point and is more susceptible to change in asphalt content.

Similarly to the asphalt temperature, the increasing asphalt content improved lubrication during compaction and repeatability. As the asphalt content increased, the standard deviation and variation between samples of the same mixture decreased. For A-mix, the standard deviation decreases from 3.0 to 1.0 when compacted with 2% asphalt binder and 4.5% asphalt binder. For the same mixture, the variance decreased from 6.0 to 0.7. A similar trend can be seen for the rest of the mixtures. For BM2-mix, the standard deviation and variance decreased from 3.8 and 9.6 to 1.0 and 0.7. For D-mix, the values decreased from 3.2 and 6.9 to 1.2 and 0.9. Figure 6.4 presents a comparison between the gyratory locking points of the different types of mixtures. The linear relation could be established with high values of R^2, 0.99 for A-mix, 0.98 for BM2-mix, and 0.97 for D-mix.

It was expected that the continuous increase of asphalt content would cause instability in the newly formed skeleton and caused an increase in the locking point at high asphalt content. However, the increasing asphalt content decreased the locking point linearly throughout the asphalt content range used in this study. As mentioned above, a further increase in asphalt content was not performed due to not being practical.

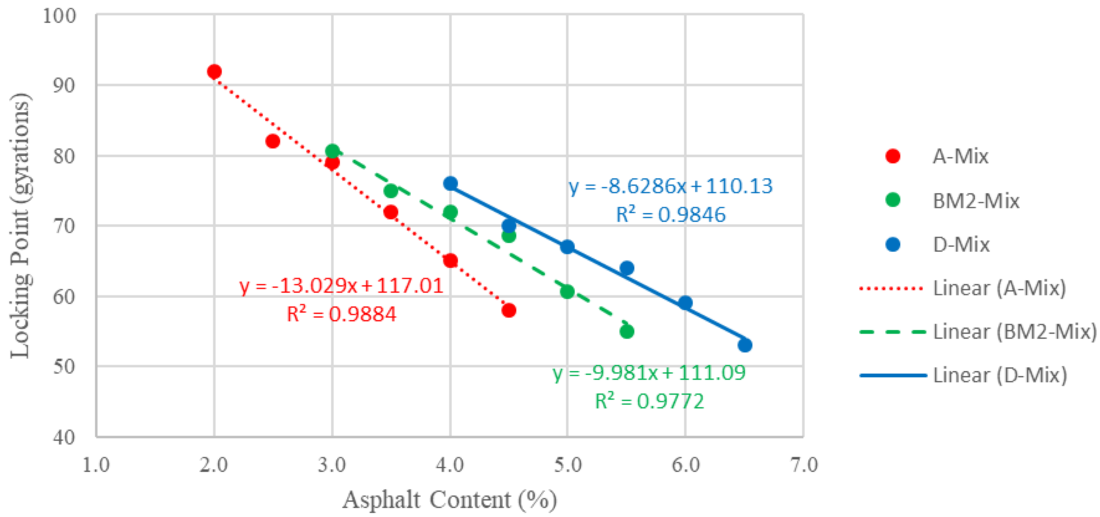

Figure 6.4. Comparison of gyratory locking points at different asphalt contents

Table 6.5 shows a summary of the results for the impact locking point. One sample was compacted at each asphalt content. The number of samples was limited due to time-consuming data analysis. For two samples of A-mix, compacted at 2% and 2.5%, it was impossible to get the locking point with 150 blows applied to the samples. It was concluded that these samples have the locking point beyond 150 blows and were marked as “>150”. For the rest of the samples, it was possible to obtain a locking point in a range between 121 and 150 blows.

Following the same pattern as during gyratory compaction, the asphalt content significantly influences asphalt mixtures' impact compaction. For A-mix, the range of locking points is more than 18 blows; for BM2-mix, the range is 22 blows, and for D-mix, the range is 20 blows.

Figure 6.5 presents comparative curves presenting the relationship between the asphalt content and the impact locking point. Similar to gyratory compaction, there is a linear relationship between asphalt content and the locking point. The lines' slope is very similar, which would indicate the locking point is equally susceptible to change in asphalt content regarding the type of the mixture.

Influence of change in mixing sequence on the locking point

To investigate the influence of the mixing sequence on the compactability of asphalt mixtures, a series of trials were performed using specimens of three types of mixtures. Each type of mixture was compacted utilizing the same aggregate gradation, optimum asphalt content, and only changing the mixing sequence. It was expected that the alternative mixing would enhance the

Table 6.5. Summary of the results for the impact locking point versus change in asphalt content

Asphalt Content (%)	Sample Blows
A-Mix	
2.0	>150
2.5	>150
3.0	148
3.5	145
4.0	138
4.5	132
BM2-Mix	
3.0	146
3.5	142
4.0	138
4.5	133
5.0	129
5.5	124
D-Mix	
4.0	141
4.5	135
5.0	131
5.5	125
6.0	123
6.5	121

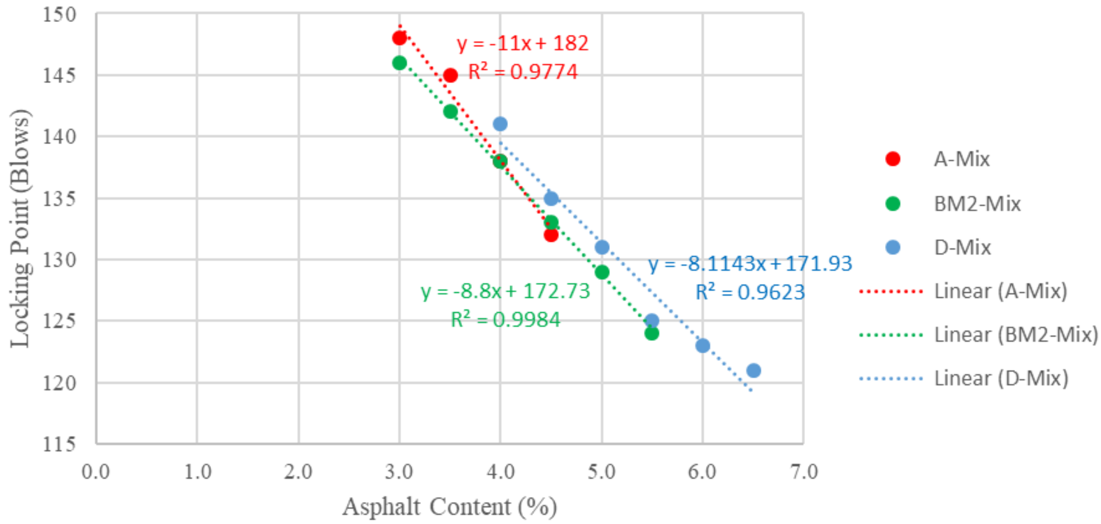

Figure 6.5. Comparison of impact locking points at different asphalt content

compactability by improving film thickness distribution and homogeneity of the mixture.

Table 6.6 presents a summary of the results for the gyratory locking point. The value of the locking point was determined as the average of three samples. As predicted, the locking point decreased by altering the traditional mixing sequence for all the mixtures in this study. For A-mix, the locking point decreased from 74 gyrations when compacted traditionally to 61 gyrations when alternative mixing was applied, a difference of 13 gyrations. For BM2- mixture, the difference between traditional and alternative mixing was 11 gyrations, decreasing from 68 gyrations to 57 gyrations. The smallest difference was recorded for D-mix, where the conventional mixing resulted in 58 gyrations and the alternative mixing in 52 gyrations (difference of 6 gyrations). The results indicated that the mixtures with larger stones benefited more from alternative mixing, which provides more even film thickness between coarse and fine aggregates.

The results of standard deviation and variance indicate that alternative mixing may significantly improve the mixtures' homogeneity. The standard deviation decreases from 3.6 to 2.0 when traditional mixing and alternative mixing were applied for A-mix. For the same mixture, the variance decreased from 8.7 to 2.7. A similar pattern can be noticed for the rest of the mixtures. For BM2-mix, the standard deviation and variance decreased from 4.0 and 10.9 to 1.0 and 0.7. For D-mix, the values decreased from 3.5 and 8.2 to 1.5 and 1.6.

Table 6.6. Summary of the results for gyratory locking point versus change in the mixing sequence

Mixing	Sample 1	Sample 2	Sample 3	**Average Gyrations**	Standard Deviation	Variance
A-Mix						
Traditional	70	75	77	**74**	3.6	8.7
Alternative	63	59	61	**61**	2.0	2.7
BM2-Mix						
Traditional	72	67	64	**68**	4.0	10.9
Alternative	56	58	57	**57**	1.0	0.7
D-Mix						
Traditional	55	62	58	**58**	3.5	8.2
Alternative	50	53	52	**52**	1.5	1.6

Additionally, it was observed that during the mixing process, the alternative mixing significantly improved mixing efficiency and reduced the time required for mixing. Table 6.7 presents the comparison of mixing time for the mixtures used in this study. The time recorded was taken with the naked eye, considering the technician's experience, and describing the time required to coat all visible particles with asphalt binder. The mixtures were prepared at the optimum asphalt content and temperature indicated by the asphalt binder supplier. The time required for mixing was reduced by 44 seconds from A-mix to 34 seconds for D-mix. It indicated that mixtures with larger stones benefited more from alternative mixing than the mixtures with smaller aggregates. The coarse aggregate must compete with fine aggregate for adequate coating by asphalt binder in the traditional mixing. During alternative mixing, the coarse aggregate is the first to mix with asphalt binder and does not compete with fine particles.

Table 6.8 presents a summary of the results for the impact locking point. The locking point was calculated as the average of three samples and decreased when alternative mixing was utilized. For A-mix, the locking point decreased from 146 blows when mixed traditionally to 140 blows when alternative mixed (difference of 6 blows). For BM2-mix, the difference between traditional and alternative mixing was 4 blows, decreasing from 135 blows to 131 blows. Similarly to gyratory compaction, the smallest difference was obtained for D-mix, where the traditional mixing resulted in 125 blows and the alternative mixing in 123 blows (difference of 2 blows). The results showed that the mixes with larger stones

Table 6.7. Summary of the mixing time

Mixing	Sample 1 (sec.)	Sample 2 (sec.)	Sample 3 (sec.)	**Average**
A-Mix				
Traditional	128	134	120	**127**
Alternative	83	89	79	**84**
BM2-Mix				
Traditional	105	114	111	**110**
Alternative	72	76	68	**72**
D-Mix				
Traditional	85	91	88	**88**
Alternative	58	50	55	**54**

Table 6.8. Summary of the results for impact locking point versus change in the mixing sequence

Mixing	Sample 1	Sample 2	Sample 3	**Average**	Standard Deviation	Variance
A-Mix						
Traditional	143	148	146	**146**	2.5	4.2
Alternative	141	139	139	**140**	1.2	0.9
BM2-Mix						
Traditional	132	135	137	**135**	2.5	4.2
Alternative	130	131	131	**131**	0.6	0.2
D-Mix						
Traditional	123	127	125	**125**	2.0	2.7
Alternative	122	122	124	**123**	1.2	0.9

improve compactability more when alternative mixing than mixtures with smaller aggregates for gyratory and impact compaction.

The results of standard deviation and variance indicate that alternative mixing improves the homogeneity of the mixtures. For A-mix, the standard deviation decreases from 2.5 to 1.2 when traditional and alternative mixing was applied. For the same mixture, the variance decreased from 4.2 to 0.9. A similar pattern can be noticed for the rest of the mixtures. For BM2-mix, the standard deviation and variance decreased from 2.5 and 4.2 to 0.6 and 0.2. For D-mix, the values decreased from 2.0 and 2.7 to 1.2 and 0.9.

Conclusions

The present study investigated the influence of asphalt binder on the lab compactability of different types of asphalt mixtures and different compaction methods by applying the locking point concept. A total of three types of hot mix asphalt were utilized in this study. Each type of mixture was designed with the same set of aggregates: limestone and natural sand and unmodified PG 64-22 asphalt binder. The impact locking point data were obtained with the accelerometer placed on the Marshall Hammer's falling mass. The impact locking point was defined as the first blow during the compaction, after which the duration of the impact and the peak acceleration does not change significantly (±5%). The gyratory locking point was captured from densification curves as the first gyration in the first set of three gyrations at the same height preceded by two sets of two gyrations at the same height. Based on the results obtained in this study, the following conclusions were reached:

- The mixing sequence significantly influences the asphalt mixtures' lab compactability regardless of the compaction method. The alternative mixing alters traditional mixing and permits improvement in the film thickness of coarse aggregates, which may be translated in the asphalt mixture's homogeneity.
- The mixing sequence influenced the mixtures with larger stones since it is more challenging to get an adequate coating on the largest particles when traditionally mixed. Alternative mixing allows the coarse aggregate to be mixed in the first stage with asphalt binder and good coating before filler and fine aggregate are added.
- The mixing sequence affects mixing efficiency. On average, the alternative mixing permitted around 35% faster coating of aggregate particles than traditional mixing.
- Decreasing viscosity (increasing temperature of asphalt binder) increases the lubricative properties of asphalt binders. There is a linear relationship between the temperature of the mixture and the locking point for gyratory compaction. For impact compaction, there is a 4^{th} order polynomial relation between temperature and the locking point. At higher temperatures, the lubricative properties do not improve as fast as at the lower temperature.

- The lab compactability of asphalt mixture is improved by higher asphalt content. There is a linear relation between asphalt content and the locking point for both gyratory and impact compaction. For gyratory compaction, the mixtures with larger stone are more susceptible to change in asphalt content. For impact compaction, there is no significant difference in susceptibility regardless of the maximum aggregate size.

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CHAPTER SEVEN

AGGREGATE AND MIXTURE TYPES TO OVER-COMPACTION IN THE HOT MIX ASPHALT

A version of this chapter is currently in preparation to be submitted to a Transportation Research Record: *Journal of the Transportation Research Board* as Polaczyk, P., Hu, W., Ma, Y., Xiao, R., Jiang, X., and Huang, B. "Aggregate and Mixture Types to Over-compaction in the Hot Mix Asphalt."

My contribution to this paper was performing majority of the experimental tests, data analysis, and preparing the original draft and all figures and tables.

Abstract: Correct compaction is vital for the asphalt mixture service life. An adequately compacted mixture with inferior properties can achieve better performance than a mixture with excellent properties but poorly compacted. In this study, the resistance to damage caused by over-compaction was investigated by utilizing the locking point concept. Over-compaction might cause damage to the aggregate structure and decrease service life. The locking point is defined as the moment during mixture compaction at which an aggregate skeleton is developed and becomes stable. Beyond the locking point, more compaction energy does not significantly increase mixture density and can damage aggregate particles. A total of fifteen mixtures was utilized and evaluated using the gyratory compactor. Among them, five dense-graded plant mixtures contained different aggregates and binders. Ten laboratory mixtures (three types: the surface, the base, and SMA) were designed with the most popular coarse aggregates in Tennessee: hard limestone, soft limestone, gravel, and granite. The results of this study show that the highest locking point was reached by the mixtures containing gravel. The SMA mixtures have, on average, lower locking points than the dense-graded mixtures.

Most of the dense-graded mixtures made with crushed stones failed in the range of +20 to +30 gyrations, whereas the samples made with gravels failed in the range of +30 to +40 gyrations, indicating that gravel seems to be the most resistant to damage.

Introduction

Compaction is a procedure utilized to compress and decrease the material's volume, which provides essential properties that influence the pavement's performance. During asphalt mix compaction, the aggregates coated with asphalt binder are compressed together, following an increase in interparticle friction and surface contact. Finally, the particles interlock, providing resistance to deformation. At the same time, the permeability is decreased, and the durability is increased. In dense-graded mixtures, air voids decrement to the designed level can deliver a flexible pavement characterized by imperviousness. For poorly compacted dense-graded mixtures is typical to have connected air voids. This interconnection permits water and solvents to penetrate the asphalt layer and even the entire pavement structure.

Water causes damage to the pavement structure and decreases pavement service life by causing asphalt binder oxidation, cracking, premature aging, and stripping. If the water reaches the base course, it can decrease the strength or damage by the freeze-thaw cycles. Besides, the insufficient compaction during construction will result in further densification by the traffic. Compaction provided by the traffic is mostly applied in the wheel paths creating a longitudinal waterway, resulting in a safety hazard, especially during rainy weather or during the night. Over-compaction can be defined as additional energy applied to the asphalt mixture, which might damage the newly developed aggregate skeleton (Bonnot 1997; Polaczyk et al. 2019; Roberts et al. 1991).

Correctly compacted mixture with inferior properties can achieve better performance than a mixture with excellent properties but poorly compacted. Several factors affect compaction. They can be divided into the following categories: compaction energy, mixture temperature, time allocated for compaction, properties of underlying layers (base, subbase, subgrade), thickness, environmental condition, and asphalt mixtures properties. The aggregates gradation, angularity, and texture influence the energy required to reach adequate compaction. As the angularity and maximum aggregate size increases, the energy required to compact the mixture also increases. The hardness of aggregates also affects compactability. The harder the aggregate, the harder it is to be compacted, such as limestone and granite. Angular particles are more difficult to allow their reorientation by the roller than around particles, requiring more compaction energy. The type and amount of asphalt binder also influence the ability to densify the mixture. The stiffer the mix, the more energy is required to achieve the required density. Lower asphalt binder content provides mixtures with higher stiffness, and it is more challenging to be compacted, while the excess of asphalt binder provides easier compaction, or the mix may become tender during the compaction (Gong et al. 2019; Jia et al. 2019; Polaczyk et al. 2019; Vavrik 2000).

Objectives and Scope

This study aims to investigate how much different asphalt mixtures can be over-compacted without causing damage to aggregate. The investigation was conducted by utilizing the concept of locking point. Four of the most common coarse aggregates utilized in Tennessee`s paving industry were included in this study. A total of fifteen asphalt mixtures (five plant mixtures and ten laboratory mixtures) were tested in the laboratory using a gyratory compactor. The Marshall mix design was utilized to determine optimum asphalt content for plant mixtures and lab mixtures. The locking point was tested on the samples that were compacted in the 150-mm Superpave mold. One type of binder, PG 64-22 (the Superpave performance grade), was used for all laboratory asphalt mixtures. In contrast, the plant mixtures included various asphalt binders utilized in Tennessee: PG 64-22, PG 70-22, PG 76-22.

Laboratory Experiments

Materials

A total of fifteen asphalt mixtures were used in this study. Five plant mixtures contained different aggregates and binders were collected at asphalt plants in East Tennessee. Ten laboratory mixtures were designed with the most popular coarse aggregates in Tennessee: hard limestone, soft limestone, gravel, and granite. Limestone is one of the most popular crushed stones in the United States that makes up around 70% of crushed stone production. It is a sedimentary rock built of more than 50% calcium carbonate. The sedimentary rocks are formed by a biochemical process or a mechanical consolidation of sediment. The limestone is consolidated chemically or biochemically and generally an excellent source of aggregates. In Tennessee, the hard limestone is used for surface mixtures, which require polish-resistant aggregates. The hard limestone is classified as containing more than 40% of Silica Dioxide and less than 32% of Calcium Carbonate. The limestone, which does not mean this specification, is classified as soft limestone. Granite is another type of crushed stone aggregate. It is an igneous rock, and in the United States, it takes around 15% of crushed stone production. Igneous rock is a molten rock generated by geothermal energy. Granite is an intrusive igneous rock that is solidified at a deep depth with high pressure. These rocks have a large mineral crystal that is formed during a long cooling time. The gravel is the product of bedrock erosion, transport, abrasion, and deposition. The geological agent responsible for gravel deposit creation is water. Gravel is widely distributed in glaciated areas, alluvial basins, and near rivers.

The laboratory mixtures were divided into three types; the surface mixture (½”), the base mixture (1 ¼”), and the Stone Mastic Asphalt mixture (12.5mm). The surface mixtures and the base mixtures were prepared with four different coarse aggregates. The Stone Mastic Asphalt mixtures were prepared with granite and soft limestone. The aggregates were screened thru the same set of sieves: 1 ¼”, 1”, ¾”, 5/8”, ½”, 3/8”, No. 4, No.8, No. 30, No. 50, No. 100 and No. 200. The goal of the screening was to get less possible variability in aggregates gradation. For all the laboratory mixtures, the same unmodified binder PG 64-22 was utilized. The compaction temperature for the asphalt cement used for laboratory mixes was 300°F, and the mixing temperature was 310°F. Table 7.1 summarizes the aggregate composition of all the mixtures. Table 7.2 includes the lab mixtures' coarse aggregates properties. The fine aggregate angularity is 36% for natural sand and 44% for soft limestone.

The only difference among laboratory mixtures is the coarse aggregate. The fine part of the granulometric composition was provided by the soft limestone #10 screenings and natural sand for all the mixtures. The mixtures within the same type had the same granulometric composition (1/2” surface, 1 ¼” base, and 12.5mm SMA), which was chosen to be in the mid-point between upper and lower limits from the specifications.

Specimen Preparations

The mix designs for the laboratory mixtures were prepared using a standard Marshall Compactor and 4-inch molds *(ASTMC127 2015; ASTMC128 2015; ASTMD2041 2011; ASTMD2726 2017; TDOT 2015)*. Four samples (1,200 grams each) with different asphalt content were prepared and tested to define the optimum asphalt content. The summary of mix design data is presented in Table 7.3. The mix design data for plant mixtures were taken from the asphalt plants' job mix formula. An SGC and 150-mm molds were used to obtain the locking points for all the mixtures. Each mixture consisted of 5 samples (4,800 grams each) compacted to a different number of gyrations. The material was heated up to the compaction temperature indicated in the plant mixtures' job mix formula. The

Table 7.1. Summary of asphalt binder and aggregates types

No	Type	PG	Materials	Compaction Temperature
P-1	Surface ½”	64-22	Granite D-Rock	270°F
			Soft Limestone #10	
			Natural Sand	
			Baghouse Fines	
P-2	Surface ½”	76-22	Hard Limestone #7	275°F
			Slag	
			Hard Limestone #10	
			Soft Limestone #10	
			Natural Sand	
			RAP ½	
P-3	Surface ½”	70-22	Gravel D-Rock	300°F
			Soft Limestone #10	
			Natural Sand	

Table 7.1 continued

No	Type	PG	Materials	Compaction Temperature
P-4	Base 1 ¼"	76-22	Gravel BM-2 Rock	300°F
			Soft Limestone #57	
			Natural Sand	
			Soft Limestone #10	
			RAP ½	
			RAP 5/16	
P-5	Base 1 ¼"	64-22	Soft Limestone BM-2	270°F
			Soft Limestone #7	
			Natural Sand	
			RAP ¾	
			RAS ⅜	
LD-1	Surface ½"	64-22	Hard Limestone D-Rock	300°F
			Soft Limestone #10	
			Natural Sand	
LD-2	Surface ½"	64-22	Soft Limestone D-Rock	300°F
			Soft Limestone #10	
			Natural Sand	

Table 7.1 continued

No	Type	PG	Materials	Compaction Temperature
LD-3	Surface ½”	64-22	Gravel D-Rock	300°F
			Soft Limestone #10	
			Natural Sand	
LD-4	Surface ½”	64-22	Granite D-Rock	300°F
			Soft Limestone #10	
			Natural Sand	
LB-1	Base 1 ¼”	64-22	Hard Limestone BM-2-Rock	300°F
			Soft Limestone #10	
			Natural Sand	
LB-2	Base 1 ¼”	64-22	Soft Limestone BM-2-Rock	300°F
			Soft Limestone #10	
			Natural Sand	
LB-3	Base 1 ¼”	64-22	Gravel BM-2-Rock	300°F
			Soft Limestone #10	
			Natural Sand	

Table 7.1 continued

No	Type	PG	Materials	Compaction Temperature
LB-4	Base 1 ¼”	64-22	Granite BM-2-Rock	300°F
			Soft Limestone #10	
			Natural Sand	
SMA-1	12.5	64-22	Granite	300°F
			Soft Limestone #10	
			Natural Sand	
SMA-2	12.5	64-22	Soft Limestone	300°F
			Soft Limestone #10	
			Natural Sand	

Table 7.2. Coarse aggregates properties of lab mixture

Aggregate	Abrasion (%)	Fractured Faces (%)		Flat and elongated particles (%)
		1 Face	2 Faces	
Hard Limestone	29	100	88	2.8
Soft Limestone	35	100	83	3.1
Gravel	27	87	67	4.1
Granite	39	100	93	9.3

Table 7.3. Summary of the mix designs data

	Optimum AC (%)	**Air Void (%)**	**VMA (%)**	**VFA (%)**
P-1	5.7	3.9	17.4	78
P-2	5.7	4.1	18.4	78
P-3	5.8	4.0	17.0	76
P-4	4.8	4.0	15.0	73
P-5	4.2	3.8	13.6	72
LD-1	5.8	4.0	14.9	73
LD-2	5.8	4.0	14.6	73
LD-3	5.6	4.0	14.9	73
LD-4	5.7	4.0	15.2	74
LB-1	4.5	4.0	14.3	72
LB-2	4.6	4.0	14.6	73
LB-3	4.5	4.0	15.4	74
LB-4	4.5	4.0	15.7	75
SMA-1	6.2	3.5	17.2	80
SMA-2	6.6	3.5	17.8	80

laboratory mixtures were prepared in the mechanical mixer and placed in the oven for two short-term aging hours. Figure 7.1 presents the granulometric composition of plant mixtures, and Figure 7.2 shows the granulometric composition of laboratory mixtures.

Testing Procedure

The 4,800 grams specimens of each mixture were compacted with 150 gyrations to determine the locking point (LP2-2-3). Then, the four specimens (4,800 grams) were compacted at a different number of gyrations representing: [1] the locking point (LP), [2] 10 gyrations above the locking point (LP+10), [3] 20 gyrations above the locking point (LP+20), and [4] 30 gyrations above the locking point (LP+30). For each sample, post-compaction sieve analysis was performed to identify the mixture's damage caused by excessive compaction. The post-compaction gradation was compared to the results obtained from uncompacted mixtures. If the gradation was outside of a specific range, it was confirmed that the mixture was damaged and did not fulfill the specification. Table 7.4 presents the permitted limits established for each sieve (TDOT 2015).

A similar procedure was performed for the lab mixtures. For each of the samples, post-compaction sieve analysis was performed. The post-compaction gradation was compared to the results obtained from uncompacted mixtures. If the gradation was outside of a specific range, it was concluded that the mixture was damaged.

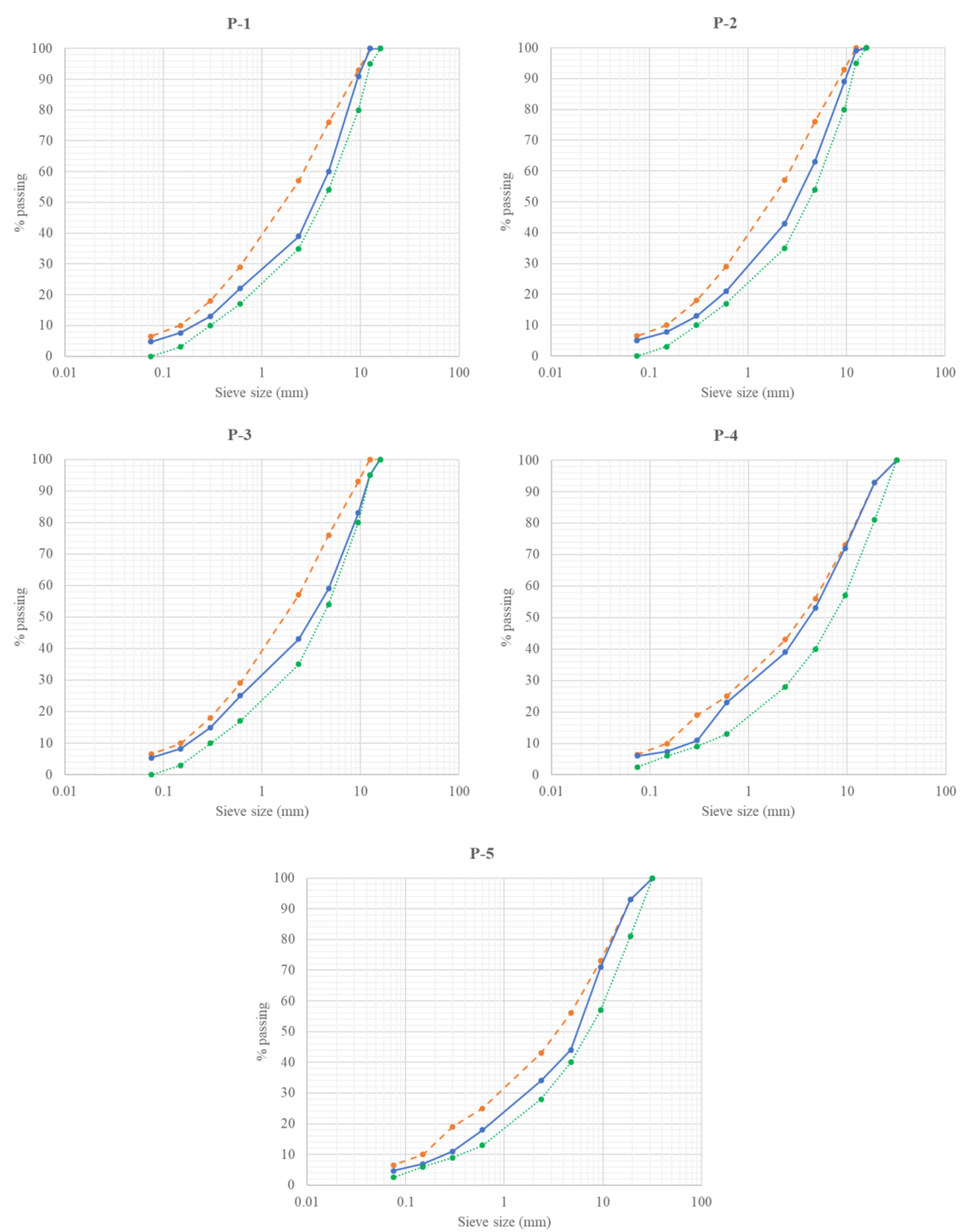

Figure 7.1. The granulometric composition of plant mixtures

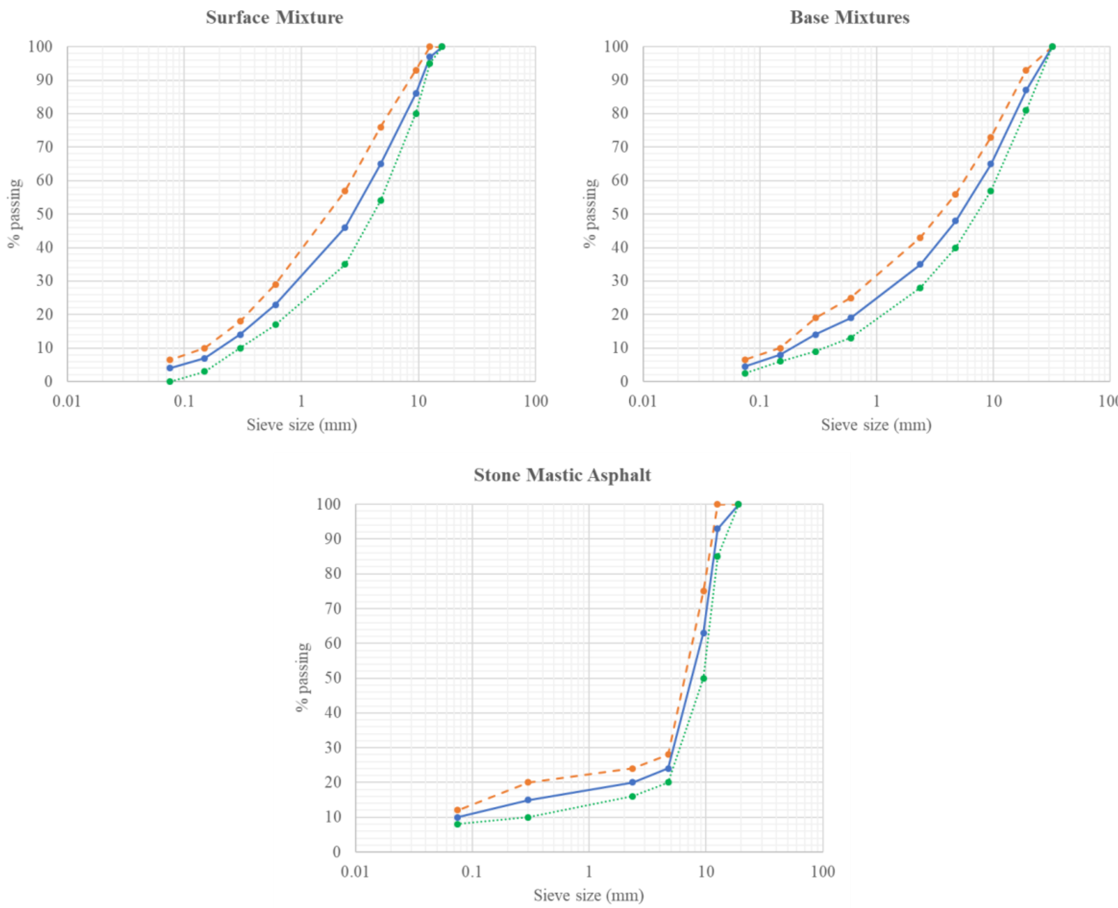

Figure 7.2. The granulometric composition of laboratory mixtures

Table 7.4. Asphalt mixture gradation tolerance (TDOT 2015)

Sieve Size	**Gradation Tolerance**
1/2-inch sieve and larger	±8%
3/8-inch sieve	±7%
No. 4 sieve	±7%
No. 8 sieve	±5%
No. 30 sieve	±4%
No. 200 sieve	±2%

If the mixture has not failed when compacted 30 gyrations above the locking point, additional samples compacted 40 gyrations above the locking point were performed.

Results and Discussion

Locking Point

Table 7.5 summarizes the locking point obtained for each mixture and the number of gyrations above the locking point utilized in this study. The locking point was determined based on the average result from three specimens. For the surface plant mixtures, the locking point range from 55 gyrations to 62 gyrations. The highest locking point was obtained for the mixtures that contain gravel (P-3), which may be caused by the shape and angularity of this aggregate. Mixtures P-1 and P-2 have close results of 56 gyrations and 55 gyrations, respectively. These mixtures are made of crushed stone that is more angular than gravel as water erosion. Also, the mixture P-1 and P-2 have the same asphalt content, and since asphalt binder works as a lubricant, it can provide similar lubrication, which results in the close locking points. The base mixtures P-4 and P-5 have the locking point of 76 gyrations and 71 gyrations. It could be noticed that with increasing maximum aggregate size, the locking point also increased. The base mixtures contained more recycled materials than the surface mixtures, and it can influence the compactability of the mixture because of the introduced aged binder from the recycled asphalt pavement (RAP) or recycled asphalt shingles (RAS). It is difficult to compare the compactability of plant mixtures because of the variety of

Table 7.5. Summary of the locking points

	LP (gyrations)	**LP+10 (gyrations)**	**LP+20 (gyrations)**	**LP+30 (gyrations)**	**LP+40 (gyrations)**
P-1	56	66	76	86	---
P-2	55	65	75	85	---
P-3	62	72	82	92	102
P-4	76	86	96	106	---
P-5	71	81	91	101	---
LD-1	53	63	73	83	---
LD-2	49	59	69	79	---
LD-3	59	68	78	88	98
LD-4	52	62	72	82	---
LB-1	71	81	91	101	---
LB-2	75	85	95	105	---
LB-3	79	89	99	109	119
LB-4	69	79	89	99	---
SMA-1	44	54	64	74	---
SMA-2	51	61	71	81	---

factors that differs from these mixtures, such as gradation, aggregates, asphalt content, and asphalt binder.

The laboratory mixtures can limit the number of factors that affect the locking point of different mixtures. Laboratory mixtures were divided into three groups: the surface mixtures, the base mixtures, and the Stone Mastic Asphalt mixtures. For all the mixtures, only the biggest aggregate varied. This material forms the asphalt mixture's skeleton, and the asphalt binder and granulometric composition for each group were the same. It can be observed that the Stone Mastic Asphalt obtained the lowest locking point (from 44 gyrations to 51 gyrations), that might be related to higher asphalt content, more angular aggregates, and the limited participation of intermediate material in the granulometric composition. On average, the surface mixture obtained a slightly higher locking point (from 49 gyrations for soft limestone aggregates to 59 gyrations for gravel) than SMA. The base mixtures have the highest locking point. It ranged from 69 gyrations for granite aggregates to 79 gyrations for gravel aggregates. When comparing the surface mixtures and the base mixtures, it could be seen that the mixtures containing grave had the highest locking point, whereas the lowest locking point is different for these two types of mixtures. For the surface mixture, the lowest locking point is 49 gyrations for soft limestone, and for base mixtures, the lowest locking point was obtained for granite aggregate. The range for both surface and base mixtures is 10 gyrations.

Post-compaction damage analysis

The post-compaction damage analysis was conducted on the samples compacted to the locking point and three samples for each mixture compacted beyond the established locking point. For three mixtures, additional samples were compacted 40 gyrations above the locking point. Figure 7.3 presents how the aggregates damaged by over-compaction modify the original granulometric composition so that the values at some sieves were out of gradation tolerance. The same analysis was made for all the mixtures that participated in this study.

The sieve analyses performed on the uncompacted mixtures were used as a baseline to define gradation tolerance. Figure 7.3 shows as more compaction energy are applied to the specimen, and more aggregates suffered breakage until, in the last figure (LD-1 LP+30), sieve No. 4 and No. 30 ran out of the gradation tolerance.

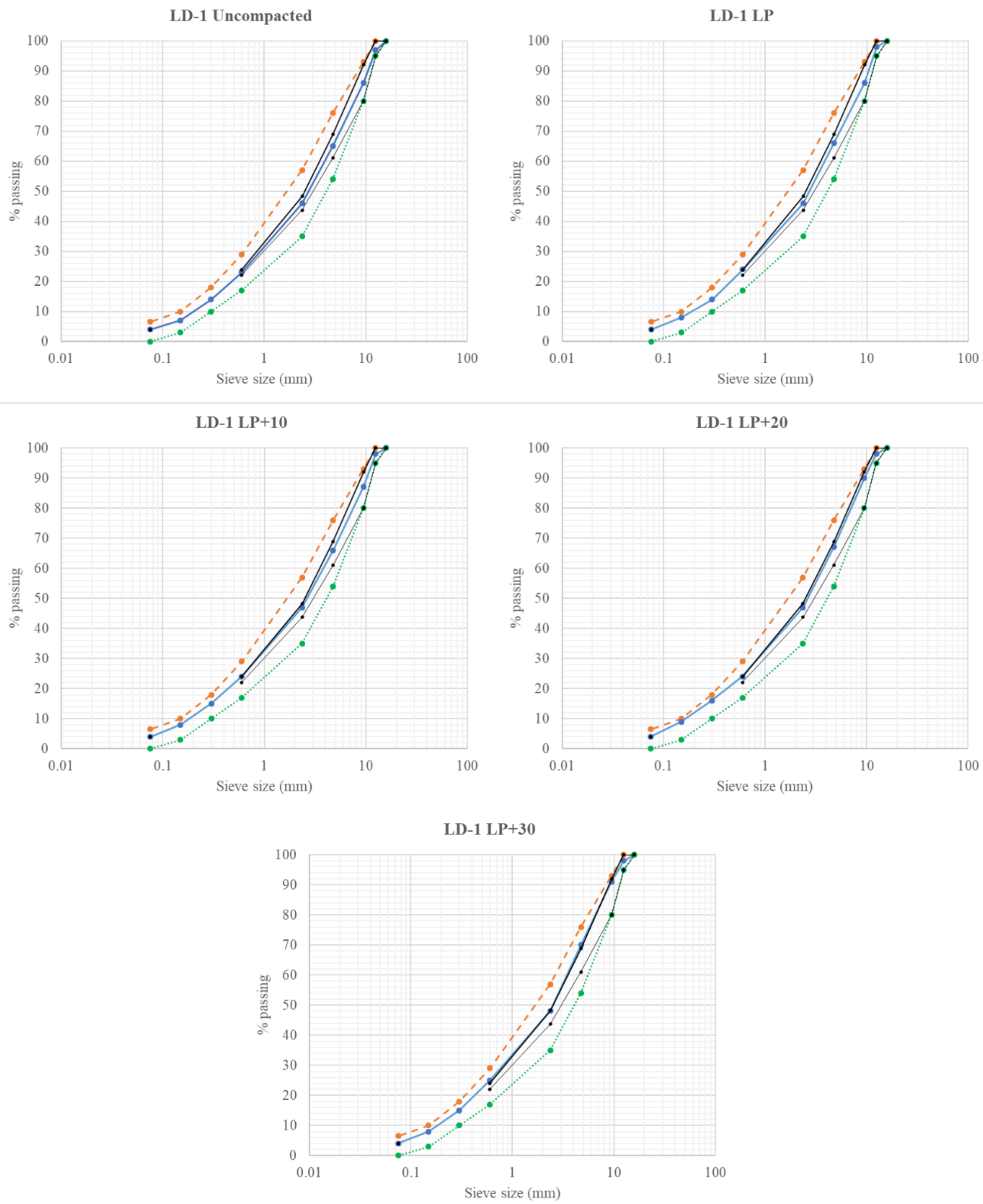

Figure 7.3. The change in granulometric composition cause by over-compaction

Table 7.6 shows the results of post-compaction sieve analysis for all the mixtures. The gradation tolerance mixtures are marked with “OK,” and the samples outside of this tolerance are marked with “X.”

Additional samples were required for three mixtures (P-3, LD-3, and LB-3) because there was not enough damage to the aggregates during the first +30 gyrations above the locking point to break the gradation tolerance. For two mixtures (P-3 and LB-3), the failure was found between +30 and +40 gyrations above the locking point, and for one mixture (LD-3), there was still without the failure even reached +40 gyrations. It can be noticed that all three mixtures that

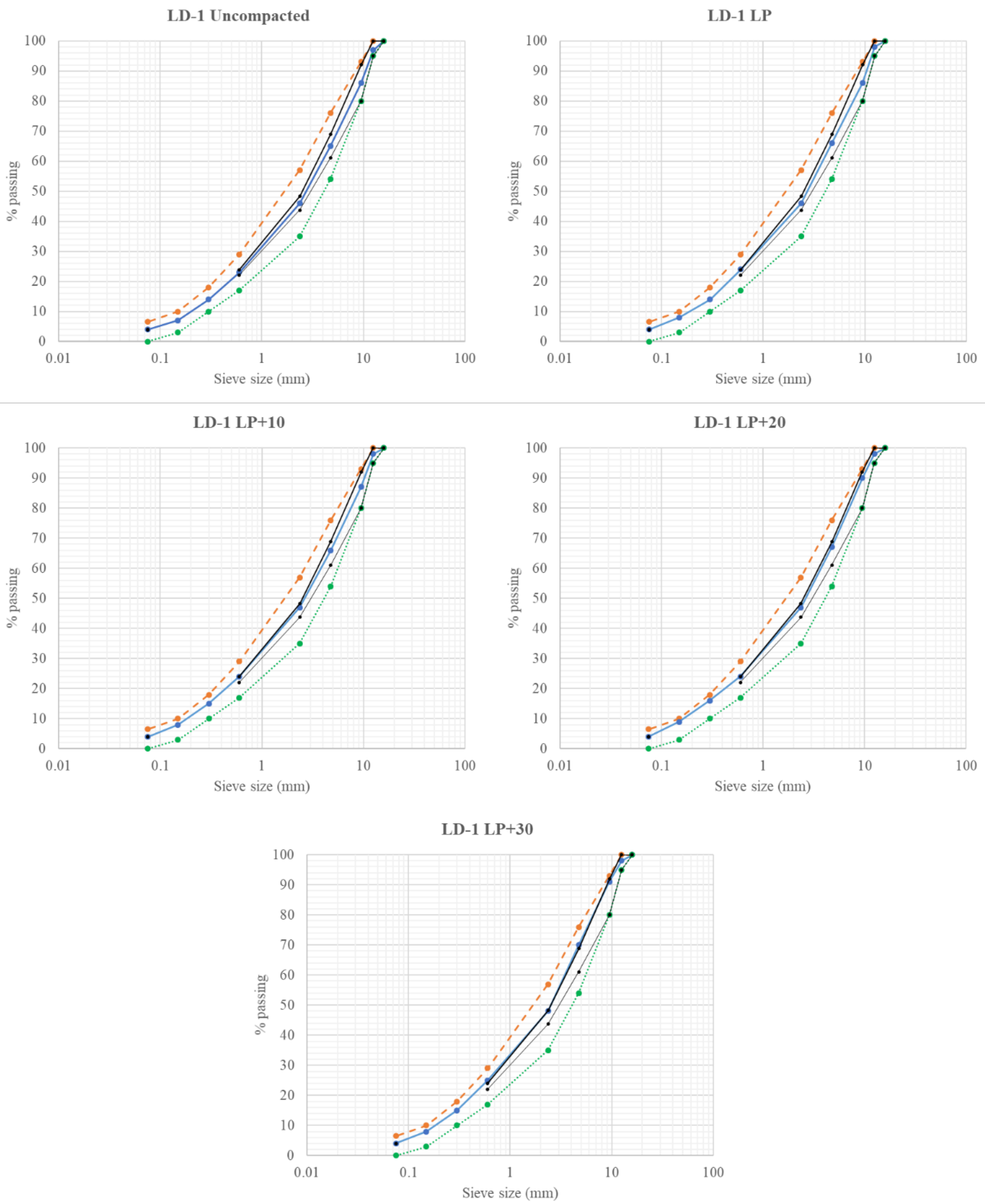

Figure 7.3. The change in granulometric composition cause by over-compaction

Table 7.6. Summary of gradation tolerance fulfillment

	LP	**LP+10**	**LP+20**	**LP+30**	**LP+40**
P-1	OK	OK	X	X	---
P-2	OK	OK	OK	X	---
P-3	OK	OK	OK	OK	X
P-4	OK	OK	OK	X	---
P-5	OK	OK	X	X	---
LD-1	OK	OK	OK	X	---
LD-2	OK	OK	OK	X	---
LD-3	OK	OK	OK	OK	OK
LD-4	OK	OK	OK	X	---
LB-1	OK	OK	OK	X	---
LB-2	OK	X/OK	OK	X	---
LB-3	OK	OK	OK	OK	X
LB-4	OK	OK	X	X	---
SMA-1	OK	X	X	X	---
SMA-2	X	X	X	X	---

required additional samples were prepared with gravel. It may indicate that gravel resists over-compaction better, or due to the low angularity, it never wholly interlocks.

For the mixture LB-2 compacted +10 gyrations, the first sample had enough damage to fail gradation tolerance. However, after obtaining positive results from the +20 sample, another sample for +10 was prepared that gave a positive result, and the mixture failed between +20 and +30 gyrations.

Most of the dense-graded mixtures produced with crushed stone have failed in the range of +20 to +30 gyrations. Due to the high amount of material utilized in this study, the failure is described as a range of 10 gyrations rather than a specific point. There are three dense-graded mixtures (P-1, P-5, and LB-4) that failed at the range between +10 and +20 gyrations. Surprisingly, two of the mixtures were granite mixtures (P-1 and LB-4). It was assumed that granite mixtures would be the most resistant to damage from over-compacting. The third mixture that has failed in the range +10 and +20 was plant mix P-5 produced with soft limestone as coarse aggregate. The soft limestone was expected to be the least resistant to damage from all the aggregates. However, most of the samples still could handle more than 20 gyrations of over-compaction.

The Stone Mastic Asphalt mixtures were the most vulnerable to over-compaction energy and the fracture of aggregates. The mixture SMA-1 that contained granite was failed in the range between the locking point and +10 gyrations. The mixture SMA-2 was damaged even before reaching the locking point. The results obtained for SMA mixtures might be more sensitive to additional compaction than dense-graded mixtures. They might also be necessary to define a new locking point for SMA, which would be lower than LP2-2-3. On the other hand, the SMA is premium mixtures that require the best quality of aggregates, and the materials utilized in this study were not good enough.

The most common sieve responsible for the failure of surface mixtures, including plant and laboratory, was the sieve No. 4, while for base mixtures, it was the sieve 3/8”. Similarly to surface mixtures for Stone Mastic Asphalt, the failing most commonly was the sieve No. 4. Most of the failures were observed in the granulometric composition's coarser part above sieve No. 8. Only in two cases, mixtures LD-1 and LB-2, the finer part of the granulometric composition was affected and failed. For mixture LD-1, sieve No. 30, and mixture LB-2, it was sieve No. 8.

It was impossible to determine if asphalt content influenced the resistance to damage of the established aggregate skeleton. The SMA mixtures with higher asphalt content were more sensitive to damage than dense-graded mixtures. It might be that once the skeleton is created, there is no effect of asphalt binder on its resistance.

Conclusions

The present study explored how much different asphalt mixtures could be over-compacted by the gyratory compactor without causing unacceptable aggregate damage. The investigation was conducted utilizing the concept of the locking point. This parameter is based on the change of the sample height during the gyratory compaction. The locking point defines a point on the densification curve beyond which the mixture skeleton starts to resist further compaction, and aggregates can be damaged. A total of fifteen different hot mix asphalt mixtures were analyzed. Mixes were divided into two groups, plant mixtures (surface and base) and laboratory mixtures (surface, base, and SMA). The most common coarse aggregates utilized in Tennessee were part of this study: soft limestone, hard limestone, gravel, and granite. The sieve analysis of uncompacted plant mixtures was performed to determine the initial composition. The specimens of each mixture were compacted with 150 gyrations to determine the locking point (LP2-2-3). Next, the four specimens were compacted at different gyrations representing the locking point, 10 gyrations above the locking point, 20 gyrations above the locking point, and 30 gyrations above the locking point. For each sample, post-compaction sieve analysis was performed to assert the mixture's damage by additional compaction. The post-compaction gradation was compared to the results obtained from uncompacted mixtures. If the gradation was outside of the specific range, it was marked that the mixture was damaged. Based on the results obtained in this study, the following conclusions were reached:

- The highest locking point was obtained by the mixtures containing gravel. It was the only non-crushed aggregate in this study, and the shape and low angularity of it might require more compaction energy to interlock the aggregates. Also, as non-crushed aggregate, gravel has a lower surface area and requires lower asphalt content, less lubricant during compaction.

- The plant mixtures containing granite and hard limestone had close results of the locking point. Both mixtures had the same optimum asphalt content. Similarly, the laboratory mixtures containing granite and hard limestone had similar locking points. The asphalt content was close for mixes LD-1 and LD-4, and for mixes LB-1 and LB-4, it was the same.
- The RAP and RAS might influence the compactability of the mixtures. Since these materials were not part of this study's scope, further research is required to confirm this conclusion.
- SMA mixtures have a lower average locking point than dense-graded mixtures. It might be caused by a specific open-graded composition and by a higher asphalt content. Also, these mixtures are the most vulnerable ones to over-compaction. Usually, the SMA is a premium mixture and requires premium aggregates. In this study, the materials usually utilized for dense-graded mixtures were used to prepare SMA.
- Most of the dense-graded mixtures failed in the range of +20 to +30 gyrations over the locking point. These mixtures were mainly made with crushed stones. Gravel seems to be most resistant to damage because most of the samples failed in the range of +30 to +40 gyration. The surface gravel mixture has not failed even after reaching +40 gyrations. It may

suggest that gravel resists better over-compaction, or due to the low angularity, it never wholly interlocks.

- Mixtures made with granite had lower resistance to damage than other materials in this study. Most granite mixtures failed in the range of +10 to +20 gyrations. The mixtures containing gravel resulted in the highest resistance to over-compaction. It indicates that higher abrasion results in lower resistance to over-compaction.
- It seems that the type of mixture does not influence the resistance to damage for the dense-graded mixture. However, in this study, only two types of mixtures were included. Further study might be required to include more surface and base mixtures.

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CHAPTER EIGHT

CHARACTERIZATION OF AGGREGATE INTERLOCKING IN HOT MIX ASPHALT BY MECHANISTIC PERFORMANCE TESTS

A version of this chapter was submitted to the *Road Materials and Pavement Design* journal as Polaczyk, P., Ma, Y., Xiao, R., Hu, W., Jiang, X., and Huang, B. “Characterization of Aggregate Interlocking in Hot Mix Asphalt by Mechanistic Performance Tests.”

My contribution to this paper was performing majority of the experimental tests, data analysis, and preparing the original draft and all figures and tables.

Abstract: Compaction has a significant influence on the performance of asphalt mixtures. During compaction, the aggregates coated with bitumen are brought together, the air void decreases, density increases, and finally aggregates interlock forms a stable skeleton. The interlocking of aggregates is an important critical during compaction. Nevertheless, few mix design specifications include any specific requirements for locking points, mostly because it is difficult to precisely determine when interlocking happens during compaction. This study's objective was to validate the locking point concept by applying performance tests and evaluating aggregate interlocking influence on the rutting resistance and the fatigue cracking. Two types (surface and base) of hot mix asphalt composed of limestone aggregates and PG 64-22 asphalt binder and designed at different Ndesign (55, 65, and 75 gyrations) were used to conduct this study. Two types of performance tests, the Flow Number and the IDEAL CT were used to determine the locking point's adequate definition. Results showed that the LP2-2-3 and LP3 definitions during Superpave gyratory compaction being the most reasonable to

define the locking point based on the axial strain from the Flow Number test and CTindex from the IDEAL CT test. It was also found that over-compaction did become an issue beyond the locking point that may lead to the damage of the aggregate structure.

Introduction

Compaction is a process of densification of initially loose asphalt mixture through the application of mechanical energy. During compaction, the aggregates coated with bitumen are brought together, the air void decreases, density increases, and finally, aggregates interlock creates a stable skeleton (Roberts et al. 1991). The performance of asphalt mixtures intimately related to the quality of compaction. Inadequate compaction leads to deficient pavement performance even if all materials have the highest quality, and the design process resulted in a high-performance mixture. Poor compaction can result in different types of pavement distresses such as rutting, moisture damage, or aging (Anderson 2002; Bonnot 1997).

The locking point may become a valuable tool to determine the compactability and interlocking properties of asphalt mixtures. However, the locking point's multiple definitions reveal its subjective nature, which has limited confirmation from the performance test's direct measurements. Li and Gibson (2011) conducted research to evaluate the asphalt mixture's performance related to aggregate packing. The study included three asphalt mixture, one compaction effort, and implemented the Flow Number test. The results indicated that the locking point range was between 55 and 80 gyrations. Based on Li and Gibson (2011) work, it is recommended to conduct the research with different compaction efforts and to include fatigue cracking characterization.

Objective and Scope

The objectives of this study were (1) to find the confirmation that the interlocking phenomena exist by applying the mechanical performance tests, rather than the subjective pattern of height change obtained from Superpave Gyratory Compactor; (2) to evaluate the influence of aggregate interlocking on the rutting resistance and fatigue cracking of asphalt mixtures.

One type of aggregate (limestone) and one type of bitumen PG64-22 were utilized in this study. Two types of asphalt mixtures, D (1/2") and BM2 (1 ¼"), were designed utilizing Superpave Gyratory Compactor at different compaction effort of 55, 65, and 75 gyrations. D-mix is a surface mixture, and BM2 is a base mixture used in Tennessee, United States.

Laboratory Experiments

Materials and Equipment

Two types (surface and base) of hot mix asphalt were utilized in this study, compacted at different N_{design} (55, 65, and 75 gyrations). Each type of mixture was composed of limestone aggregates. The aggregates were collected in East Tennessee, United States. The primary task was to reduce variability in materials, so the aggregates were separated through the set of sieves: 25 mm (1"), 19 mm (¾"), 16 mm (5/8"), 12.5 mm (½"), 9.5 mm (3/8"), No. 4, No.8, No. 30, No. 50, No.

100 and No. 200. The screening was performed to obtain possible uniform aggregates and thus limit variability in the test results. The aggregate properties are presented in Table 8.1 (ASTMD131 2014; ASTMD1252 2017; ASTMD5821 2017; ASTMD6928 2017). One type of bitumen, PG 64-22, was utilized. Figure 8.1 shows the rotational viscosimeter data used to determine the asphalt binder's mixing and compaction temperatures (ASTMD4402 2015). The mixing temperature for asphalt mixtures was 155 °C, and the compaction temperature was 144 °C.

The mix design samples, the locking point determination, the Flow Number test, and the IDEAL CT test were prepared using a Superpave Gyratory Compactor and 150-mm molds. Samples for the Flow Number test were cored using a 101.6 mm drill and cut using a masonry saw. Samples for the IDEAL CT test were cut using a masonry saw.

Mix Design

The mix designs were prepared using standard Superpave specification (ASTMC127 2015; ASTMC128 2015; ASTMD2041 2011; ASTMD2726 2017), except for gradation. The Tennessee Department of Transportation's specifications for surface (Type D) and base (Type BM2) were utilized to design gradations (TDOT 2015). Type D surface mixture has a similar composition as 12.5 mm Superpave gradation, and Type BM2 base mixture is close to 25 mm Superpave gradation. The gradations utilized in this study are presented in Figure 8.2 and Figure 8.3. The mix designs were prepared with three different compaction

Table 8.1. Summary of aggregate properties

Aggregate Type	LA Abrasion (%)	Micro Deval Abrasion (%)	Fractured Faces (%)		Flat and elongated particles (%)	Uncompacted Void (%)
			1 Face	2 Faces		
Limestone	31.80	4.58	100	83	3.1	46.3

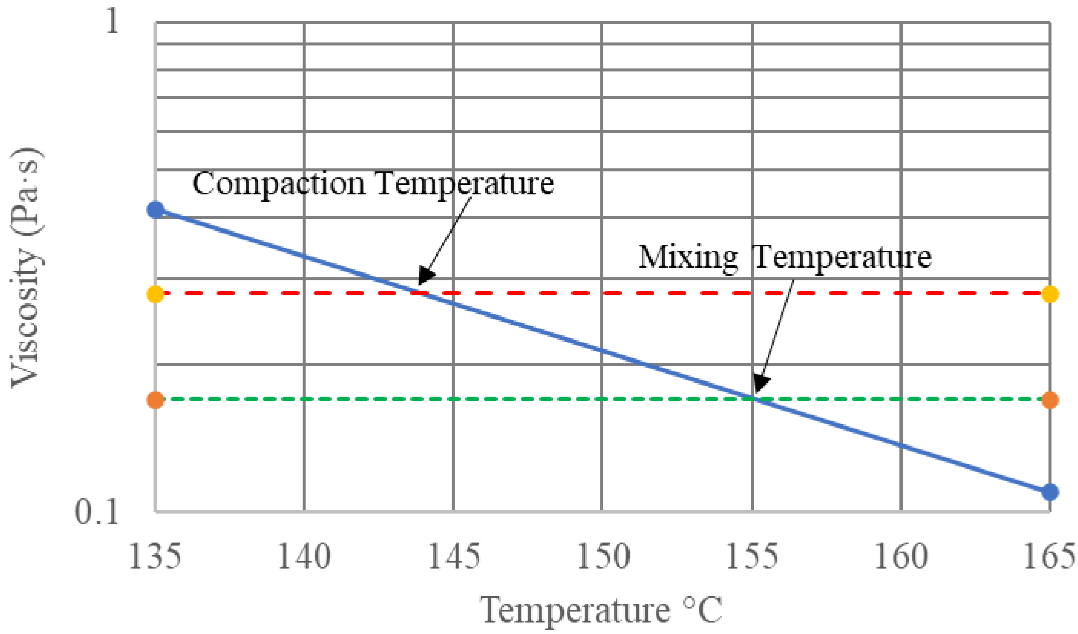

Figure 8.1. Viscosity – temperature chart for asphalt binder

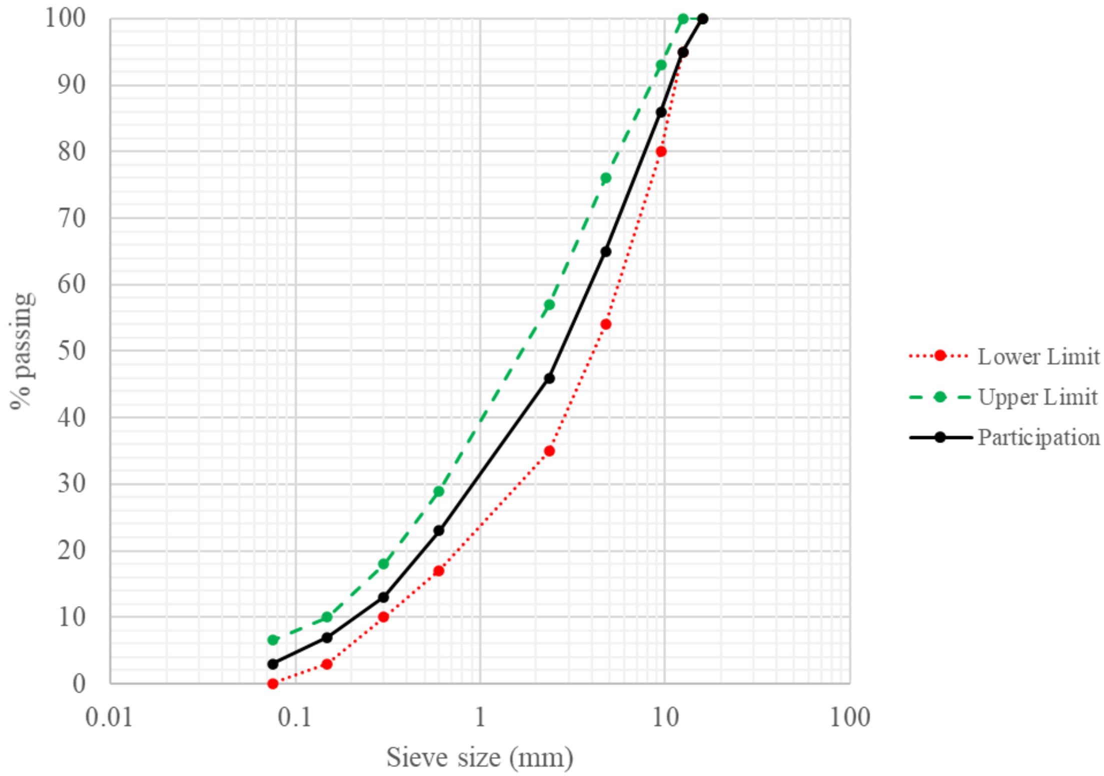

Figure 8.2. Gradation of surface (D) mixtures

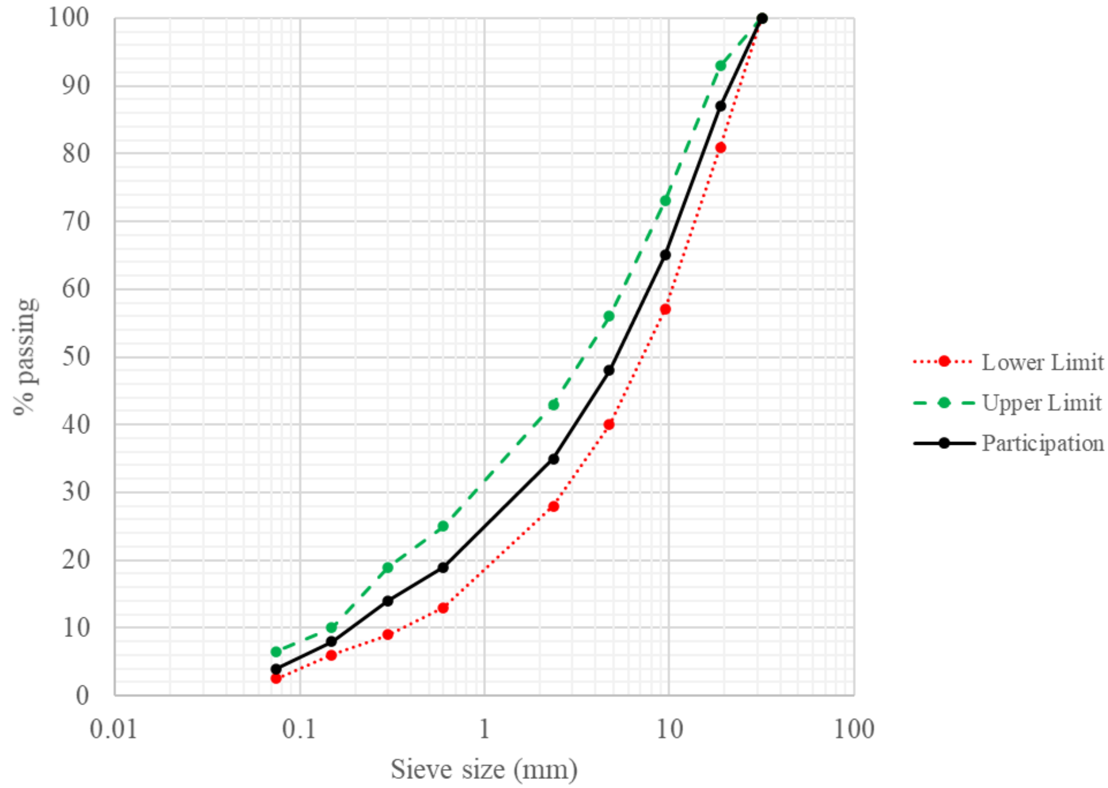

Figure 8.3. Gradation of base (BM2) mixtures

efforts 55, 65, and 75 gyrations. The aggregate and binder were mixed at 155 °C and aged for 2 hours, and the mixed samples were compacted at 144 °C. The mix design data is presented in Table 8.2.

Specimen Preparations

The specimen size required to conduct performance tests is larger than samples used for mix design. This condition could alter the locking point and interlocking determination, as different sizes of samples could return different interlocking properties. Based on the densification curves, the required amount of material and air void were calculated to obtain the minimum specimen height of 170 mm. The weight of the material required for one locking point or performance test sample was determined to be 7300 grams.

Ten samples for each of the six mixtures used to define the locking points were prepared with the optimum asphalt content and the same aggregate proportion as the mix design samples. Special care was taken to control the temperature and time during mixing and compacting, as even small variation might change the lubricative properties of bitumen and alter the compaction process (Baumgardner et al. 2012). The Flow Number test samples were mixed and compacted following the same procedure as the locking point samples. Ten samples were prepared for each mix design by applying different compaction efforts from 10 to 100 gyrations. The compacted samples had different height due to different compaction energy, so the samples were cored and cut to obtain the uniform size of samples 100 mm in diameter and 150 mm in height. The height of

Table 8.2. Mix Design Volumetrics

	N_{design} (gyration)	Optimum AC (%)	Air Void (%)	VMA (%)	VFA (%)
D-55	55	5.60	4.0	15.5	74
D-65	65	5.40	4.0	15.2	74
D-75	75	5.15	4.0	14.9	73
BM2-55	55	4.60	4.0	13.8	71
BM2-65	65	4.30	4.0	13.3	70
BM2-75	75	4.10	4.0	13.1	69

samples was obtained by cutting the same thickness of the material from the specimen's top and bottom.

The samples for the IDEAL CT test were compacted in the same way as the Flow number samples. Typically, the samples are compacted to a specific height, and there is no need for cutting. Still, in this research, the amount of material during compaction was of the highest importance, so after compaction of 170 mm tall samples, the samples were cut to obtain two samples of 75 mm each.

Locking Point Testing Procedure

Ten samples of each six mixtures were compacted, and the locking points were determined based on the height change. Five definitions of the locking point were utilized: LP2, LP2-2, LP2-2-2, LP3, and LP2-2-3. Flow Number Testing Procedure

The Flow Number (Bonaquist et al. 2003; Hajj et al. 2010) was tested on the samples under the following conditions: repeated axial stress of 600 kPa, the temperature of 54 °C, and the sample size: 100 mm x 150 mm. During the Flow Number test, a sample was tested under repeated haversine axial compressive load of 0.1 second every 1.0 second for a maximum of 8,000 cycles or until the deformation of 80,000 microstrains was reached. The point in the permanent strain curve where the rate of accumulation of permanent strain reaches a minimum value has been defined as the flow number. The permanent axial strain obtained during the test is measured as a function of the load cycles. The flow number is defined as the number of load cycles in relation to the minimum rate of change of axial strain. It can be related to resistance to permanent deformation (rutting). The Flow Number test should be performed on the samples that are 150-mm height and 100-mm in diameter. The sample is cored and cut from a larger sample around 170-mm in height and 150-mm in tests. The test is performed at a specific temperature, and the testing chamber should equilibrate temperature for at least 1 hour. Figure 8.4 presents the example of a specimen after the Flow Number test.

IDEAL CT Testing Procedure

The IDEAL CT test is used to evaluate the cracking resistance of asphalt mixture (Zhou et al. 2017). The test was conducted on all the mixtures following the ASTMD8225 (2019) procedure. As shown in Figure 8.5, the compacted specimen with a 150 mm diameter and a 75 mm height was centered in the Material Test System (MTS). The load was applied at a rate of 50.0±2.0 mm/min. The load and load-line displacement (LLD) were collected, plotted, and the CT_{index} calculated following ASTM D8225 standard (Figure 8.6).

The work of failure (W_f) is calculated as the area under the load versus LLD curve through the equation. The failure energy (G_f) is calculated afterward by dividing the work of failure by the specimen's cross-sectional area. Finally, CT_{index} is obtained from the parameters in the load-displacement curve.

Results and Discussion

Locking Point

Table 8.3 presents the locking point results for all the mixtures, including mean values, standard deviations (SD), and variances (V). Generally, it could be

Figure 8.4. Specimen after the Flow Number test

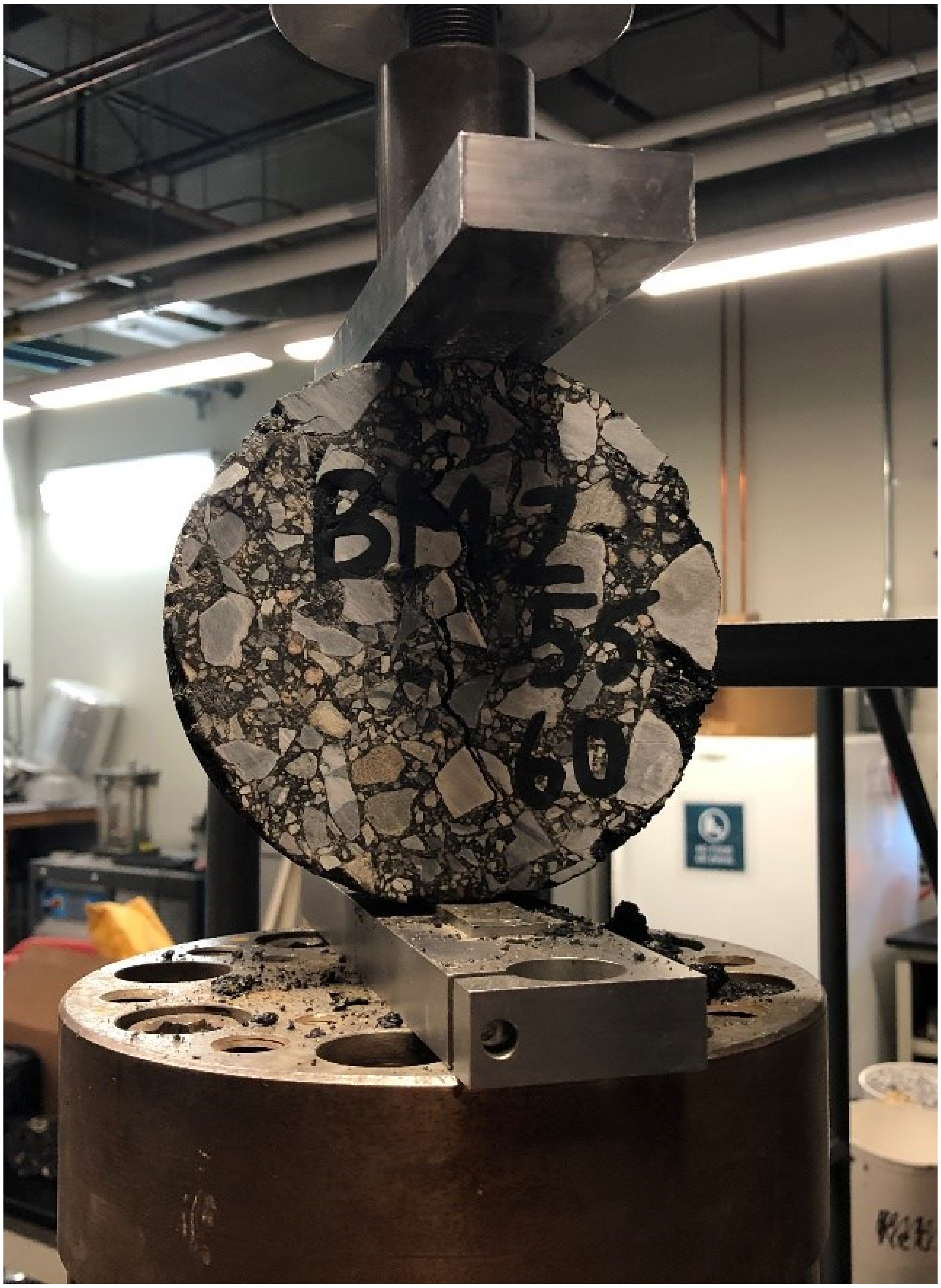

Figure 8.5. Specimen after the IDEAL CT test

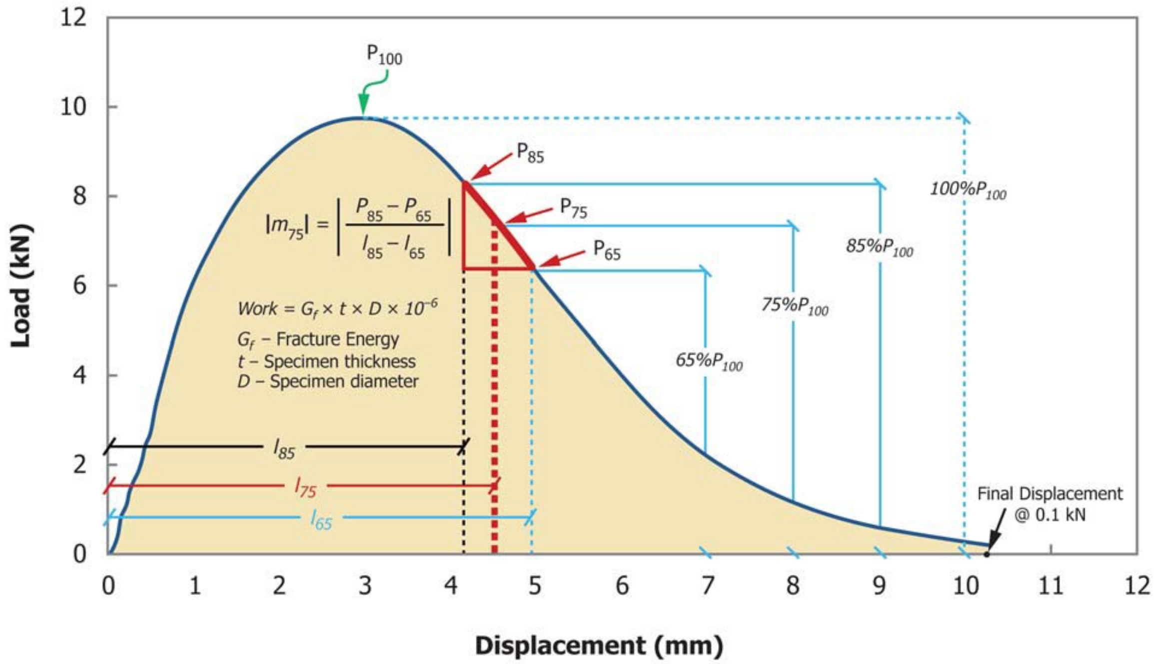

Figure 8.6. Recorded load versus load-line displacement curve (ASTM D 8225)

Table 8.3. Results of the locking point

LP2			
Mix	**Mean**	**Standard Deviation**	**Variance**
D-55	24	2.0	3.6
D-65	31	2.2	4.4
D-75	44	2.3	4.6
BM2-55	29	2.5	5.6
BM2-65	36	2.6	6.1
BM2-75	46	3.2	9.1
LP2-2			
Mix	**Mean**	**Standard Deviation**	**Variance**
D-55	35	1.3	1.6
D-65	45	1.4	1.8
D-75	55	1.7	2.7
BM2-55	43	1.5	2.0
BM2-65	50	1.7	2.7
BM2-75	65	2.0	3.6

Table 8.3 continued

LP2-2-2			
Mix	**Mean**	**Standard Deviation**	**Variance**
D-55	40	1.1	1.2
D-65	49	1.0	0.8
D-75	61	1.2	1.2
BM2-55	47	1.2	1.4
BM2-65	55	1.3	1.6
BM2-75	69	1.6	2.2
LP3			
Mix	**Mean**	**Standard Deviation**	**Variance**
D-55	53	0.7	0.5
D-65	64	0.9	0.7
D-75	75	1.0	0.9
BM2-55	62	1.0	0.9
BM2-65	71	1.0	1.0
BM2-75	84	0.9	0.8

Table 8.3 continued

LP2-2-3			
Mix	**Mean**	**Standard Deviation**	**Variance**
D-55	53	0.7	0.5
D-65	64	0.9	0.7
D-75	75	1.0	0.9
BM2-55	61	0.9	0.7
BM2-65	71	0.8	0.5
BM2-75	84	0.5	0.2

observed that the locking point increases with decreasing asphalt content, and a larger maximum aggregate size results in the higher locking point. The LP2 definition always provided the lowest locking point, while the LP3 and LP2-2-3 returned the highest locking point. For all the mixtures, the LP3 and LP2-2-3 had the same value. However, for the BM2 mix, it was not possible to obtain the LP2-2-3 pattern for all the samples. The LP2 had the highest standard deviation and variance, while LP3 and LP2-2-3 had the lowest.

The LP2 definition resulted in the highest values of standard deviation and variance. Standard deviation ranged from 2.0 for D-55 mix to 3.2 for BM2-75, while the variance ranged from 3.6 for D-55 to 9.1 for BM2-75. The LP2-2 definition resulted in a lower standard deviation and variance than LP2. Standard deviation ranged from 1.3 for D-55 mix to 2.0 for BM2-75, and the variance ranged from 1.6 for D-55 to 3.6 for BM2-75. The LP2-2-2 definition had a lower standard deviation and variance than LP2 and LP2-2. Standard deviation ranged from 1.1 for D-55 mix to 1.6 for BM2-75, and the variance ranged from 1.2 for D-55 to 2.2 for BM2-75. The LP3 and the LP2-2-3 definitions had the lowest standard deviation and variance. Standard deviation ranged from 1.1 for D-55 mix to 1.6 for BM2-75, and the variance ranged from 1.2 for D-55 to 2.2 for BM2-75. For various samples of the base mixtures, it was impossible to determine LP2-2-3, so even that the average result of the LP3 and LP2-2-3 were the same, the statistical results were different. For LP3, standard deviation ranged from 0.7 for D-55 to 1.0 for D-75, BM2-55, and BM2-65, while variance ranged from 0.5 for D-55 to 1.0 for BM2-65.

For LP2-2-3, a smaller number of samples were utilized to calculate the average value and standard deviation ranged from 0.5 for BM-75 to 1.0 for D-75, and variance ranged from 0.2 for BM2-75 to 0.9 for D-75.

Overall, it could be concluded that the LP3/LP2-2-3 had the most consistent data based on standard deviation and variance analysis. It is also preferable to use the LP3 definition rather than the LP2-2-3 one. For the base mixtures, there were various samples where the LP2-2-3 definition has not been detected.

Flow Number

The axial strain obtained from the Flow Number test is presented in Figure 8.7 to Figure 8.12. The y-axis is the axial strain; the x-axis is the number of flow number cycles. Finally, the numbers above the lines indicate the number of gyrations utilized to compact the sample.

For surface mixture D-55, the number of cycles to reach maximum axial strain increased with an increasing number of gyrations until it reached about 50 gyrations. At this point, further compaction above 50 gyrations did not provide a significant change in the axial strain. These results indicate there was no increase in permanent deformation once 50 gyrations are reached, which might suggest that at this point, the skeleton of the mixture has been formed and resists further compaction. For mixture D-65, the number of cycles required to reach maximum axial strain increased compared to the D-55 mixture. It was due to lower asphalt content and higher resistance to deformation.

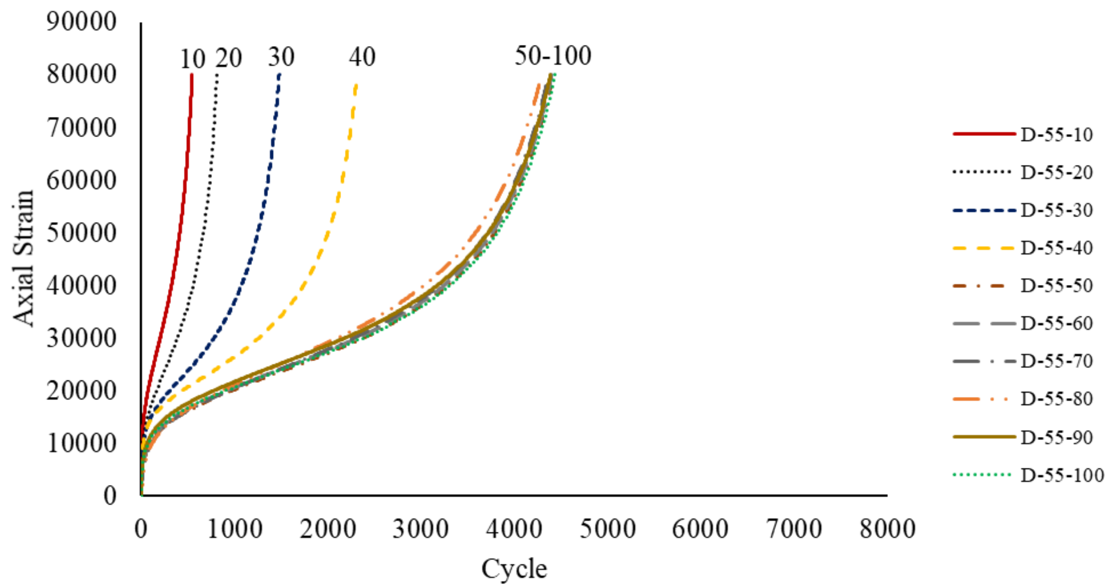

Figure 8.7. Axial strain vs. Flow Number Cycles for D-55 mixture

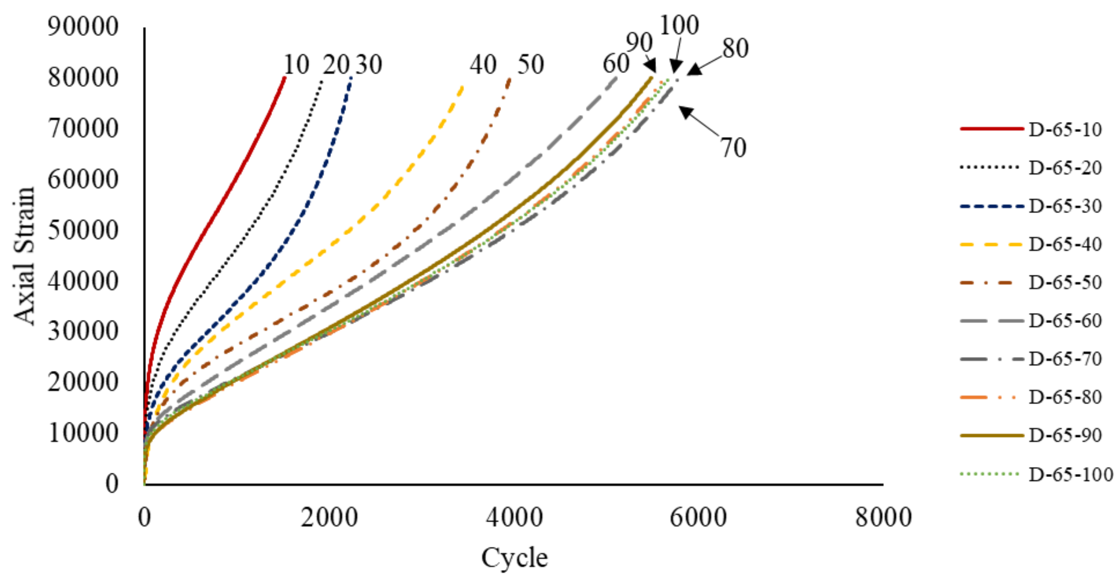

Figure 8.8. Axial strain vs. Flow Number Cycles for D-65 mixture

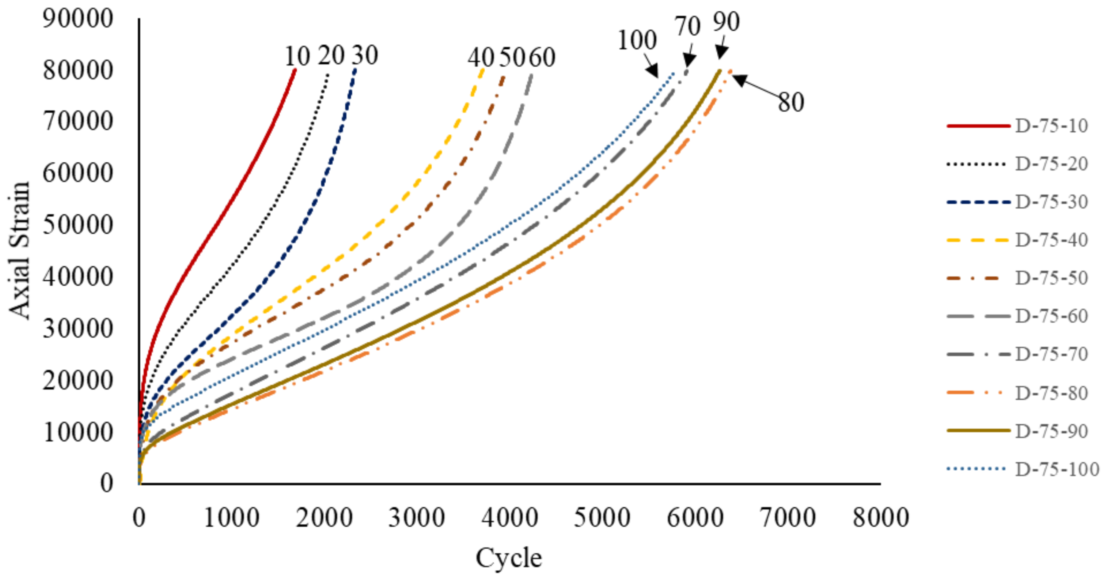

Figure 8.9. Axial strain vs. Flow Number Cycles for D-75 mixture

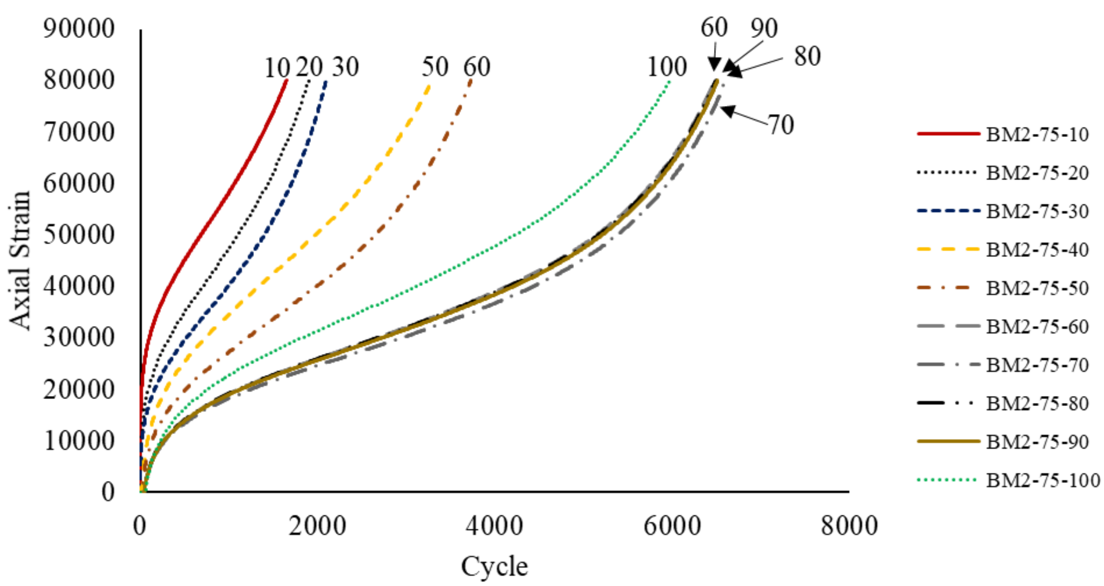

Figure 8.10. Axial strain vs. Flow Number Cycles for BM2-55 mixture

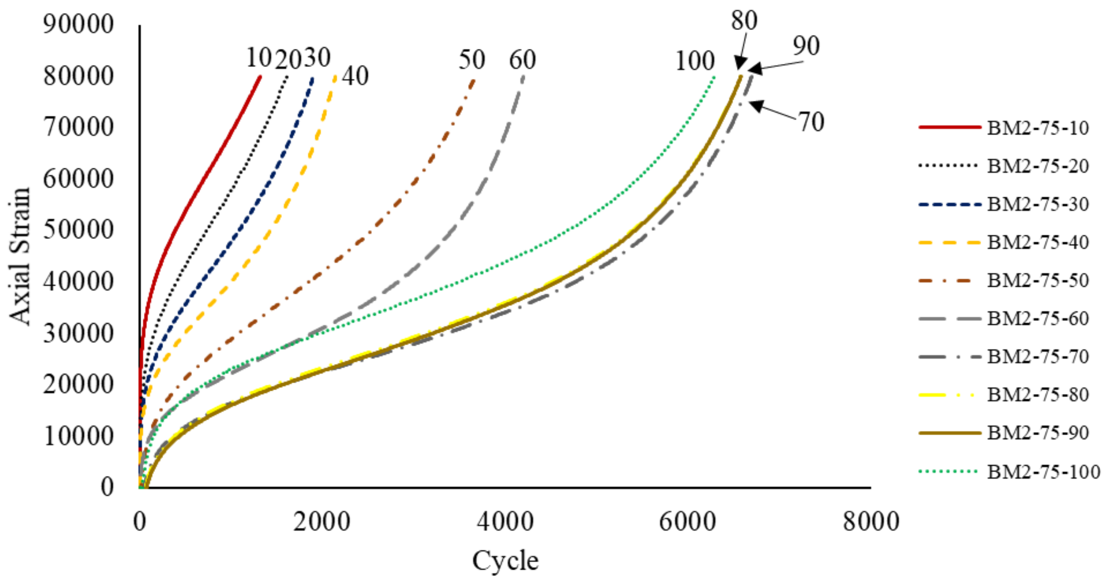

Figure 8.11. Axial strain vs. Flow Number Cycles for BM2-65 mixture

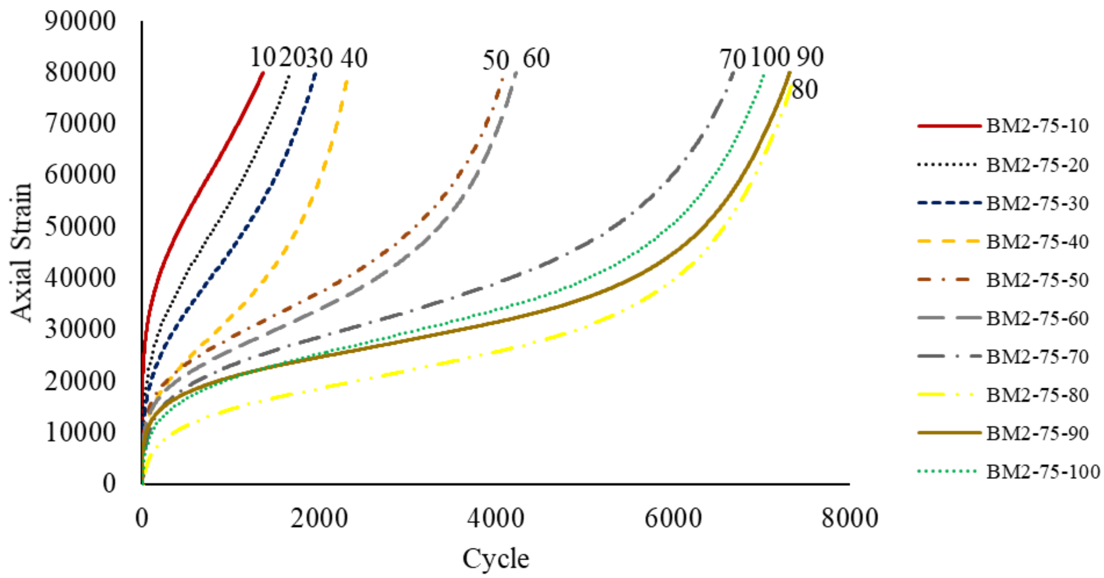

Figure 8.12. Axial strain vs. Flow Number Cycles for BM2-75 mixture

Similarly to the D-55 mix, the number of cycles to reach maximum axial strain increased with an increasing number of gyrations until it reached about 70 gyrations. Next, for the samples compacted from 80 to 100 gyrations, the number of cycles to achieve maximum axial strain decreased compared to 70 gyrations. The reason for this behavior change might be the damage to aggregate caused by over-compaction. For mixture D-75, a similar pattern was observed as for previous mixtures. The number of cycles to reach maximum axial strain increase with an increasing number of gyrations until it reached around 80 gyrations. Then, similarly to the D-65 mixture, the number of cycles decreased.

Base mixtures had similar patterns as the surface mixtures; however, it required a higher number of cycles to reach the maximum axial strain as expected. For the BM2-55 mix, the number of cycles to achieve maximum axial strain increased with an increasing number of gyrations until it reached about 60 gyrations. The further increase in the number of gyrations above 50 did not significantly change the axial strain. For the BM2-65 mix, the number of cycles to reach maximum axial strain increased with an increasing number of gyrations until it reached about 70 gyrations. For the samples compacted from 80 to 100 gyrations, the number of cycles to achieve maximum axial strain decreased compared to 70 gyrations. It was especially visible for the sample compacted at 100 gyrations. For the BM2-75 mix, the number of cycles to reach maximum axial strain increased with an increasing number of gyrations until it reached about 80 gyrations. For the samples compacted from 90 to 100 gyrations, the number of cycles to reach maximum axial strain decreased compared to 80 gyrations.

All the samples failed due to reaching the maximum axial strain, which was set at 80000, and no sample reached 8000 cycles. The results indicated that higher N_{design}, which could be translated into the lower asphalt content, provided better resistance to permanent deformations. The base mixtures had higher results of the number of cycles to reach maximum axial strain than surface mixtures. The decrease in the number of cycles after reaching a certain number of gyrations will be further analyzed to verify the possible damage to aggregates due to the over-compaction.

Next, the axial strains were reduced to the relationship between a specific strain as a function of compaction effort. The axial strain at 500 cycles was determined for each number of gyrations to understand the connection between these two parameters better and compare it to the locking points. The 500^{th} cycle was chosen because it permitted the inclusion of axial strain from all the samples. Figure 8.13 to Figure 8.18 presents the relation between the axial strain at 500 cycles and the number of gyrations. The data showed a decrease in the axial strain with increased compaction effort until the specific number of gyrations was reached. Then there was no decrease in axial strain results for the increasing compaction effort, or there was an increase in the axial strain that might be caused by the damage in the aggregate structure.

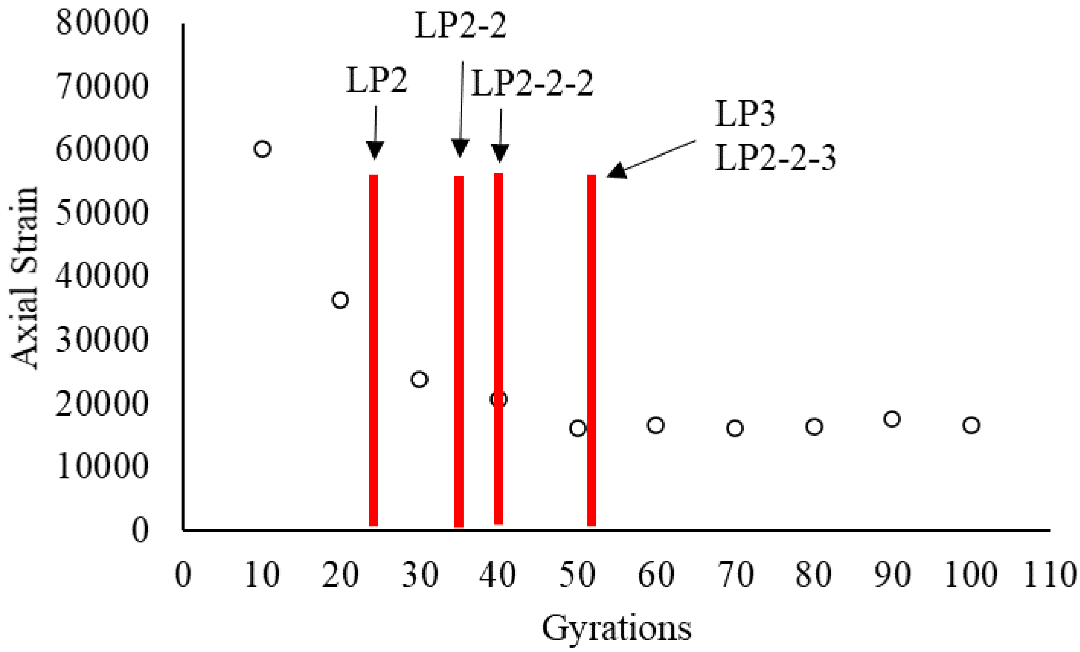

Figure 8.13. Axial Strain at 500 cycles vs. gyrations for D-55 mixture

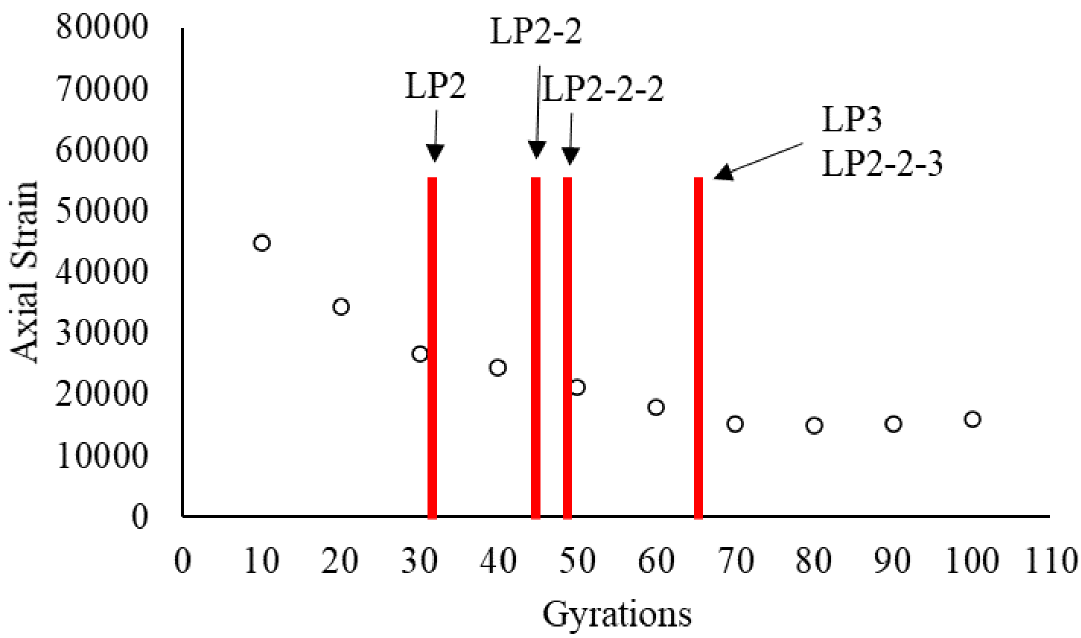

Figure 8.14. Axial Strain at 500 cycles vs. gyrations for D-65 mixture

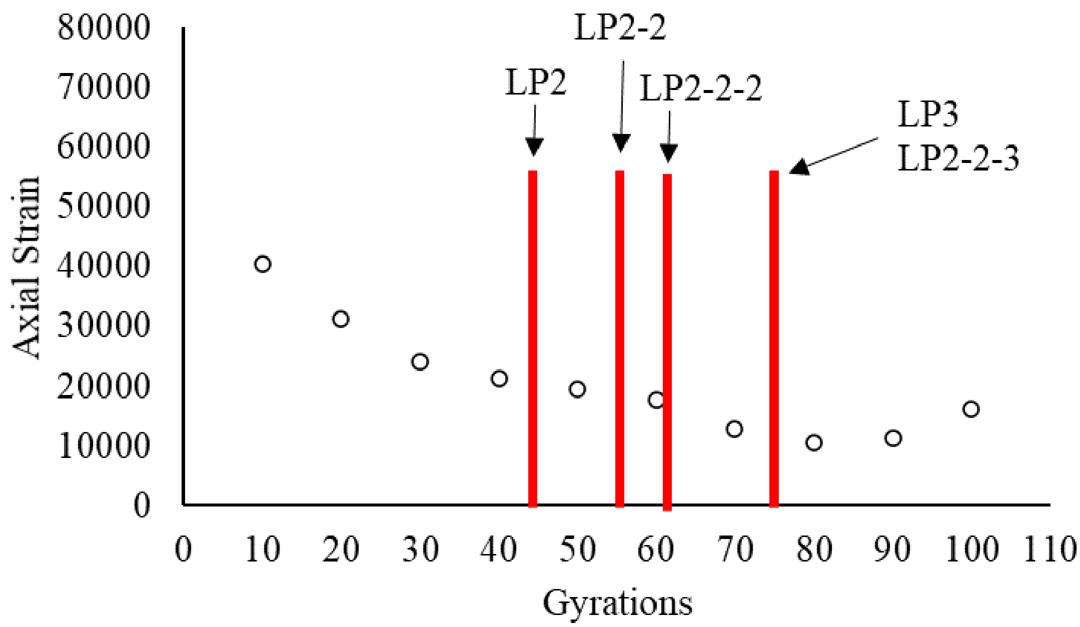

Figure 8.15. Axial Strain at 500 cycles vs. gyrations for D-75 mixture

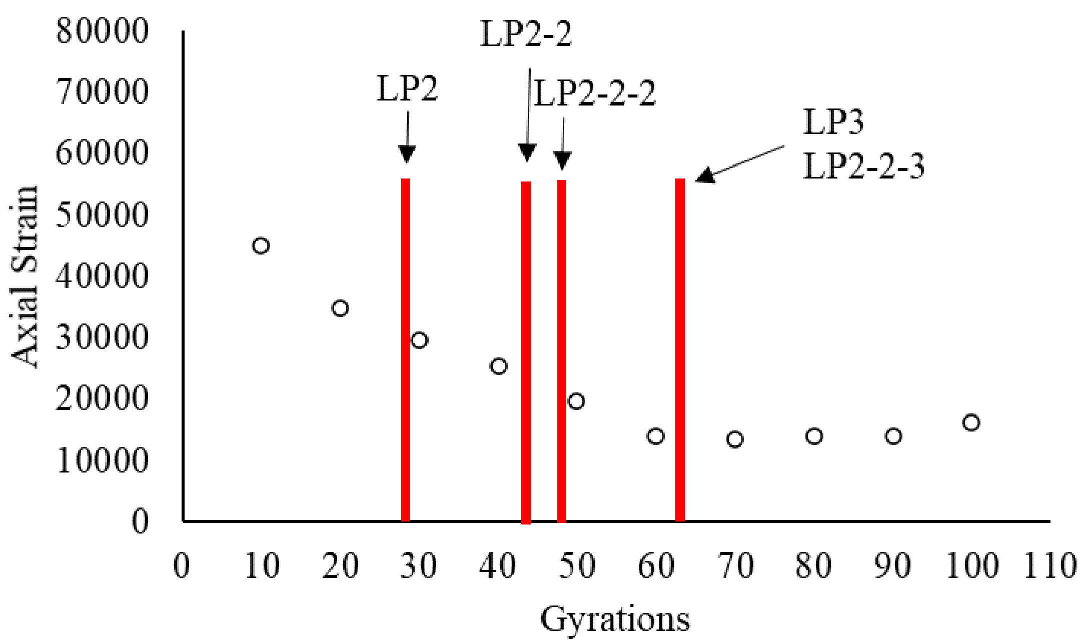

Figure 8.16. Axial Strain at 500 cycles vs. gyrations for BM2-55 mixture

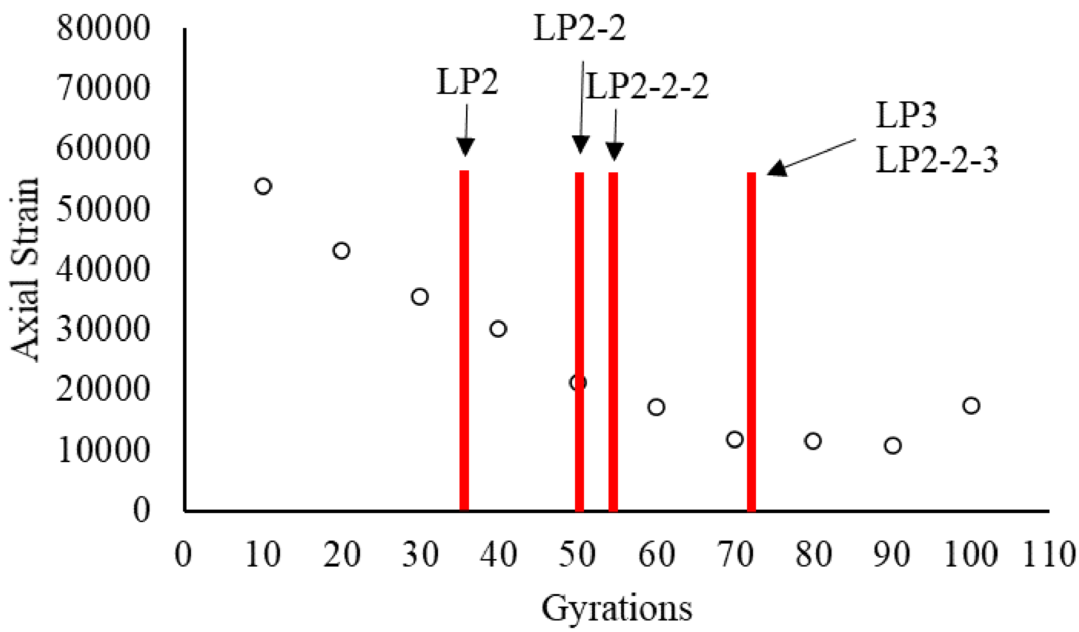

Figure 8.17. Axial Strain at 500 cycles vs. gyrations for BM2-65 mixture

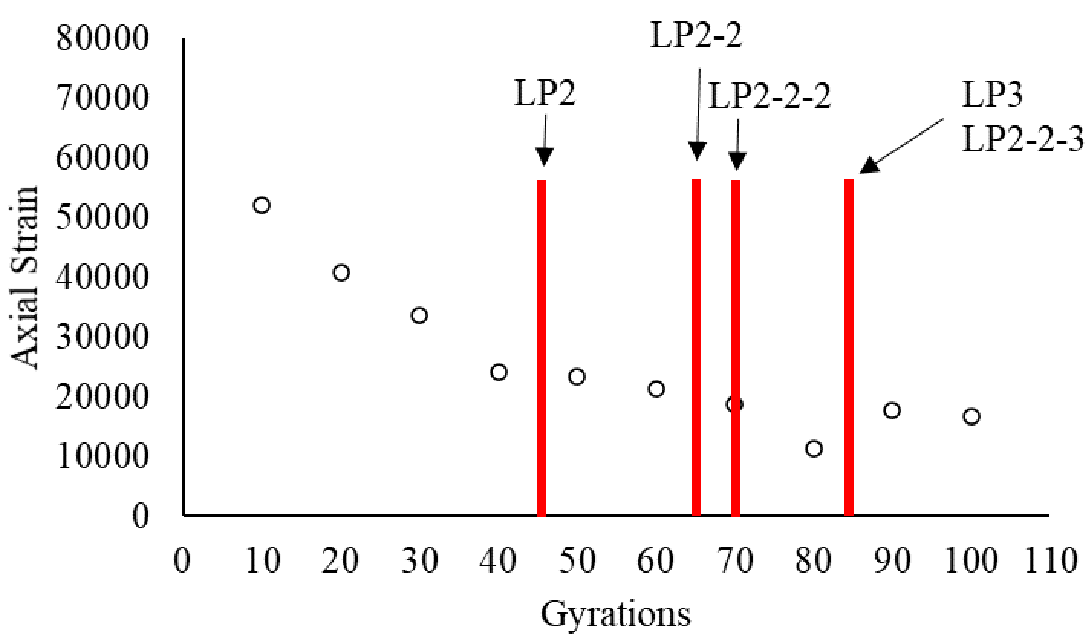

Figure 8.18. Axial Strain at 500 cycles vs. gyrations for BM2-75 mixture

For the D-55 mixture, the axial strain data indicated that the locking point was reached around the 50th gyration, which corresponds to the LP3/LP2-2-3 (53 gyrations). The LP2 occurred during a steep decrease in the axial strain, similarly to the LP2-2 and LP2-2-2. After reaching the 50th gyration, there was no significant variation in axial strain. For the D-65 mixture, the axial strain data indicated that the locking point was reached around the 70th gyration, which corresponded to the LP3/LP2-2-3 (64 gyrations). The LP2 occurred during a decrease in the axial strain, similarly to the LP2-2 and LP2-2-2. After reaching the 70th gyration, there was no significant variation in axial strain. For the D-75 mixture, the axial strain data showed that the locking point was reached around the 80th gyration, which corresponded to the LP3/LP2-2-3 (75 gyrations). The LP2, LP2-2, and LP2-2-2 were occurring during a decrease in the axial strain. After reaching the 80th gyration, an increase in axial strain was observed, and it was especially pronounced for the sample compacted with 100 gyrations.

Base mixtures followed the same pattern as surface mixes, but the damage seems to occur even for the mixture designed with 55 gyrations. For the BM2-55 mixture, the axial strain data pointed out that the locking point was reached around the 60th gyration, which again matched the LP3/LP2-2-3 (61 gyrations). The LP2, LP2-2, and LP2-2-2 took place during a decrease in the axial strain. After reaching the 60th gyration, there was no significant axial strain variation until the 100th gyration, where axial strain slightly increased. For the BM2-65 mixture, the axial strain data indicated that the locking point was reached around 70th gyration, which again corresponded to the LP3/LP2-2-3 (61 gyrations). The LP2, LP2-2, and LP2-2-2 occurred during a decrease in axial strain. After reaching the 70th gyration, there was no significant variation in axial strain until the 100th gyration, where axial strain considerably increased. For the BM2-75 mixture, the axial strain data indicated that the locking point was reached around the 80th gyration, which again corresponded to the LP3/LP2-2-3 (84 gyrations). The LP2, LP2-2, and LP2-2-2 happened during the decrease in axial strain. After reaching the 80th gyration, axial strain increased for samples compacted at 90 and 100 gyrations.

Overall, it seems that the LP3 and LP2-2-3 definition of the locking point is the closest to the interlocking indication provided by axial strain. For the mixtures designed with a higher number of gyrations, which in this research means lower asphalt content, there was possible damage caused to the mixture skeleton caused by over-compaction.

Table 8.4 presents the flow number results obtained for all the samples. The results followed a similar pattern as the axial strain result. The flow number increased during compaction until it reached the point that it decreased again when it became stable or after the stable part. In the case that the flow number decreased, it matched axial strain results. The data showed that to achieve the best rutting resistance, the compaction process should reach the interlocked stage. However, further uncontrolled compaction may compromise earlier archived rutting performance. For the D-55 mixture, the flow number increased until the 60th gyration, when it reached 1509 cycles and then maintained at the same level.

Table 8.4. Results of Flow Number

Gyrations	D-55	D-65	D-75	BM2-55	BM2-65	BM2-75
10	124	304	547	689	754	998
20	254	378	559	745	895	1026
30	547	645	898	1023	1102	1165
40	985	1247	1388	1845	1204	1304
50	1387	1387	1475	1988	1985	2005
60	1509	1678	1578	2359	2541	2087
70	1388	1845	1898	2271	2954	3087
80	1525	1799	2045	2254	2965	3289
90	1499	1874	1954	2302	3002	3014
100	1515	1850	1751	2012	2845	2978

Similar to the axial strain results, these results matched the LP3/LP2-2-3 definitions. For the D-65 mixture, the flow number increased until the 70th gyration, when it reached 1845 cycles and then maintained at the same level. Again, these results matched the LP3/LP2-2-3 definitions. For the D-75 mixture, the flow number increased until the 80th gyration, when it reached 2045 cycles and then went down to 1751 cycles at 100 gyrations. For the BM2-55 mixture, the flow number increased until the 60th gyration, when it reached 2359 cycles and then maintained at the same level until 100 gyrations when it went down to 2012 cycles. For the BM2-65 mixture, the flow number increased until the 70th gyration, when it reached 2954 cycles, and then stayed at the same level until 100 gyrations, when it dropped to 2845 cycles. For the BM2-75 mixture, the flow number increased until the 80th gyration, when it reached 3289 cycles and then went down to 2978 cycles at 100 gyrations.

IDEAL CT

Figure 8.19 presents the results of the IDEAL CT test. A general pattern that could be observed is that CT_{index} decreased with increasing compaction effort. Once a certain compaction level is reached, the decrease rate was lower, or there was no significant change in CT_{index} values.

For the D-55 mix, the CT_{index} decreased from 436 at 10th gyration to 285 at 60th gyration. The following gyrations had not reduced CT_{index} significantly, and it was maintained until the 100th gyration. Similarly to the axial strain, the CT_{index} became stable around the 60th gyration. For the D-65 mix, the CT_{index} decreased

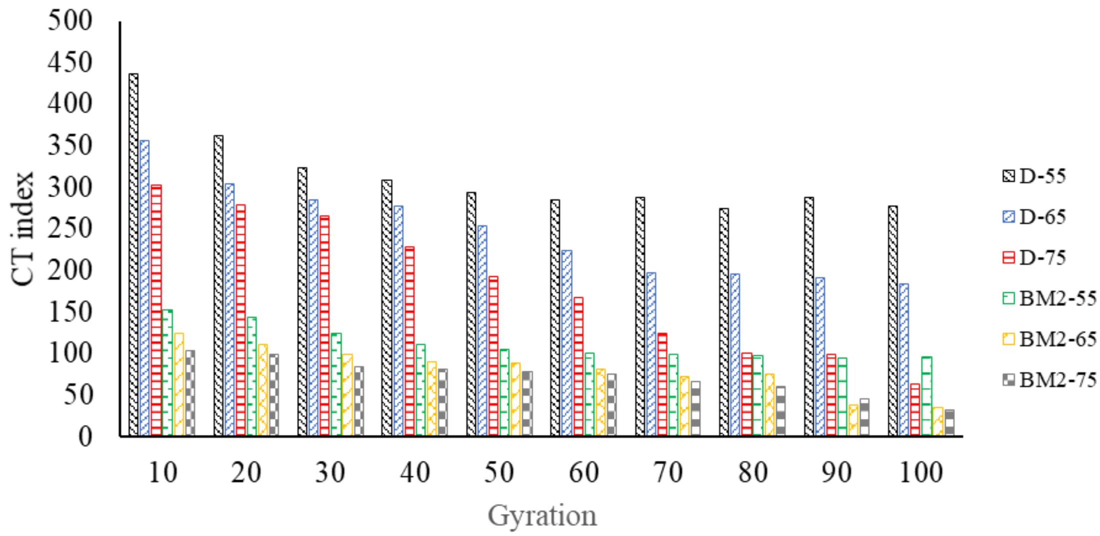

Figure 8.19. Summary of the IDEAL CT results

from 436 at 10^{th} gyration to 184 at 100^{th} gyration. After reaching 70 gyrations, the decrease rate slowed down. For the D-75 mix, the CT_{index} decreased from 302 at 10^{th} gyration to 64 at 100^{th} gyration. The CT_{index} got a similar value at 80^{th} and 90^{th} gyration, and then it went down to 64 at 100^{th} gyration.

The base mixtures had considerably smaller values of the CT_{index}. For the BM2-55 mix, the CT_{index} decreased from 152 at 10^{th} gyration to 96 at 100^{th} gyration. The decrease was similar to the D-55 mix. First, the CT_{index} was dropping with increasing compaction energy until it reached the 60^{th} gyration, then there was no significant change. For the BM2-65 mix, the CT_{index} decreased from 124 at 10^{th} gyration to 35 at 100^{th} gyration. After reaching 70 gyrations, the decrease rate slowed down, but there was a significant decrease at 90^{th} and 100^{th} gyration. For the BM2-75 mix, the CT_{index} decreased from 104 at 10^{th} gyration to 33 at 100^{th} gyration. In this case, there were no similar data patterns as for previous mixtures. After reaching the 30^{th} gyration, the decrease rate slowed down until the 70^{th} gyration was reached, and then another steep decrease was recorded.

A similar pattern could be observed for the mixtures D-55, D-65, and BM2-55. Initially, the CT_{index} decreased until it reached close to LP3/LP2-2-3, then there was no significant change. A considerable drop in CT_{index} was observed for the mixtures D-75, BM2-65, and BM2-75 at the high compaction effort, especially for 100 gyrations. Mixtures D-75 and BM2-65 followed the axial strain pattern, and the CT_{index} decrease rate slowed down at LP3/LP2-2-3. However, for the mixture BM2-75, there was no apparent change in rate after reaching LP3/LP2-2-3.

Aggregate Breakage

The data obtained from the Flow Number test and the IDEAL CT test indicated there might be a problem with the mixture skeleton at high compaction effort. The post-compaction sieve analysis was performed to investigate possible aggregate damage due to the over-compaction. Initially, the samples used for the Flow Number test and the IDEAL CT test were going to be used to check gradation. However, the coring and cutting have already altered the gradation, so it was decided to compact new samples at 10 and 100 gyrations and compare them to design gradation. Before conducting the solvent extraction and sieve analysis, the visual inspection indicated that samples of the BM2-65 mix and the BM2-75 mix had visible aggregate breakage. The rest of the samples had no noticeable damage.

Table 8.5 presents the results of the solvent extracted aggregate gradations compared to design gradation. The grey cells with bold numbers indicate a significant increase in passing material at the specific sieve. Mixtures D-75, BM2-65, and BM2-75, suffered degradation of aggregates, while mixtures D-55, D-65, and BM2-55 had no similar gradation change. The most affected sieves are No. 30 and smaller, while sieves No. 4 and No. 8 seem unaffected. The asphalt content obtained from the solvent extractions was 0.1% to 0.3% lower than the optimum asphalt content from mix design. The most probable reason might be that the solvent did not remove some small part of the absorbed binder.

Table 8.5. Summary of the post-compaction sieve analysis

D-55				D-65				D-75			
Sieve	Design	10 gyrations	100 gyrations	Sieve	Design	10 gyrations	100 gyrations	Sieve	Design	10 gyrations	100 gyrations
16 mm	100	100	100	16 mm	100	100	100	16 mm	100	100	100
12.5 mm	95	95	95	12.5 mm	95	94	96	12.5 mm	95	96	***99***
9.5 mm	86	87	88	9.5 mm	86	86	88	9.5 mm	86	88	***92***
No. 4	65	65	66	No. 4	65	66	67	No. 4	65	66	67
No. 8	46	47	47	No. 8	46	46	48	No. 8	46	47	49
No. 30	23	22	24	No. 30	23	24	24	No. 30	23	23	***27***
No. 50	13	13	14	No. 50	13	13	14	No. 50	13	12	***18***
No. 100	7.0	7.4	7.7	No. 100	7.0	7.3	7.6	No. 100	7.0	7.3	***8.4***
No. 200	3.0	3.1	3.3	No. 200	3.0	3.0	3.2	No. 200	3.0	3.4	***4.1***

Table 8.5 continued

BM2-55				**BM2-65**				**BM2-75**			
Sieve	Design	10 gyrations	100 gyrations	Sieve	Design	10 gyrations	100 gyrations	Sieve	Design	10 gyrations	100 gyrations
31.5 mm	100	100	100	31.5 mm	100	100	100	31.5 mm	100	100	100
19 mm	87	88	87	19 mm	87	88	***91***	19 mm	87	86	90
9.5 mm	65	66	67	9.5 mm	65	64	***70***	9.5 mm	65	66	***72***
No. 4	48	49	51	No. 4	48	49	50	No. 4	48	48	52
No. 8	35	34	36	No. 8	35	35	37	No. 8	35	35	38
No. 30	19	21	21	No. 30	19	20	***24***	No. 30	19	21	***23***
No. 50	14	15	15	No. 50	14	14	***17***	No. 50	14	15	***18***
No. 100	8.0	8.4	8.6	No. 100	8.0	8.2	***9.4***	No. 100	8.0	8.3	***9.5***
No. 200	4.0	4.2	4.6	No. 200	4.0	4.4	***5.1***	No. 200	4.0	4.6	***5.5***

The post-compaction sieve analysis results indicated that the aggregate breakage could be identified by the Flow Number test's axial strain results. The three samples, which sieve analysis, showed a breakage of aggregate, also suffered from a drop in the axial strain and the flow number. The IDEAL CT results also correlated with post-compaction sieve analysis. The steep decline in CT_{index} for mixtures D-75, BM2-65, and BM2-75, compacted at 100 gyrations, was also reflected in post-compaction sieve analysis.

The data obtained from the performance test and sieve analysis of the mixtures signify that the locking point concept may prevent over-compaction and damage to the laboratory compaction mix. The initial thought was that it could also apply to field compaction of the asphalt mix; however, a further study addressing the locking point's application and damage of aggregate skeleton due to over-compaction should be further investigated. Asphalt mixture compacted in the field has different boundary conditions, then mix compacted in the laboratory. The stiff wall of the laboratory mold directs the compaction energy vertically, which might increase aggregate breakage. In the field, there is no such boundary, and aggregates are easier to accommodate. On the other side, the high of the laboratory specimen is higher than a lift of the typical asphalt mixture in the field, which can provoke more severe field mixes.

The results could be concluded that locking point height pattern LP3 and LP2-2-3 are related to the axial strain and IDEAL CT results. The locking point may be influenced by various factors such as binder viscosity (temperature), binder type (modified or unmodified), aggregate type, and gradation. This study utilized one unmodified binder with strictly controlled mixing and compacting temperature, one type of aggregate (limestone), and two types of mixtures (surface and base). So, it would be beneficial to further study different binder and aggregate types and their influence on the asphalt mixture's interlocking properties.

Conclusions

The study investigated the existence of asphalt mixture interlocking and evaluated different locking points' definitions by utilizing performance tests. The common definitions of the locking point are based on the change in specimen height during the compaction process. The locking point indicates a point during compaction beyond which the mix structure starts to resist further compaction, and aggregates can be broken. Two different types of asphalt mixtures were used in this study. Each type of mixture was designed at three different compaction efforts (N_{design}) 55, 65, and 75 gyrations. First, the locking points were defined by applying different definitions (LP2, LP2-2, LP2-2-2, LP3, and LP2-2-3). Second, the Flow Number samples were compacted (from 10 to 100 gyrations), cored, cut, and tested. Third, the samples for IDEAL CT were compacted (from 10 to 100 gyrations), cut, and tested. Next, after analyzing the axial strain data and CT_{index} results, the post-compaction sieve analysis was performed to detect possible breakage of aggregates due to over-compaction. Based on the results of this study, the following conclusions were reached:

- The LP2-2-3 and LP3 are the most indicated to define the locking point based on axial strain from the Flow Number test and CT_{index} from the IDEAL CT test.
- For most of the cases, LP2-2-3 and LP3 definitions provide the same results. However, for some coarser mixtures, it is not possible to detect the LP2-2-3 pattern, so LP3 seems a better choice than LP2-2-3. There was no similar problem for the LP2-2-2 pattern as it appeared in the case of all the samples.
- The LP3/LP2-2-3 has less dispersed data concerning the mean than LP2, which is confirmed by standard deviation and variance.
- The locking point increases with decreasing asphalt content and with larger maximum aggregate size.
- After reaching the locking point LP3/LP2-2-3, there is no substantial decrease in the axial strain.
- As indicated by the axial strain and the flow number, the compaction process should reach the interlocked stage to achieve the best rutting resistance. However, further uncontrolled compaction may compromise earlier archived rutting performance.
- For mixtures with larger aggregates (primarily base mixtures) and lower asphalt content, the axial strain increases, and the CT index decreases at the highest compaction effort, which indicates the breakage of aggregates, which was confirmed by post-compaction sieve analysis.

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CHAPTER NINE

QUANTIFICATION OF ASPHALT MIXTURE INTERLOCKING UTILIZING 2D AND 3D IMAGE PROCESSING

Abstract: The internal structure of the asphalt mixture plays a vital role in performance since it deals with gradation, air void distribution, and mixture packing. While quantification of the effect of the internal structure on the mechanical behavior of HMA cannot be achieved through experimental work, the internal structure can be characterized through image-based analysis. Recent studies have used imaging techniques to understand how internal structure influences the performance of a mixture. This study attempted to quantify the interlocking properties of hot mix asphalt by 3D and 2D image analyzing process and correlate the result to the locking point concept. Two types of aggregates (limestone and gravel), one type of bitumen PG64-22, and two types of asphalt mixtures D (½") and BM2 (1 ¼") were utilized in this study. Two software was utilized to process and analyze captured images, iPas2 for 2D analysis, and Avizo Fire for 3D analysis. Based on this study's results, 3D and 2D image processing are promising non-destructive methods to quantify asphalt mixtures' interlocking properties.

Introduction

The asphalt mixture's internal structure plays an essential role in performance since it deals with gradation, air void distribution, and mixture packing. While quantification of the effect of the internal structure on the mechanical behavior of HMA cannot be achieved through experimental work, the internal structure can be characterized through image-based analysis. Recent studies have used imaging techniques to understand how internal structure influences the performance of a mixture. Two or three-dimensional (2D or 3D) image-based asphalt analysis has been employed for characterizing the distribution of the aggregate and the air voids in compacted mixtures, as well as for microstructural modeling. One of the most efficient imaging methods for use with HMA is X-ray computed tomography (CT). This nondestructive technique provides a 3D characterization of the internal structure of HMA by capturing the microstructure of asphalt mix (Cannone Falchetto 2011; Masad and Button 2004; Taniguchi et al. 2013; Zelelew and Papagiannakis 2011; Zhu et al. 2011). Figure 9.1 shows the process of obtaining the 3D CT image.

Based on material density, each component of the mixture can be determined by analyzing gray levels. Some researchers also utilized a digital camera or scanner to obtain 2D images of asphalt mixture to analyze the internal structure, such as void characteristics. The CT scan images or digital camera pictures need proper processing, allowing extraction of particles, binder, and air voids information. Image processing is a multi-level process that includes applying different filters, image segmentation, morphological analysis, and noise reduction (Chen et al. 2015; Shashidhar 1999; Shi et al. 2020).

Zhu and Nodes (2000), based on their contact mechanism analysis, indicated that the load transfer is characterized by the interaction of asphalt cement and aggregates at the contact between aggregates. Their work concluded that stress-strain distribution is affected by variations in binders and aggregates' geometrical and mechanical properties.

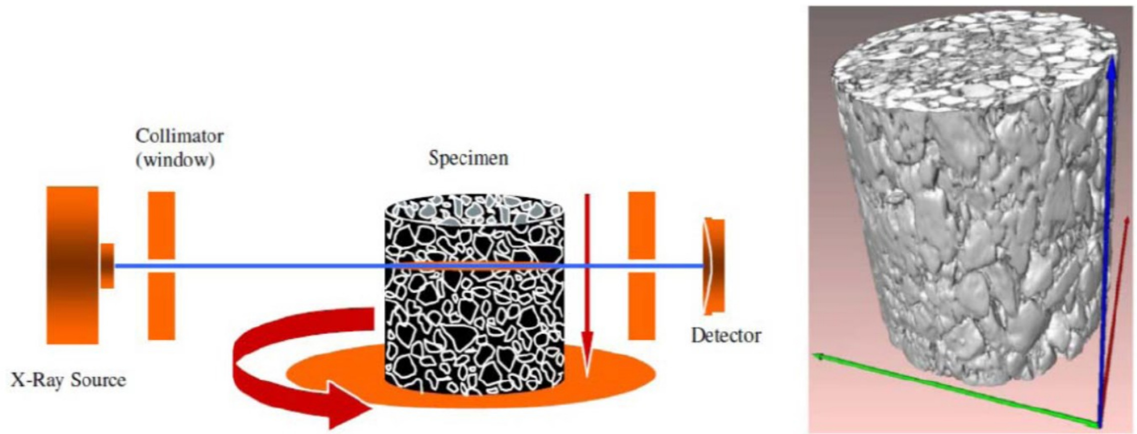

Figure 9.1. 3D CT image analysis technique (Cannone Falchetto 2011)

Sefidmazgi et al. (2012) indicated that analyzing the asphalt concrete using 2D images is more economically efficient than 3D analysis. The study proposed new parameters to characterize the structure of the asphalt mixture. The results indicated that there is a strong correlation between rutting performance and internal structure indices. As part of this study, the iPas software was developed, allowing the capture and analysis of 2D images.

Coarse aggregates create the skeleton structure of asphalt mixture and bear the majority of the traffic loads. Several parameters can be used to characterize asphalt mixture structure, such as the number of contacts between aggregates, contact length (2D) or area (3D), stress paths. The aggregate contact number indicates the connection level of the internal structure. As the number of contacts increases, there is less stress concentration and improved stress distribution. The quality of contact between aggregates can be characterized by contact length or area. Most of the load is transferred in the loading direction by interconnected aggregates. There are aggregates with only one contact point, which are not expected to participate significantly in the loading transfer (Bessa et al. 2012; Li et al. 2020; Onifade et al. 2013; Sefidmazgi 2011).

Coenen et al. (2012) researched the effects of compaction temperature on aggregate structure parameters. Based on image analysis, the temperature of the mixture and pressure of the compactor did not significantly affect aggregate orientation; however, there was a difference in the number of contact points. The contact points number was directly correlated with the common volumetric properties of the asphalt mixture.

Wang et al. (2003) introduced methods to quantify the damage of asphalt mixture specimens based on 3D CT images and established the relation between mechanical modeling and damage parameters.

Masad et al. (1999) utilized X-ray tomography to quantify the internal structure of asphalt concrete. Several parameters were described, including air void distribution, gradation, and orientation of aggregates. It was concluded that the air void distribution in the specimen is not uniform, and more voids are located at the bottom and top of the sample. Air void obtained from image processing and laboratory compared well.

Elseifi et al. (2011) utilized the X-ray CT to quantify the magnitude of damage during flow numbers and dynamic modulus tests. The results showed that the dynamic modulus test's damage is low, while the flow number test considerably damages the sample. Air voids distribution is affected by the sample preparation procedure. The addition of recycled asphalt pavement (RAP) increased mixture stiffness and resistance to rutting at high temperatures.

Liang et al. (2020) evaluated the fracture performance of asphalt concrete utilizing digital images. The research concluded that specimens with the same gradation but higher cracking resistance have a smaller angle between the coarse aggregates, higher angularity, and uniform distribution of coarse aggregates. The increase in coarse aggregate content produces mixtures less resistant to cracking, and the crack path is along the coarse aggregates edges.

Xing et al. (2019) utilized X-ray CT images processing to measure the asphalt mixture's gradation. The image processing based on the gray level can enhance the contrast and reduce the noise. The image processing can produce accurate gradation, which is similar to real sample gradation.

Ketcham and Shashidhar (2001) developed a software BLOB3D, which can process and quantitatively analyze 3D images. The research and developed software indicated that it is possible to quantitatively analyze particle size, location, aggregate-to aggregate contact vectors, and contact area using the image processing.

Objectives and Scope

This study's objective was to quantify the interlocking properties of hot mix asphalt by the 2D and 3D image processing and correlate it to the locking point concept.

Two types of aggregates (limestone and gravel), one type of bitumen PG64-22, and two types of asphalt mixtures D (½") and BM2 (1 ¼") were utilized in this study. Two software was utilized to process and analyze captured images, iPas2 for 2D analysis, and Avizo Fire for 3D analysis.

Laboratory Experiments

Materials

Different sizes of crushed limestone (BM2-mix) and gravel (D-mix) were utilized in this study. The aggregates were screened through the same set of sieves: 38.1 mm (1 ½"), 31.8 mm (1 ¼"), 25.4 mm (1"), 19.0 mm (¾"), 15.9 mm (5/8"), 12.7 mm (½"), 9.5 mm (3/8"), No. 4, No.8, No. 30, No. 50, No. 100 and No. 200. For all the mixtures, the same unmodified binder PG 64-22 was used. The mixing temperature was 154.4 °C (310 °F), and the compaction temperature for this asphalt binder was 148.9 °C (300 °F).

Specimen Preparation

The samples were prepared to utilize the same gradation, asphalt content, and the samples' weight. Initially, three samples for each type of mixture were prepared to define the locking point. Once the locking point was defined, three samples of BM2-mix were prepared for 3D X-ray CT at the different number of gyrations (locking point, five gyrations below the locking point, and 10 gyrations above the locking point). For 2D analysis, the samples were compacted at different gyrations from 20 to 100 gyrations. Each sample weighed 4,300 grams.

Testing Procedure

The locking point was determined by preparing five samples of each mixture type and measured the average height change. Five definitions of the locking point were utilized: LP2, LP2-2, LP2-2-2, LP3, and LP2-2-3.

For 3D analysis, the process involved three steps: image acquisition, processing, and analysis. The samples were scanned in X-ray CT. The equipment includes an X-ray source and a detector. The X-ray passes the specimen and is received by the detector. The absorption level depends on the density of the scanned material and the energy of the X-ray. A scintillator converts the X-ray to visible light, transmitted onto a detector, and recorded by a camera.

The equipment took 1200 cross-sectional images, which were used to reconstruct a 3D specimen. Figure 9.2 shows the sample of the reconstructed specimen. The images obtained from X-ray CT scans were processed, enhanced, and segmented utilizing the Avizo software. A median filter and an anisotropic diffusion filter were utilized on the grayscale images to enhance the contrast of edges and reduce the noise content. Once the anisotropic diffusion filter was applied, the images were binarized by the interactive thresholding module. The threshold was determined based on the image histogram (Figure 9.3). Air voxels were assigned a value of 0, and aggregate voxels the value of 1. Next, the aggregates were separated and labeled by the Separate Objects module in the software. The Separate Object module consists of different filters and algorithms like a watershed, numerical reconstruction, and distance transform, removing small contact areas between aggregates (Druckrey and Alshibli 2016; Jarrar et al. 2020).

As can be noticed in Figure 9.2 that there is a darker area in the center of the specimen and at the top and bottom of the specimen. The darker areas in the

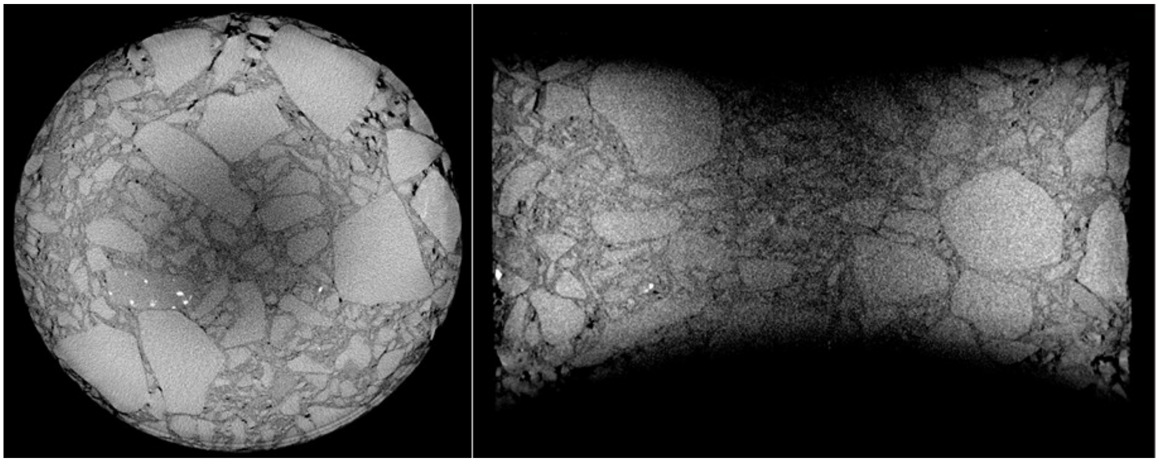

Figure 9.2. Reconstructed 3D specimen.

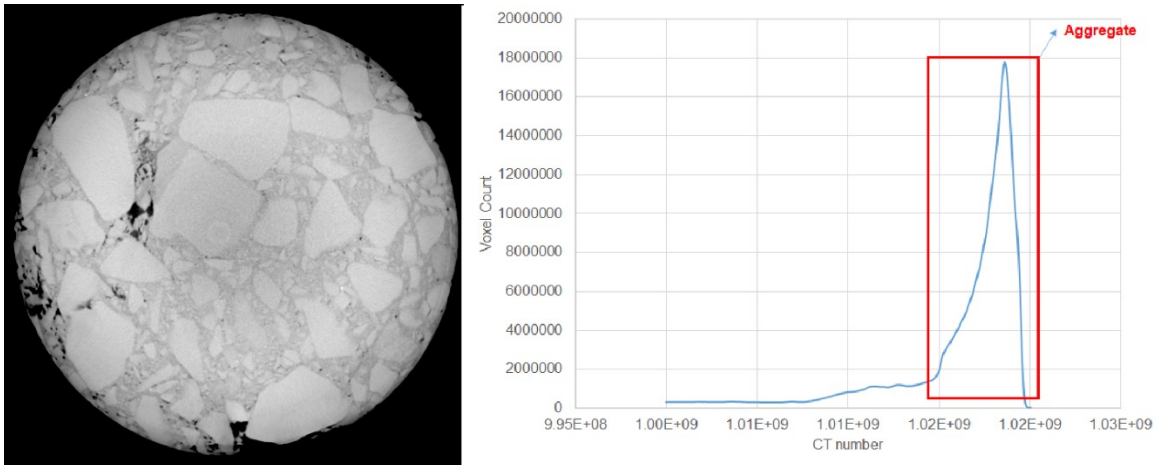

Figure 9.3. Aggregate segmentation. Filtered image and image histogram

reconstructed specimen affect the filtering results and prevent the ability to separate the aggregates and further analysis. Avizo background and flat field correction tool were utilized to correct the color in different parts of the specimen. This correction improved segmentation results. It was not possible to improve the darker areas at the top and the bottom of the specimen, so these areas were cut out in the software. Figure 9.4 presents reconstructed, filtered, and segmented specimens.

Based on the literature review presented in the introduction, the aggregate smaller than No. 8 (2.36 mm) were filtered out, and the following parameters were chosen to quantify interlocking of the aggregates: number of contacts between aggregates per volume, a ratio of interlocked particles to the total number of particles and the contact area.

For 2D analysis, the procedure to prepare the 3D samples were applied. However, after compaction and cooling down, the samples were cut vertically in four slices utilizing the masonry saw, as presented in Figure 9.5. The first cut divided the sample into two equal parts. Another cut was made 1 inch parallel from the previous cut. The samples were dried, and the surface utilized in the analysis were measured. A digital camera was utilized to acquired 2D images, as presented in Figure 9.6.

The digital camera parameters, the distance between the lens and the sample, and the light intensity were maintained constant. The iPas2 software developed by Dr. Hussain Bahia’s research group was utilized for image

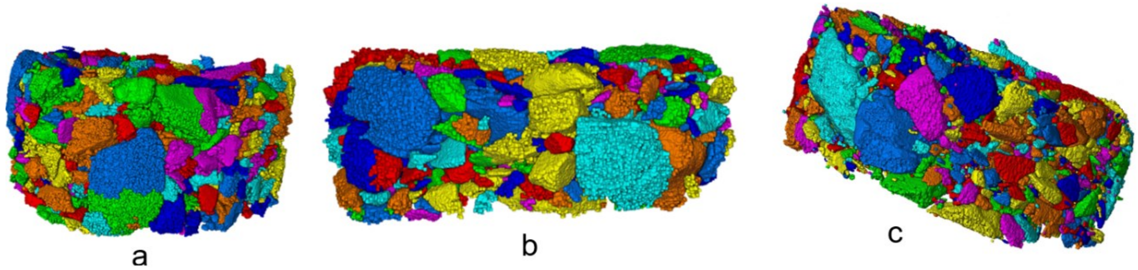

Figure 9.4. (a) Locking Point minus 5 gyrations, (b) Locking Point, (c) Locking Point plus ten gyrations

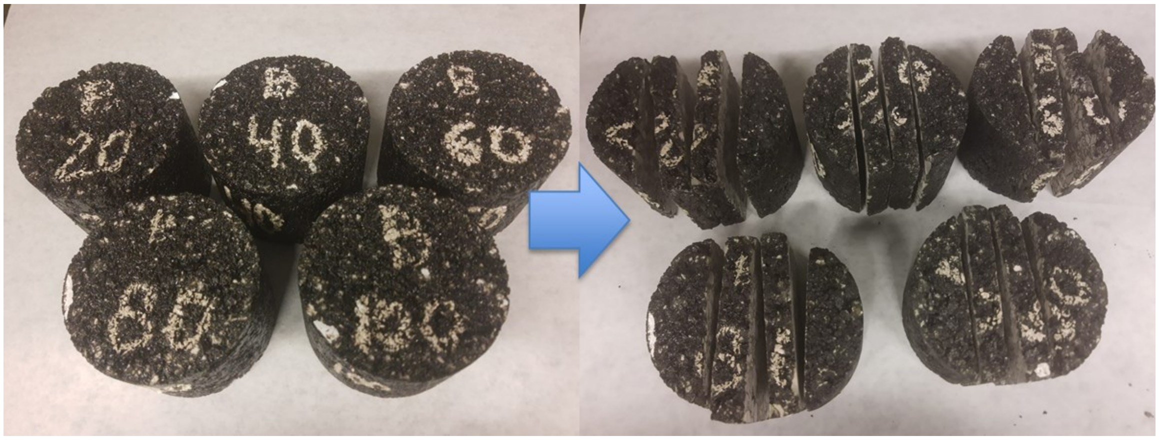

Figure 9.5. Example of the sample slicing

Figure 9.6. Set up for digital images acquisition

processing and quantitative analysis. The detailed procedure for image processing utilizing iPas2 is included in Coenen et al. (2012). Software process and analysis the image by applying watershed filtering, thresholding, and hybrid max filtering (Figure 9.7). The accuracy control is achieved by the input of the real volumetric properties and gradation of the sample. Once the image is processed, the software calculates the virtual gradation. The user can compare the real and virtual gradation and, in this way, control the quality of the analysis. The major disadvantage of 2D analysis is the necessity to assume the maximum distance between considered aggregate contact. In the software, contact is counted when two aggregates are at the maximum distance indicated by the user. The distance is represented by the pixels between the edges of two aggregates. The maximum distance between considered aggregate contact must be higher than the resolution of the picture. All the images were processed utilizing the same filters and 2.36 mm minimum particle size. Similarly to 3D image processing, the 2D software separates each particle and analyzes the interparticle contacts (Figure 9.8).

The maximum distance between considered aggregate contact is a critical parameter in 2D image processing and should not be imputed arbitrarily. Two procedures were applied to determine the most appropriate value of this parameter. First, the number of contact points at the different maximum distance between considered aggregate contact were calculated and plotted. This relationship indicates a plateau, where the different maximum distance between aggregate does not significantly change the number of contact points. Following

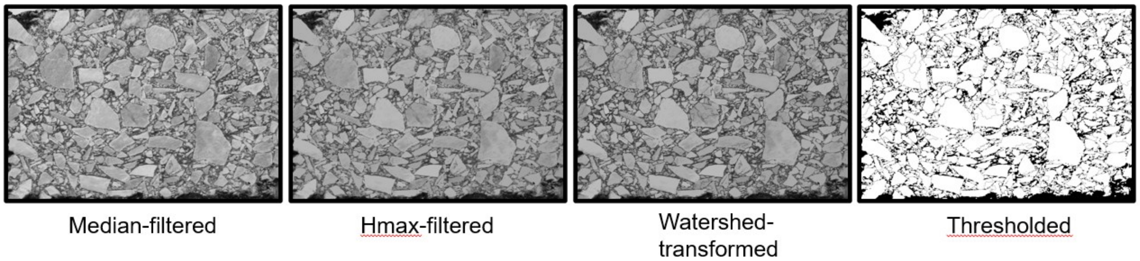

Figure 9.7. Image filtering process

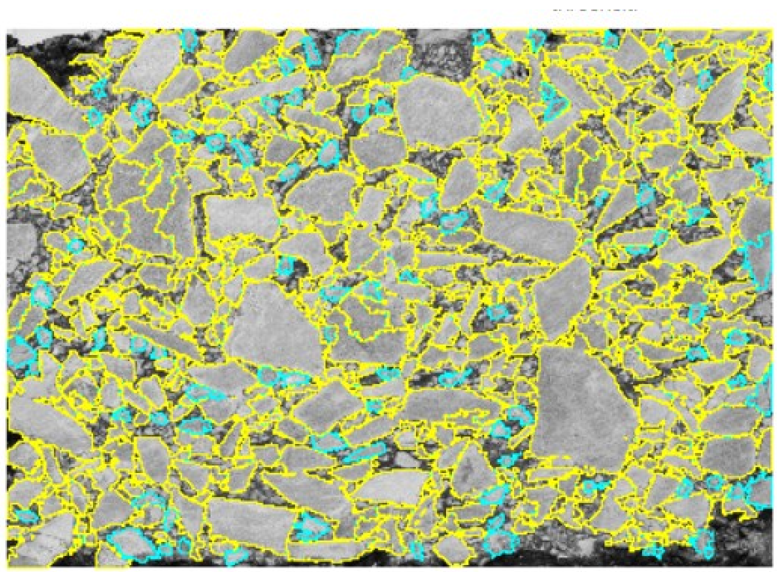

Figure 9.8. Example of the thresholded image

the plateau, there is a region with a linearly increasing number of contact points. The contact search radius increased until every aggregate can be determined in contact with all other aggregates, which is not a correct procedure. The left part of the plateau is characterized by a steep decrease to zero. It is caused by the chosen maximum distance close to image resolution, where the contact points cannot be identified. To compare the 3D and 2D analysis, the thickness of 1 mm was assumed for 2D images, which allowed comparing the number of contact points per cubic centimeter from 3D and 2D images.

Once the maximum distance between aggregate considered contact was established, the images for the BM-2 and D-mixes (Figure 9.9) were analyzed utilizing similar parameters as for 3D images: number of contacts between aggregates per area, a ratio of interlocked particles to the total number of particles and the contact length.

Results and Discussion

Locking Point

Table 9.1 presents the locking point determination result, including average, standard deviations (SD), and variances. Overall, it could be noticed that the locking point increases with larger maximum aggregate size. The LP2 definition always returned the lowest locking point, while the LP3 and LP2-2-3 returned the highest locking point. The LP3 and LP2-2-3 had the same value. The LP2 had the highest standard deviation and variance, while LP3 and LP2-2-3 had the lowest.

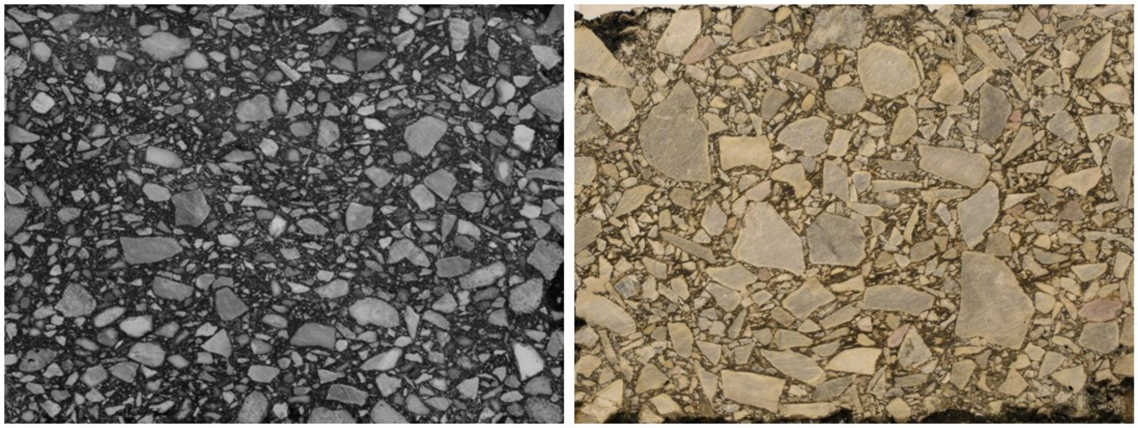

Figure 9.9. Example of D and BM2 samples

Table 9.1. Summary of the locking points

LP2			
Mix	**Mean**	**Standard Deviation**	**Variance**
D	27	1.4	5.6
BM2	38	4.1	10.3
LP2-2			
Mix	**Mean**	**Standard Deviation**	**Variance**
D	43	1.4	1.6
BM2	54	2.5	4.1
LP2-2-2			
Mix	**Mean**	**Standard Deviation**	**Variance**
D	46	0.9	0.7
BM2	59	1.2	2.0

Table 9.1 continued

LP3			
Mix	**Mean**	**Standard Deviation**	**Variance**
D	63	0.7	0.6
BM2	77	0.8	0.7
LP2-2-3			
Mix	**Mean**	**Standard Deviation**	**Variance**
D	63	0.6	0.5
BM2	77	0.6	0.4

It was concluded that the LP3/LP2-2-3 had the most consistent data based on standard deviation and variance analysis. It is also preferable to use the LP3 definition rather than the LP2-2-3 because, in some cases, the LP2-2-3 is not possible to detect. For 3D analysis, the locking point LP3/LP2-2-3 was utilized.

3D Analysis

Error! Reference source not found. presents the result of the analysis of c ontact numbers between aggregates and the interlocking parameter. Free particles are defined as aggregates with two, one, or zero contact points. Interlocked particles have three or more contact points. The interlocking parameter is calculated by dividing the number of interlocked particles by the total number of particles. The initial expectation was that the interlocked sample would have the interlocking parameter equal to 1. However, the boundary condition is changing once the samples are taken out of the mold after compaction. During 3D X-ray CT and image processing, the sample missed the mold's contact points, which resulted in values closer to 0.5. Also, there is a difference in the total number of particles between these three samples and range from 1310 to 1451. This difference may be attributed to how image processing was conducted and the necessity to remove the top and bottom specimens. It can be noticed that 5 gyrations before the locking point, the interlocking parameter equal to 0.44, once the locking point is reached, the parameter is 0.49 and ten gyrations after the locking point increased by 0.01 up to 0.50. In this case, the volume of the samples was the same 883 cm^3. However, when the samples with different volumes are analyzed, it should be considered to

Table 9.2. Summary of contact numbers and interlocking parameters

	Sample Locking Point -5 gyrations	Sample Locking Point	Sample Locking Point +10 gyrations
Free Particles	696	661	712
Interlocked Particles	615	649	739
Total Particles	1398	1310	1451
Interlocking Parameter	0.44	0.49	0.50

compare the results. The results show no significant increase in the number of interlocked particles after passing the locking point. However, with only three samples, it is impossible to draw a conclusion and further analysis.

Table 9.3 presents the results of the contact number between aggregates per volume. The primary purpose of these calculations was to obtain data that could be compared and validate the 2D analysis. The sample volume is the same, and the total number of contacts is changing with different compaction effort. Similarly to the interlocking parameter, a significant difference between the sample compacted five gyrations below the locking point and at the locking point (1.91 contacts/cm^3). The difference is smaller between the locking point and ten gyrations above the locking point (0.83 contacts/cm^3).

Figure 9.10 presents the results of contact areas at different compaction effort. Similarly to the previous parameters, the contact area presented the highest increase between the locking point and five gyrations below the locking point (247 cm^2) and a lower increase between the locking point and ten gyrations above the locking point (62 cm^2). The three parameters' results followed the same pattern indicating that after the locking point is reached, there is no more significant improvement is the asphalt mixture structure. However, as mentioned before, three samples are not enough to give strong support to this conclusion.

2D Analysis

Figure 9.11 shows the relationship between the number of contacts and the maximum distance between aggregate considered contact for three samples of

Table 9.3. Summary of the contact points per volume

	Sample Locking Point -5 gyrations	Sample Locking Point	Sample Locking Point +10 gyrations
Number of contacts	11346	13024	13754
Sample volume (cm3)	883	883	883
Contacts per volume	12.84	14.75	15.58

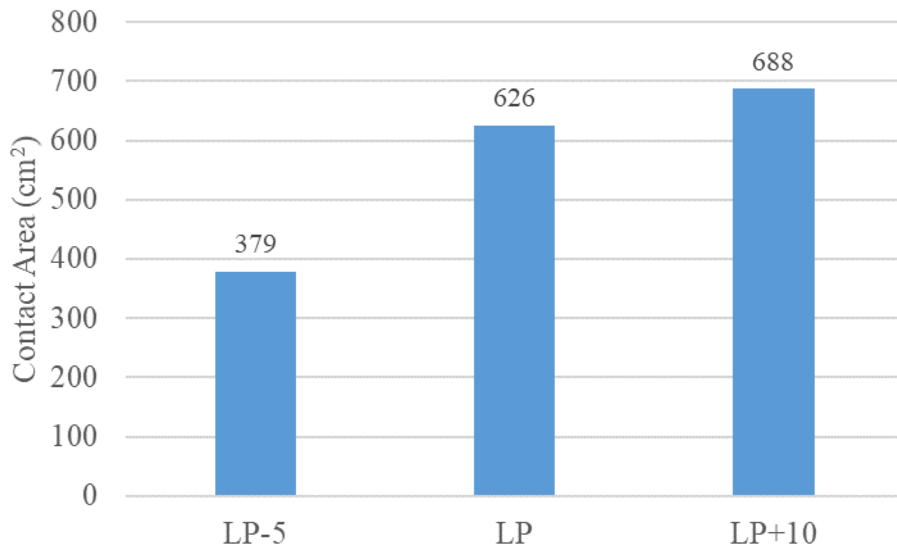

Figure 9.10. Summary of contact areas

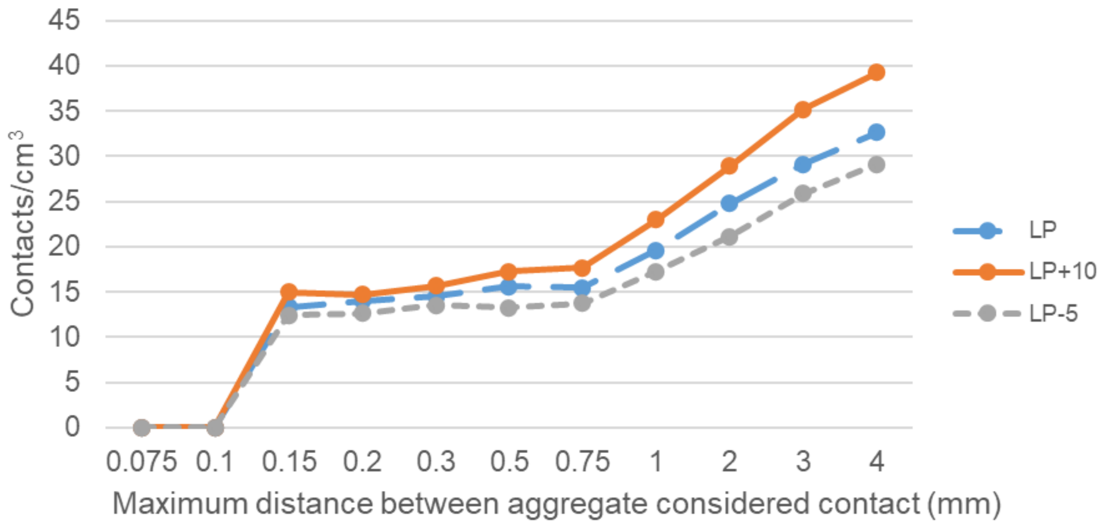

Figure 9.11. The relation between the number of contacts and the maximum distance between aggregate considered contact

the BM2-mix compacted at the locking point, five gyrations below the locking point, and ten gyrations above the locking point. The result of the number of contacts is an average of six faces obtained from cutting the specimen. It can be noticed that the plateau is from 0.15 mm to 0.75 mm. Comparing to the results obtained from 3D specimens, the maximum distance between aggregate considered contact for sample compacted to the locking point is 0.31 mm, for the sample compacted to five gyrations below the locking point is 0.20 mm, and the sample compacted ten gyrations above the locking point is 0.29 mm, in average 0.27 mm.

Once the maximum distance between aggregate considered contact was determined, the further 2D analysis was conducted utilizing area (100 cm^2) instead of volume. Figure 9.12 presents the number of contacts per area at different gyrations for the BM2 mixture. Ten samples were compacted at different compaction effort from 20 to 100 gyrations. It can be observed that by an increasing number of gyrations, the number of contacts between aggregates per area increased. From 20 to 60 gyrations, there is a constant increase in the number of contacts. Once the 60^{th} gyration is reached, there is a steeper increase in contacts until around 80 gyrations. Passing 80 gyrations, the increase in the number of contacts is slower. The red vertical lines indicate different definitions of the locking point. As can be seen, the LP3/2-2-3 definitions are located near the point on the graphic where the number of contacts became stable without a significant increase. The rest of the locking point definitions are placed on the increasing line of the number of contacts.

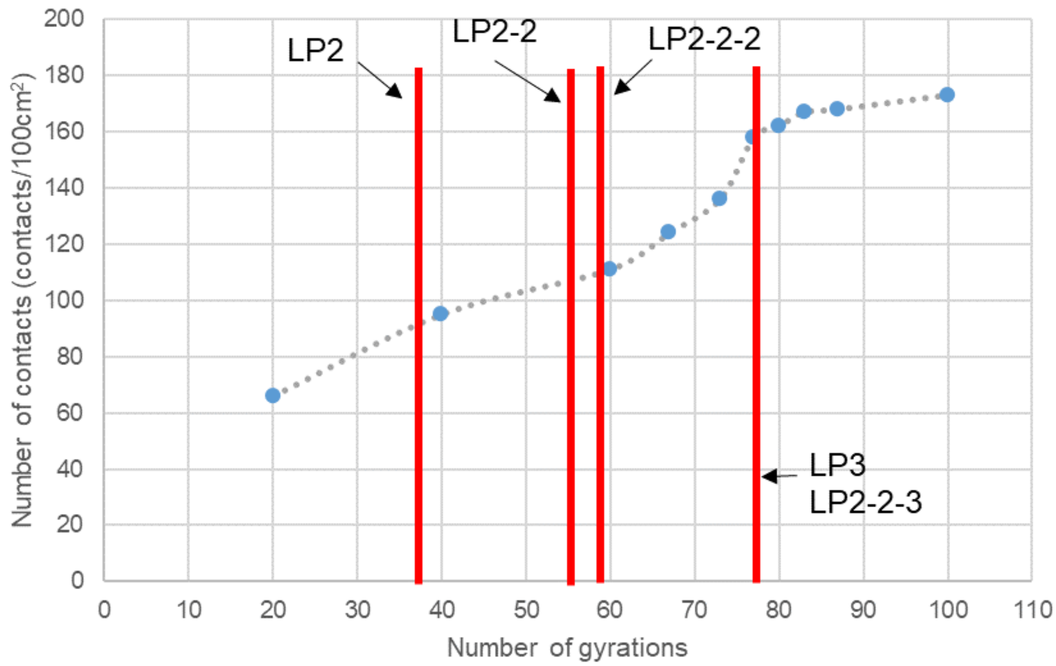

Figure 9.12. Number of contacts vs. number of gyrations for BM2 mix

Figure 9.13 presents the number of contacts per area at different gyrations for the D mixture. Similarly to the BM2 mixture, ten samples were compacted at different compaction effort from 20 to 100 gyrations. The increasing number of gyrations produced a higher number of contacts in the initial stage of compaction. Once the compaction reached 50 gyrations, the number of contact points became steeper until around 65 gyrations. Again, the LP3/2-2-3 definitions are located near the point on the curve where the number of contacts became stable without a significant increase. The rest of the locking point definitions are located on the increasing line of the number of contacts.

Figure 9.14 presents the relation between compaction energy and interlocking parameter for BM2-mix. Compaction from 20 to about 70 gyrations produced a linear increase in the interlocking parameter. After passing 70 gyrations, the increase is less steep. The locking point definition LP3/2-2-3 is located near the change in the line steepness. After reaching the locking point in the interlocking parameter, the change is not as pronounced as the number of contacts.

Figure 9.15 shows the relation between compaction energy and interlocking parameter for D-mix. For D-mix, the pattern is similar to the number of contacts. There was a slow increase in the interlocking parameter for the samples compacted at 20, 40, and 53 gyrations. From 53 to 63 gyration fast increase of the interlocking parameter and 63 gyrations, there was a slow increase of the

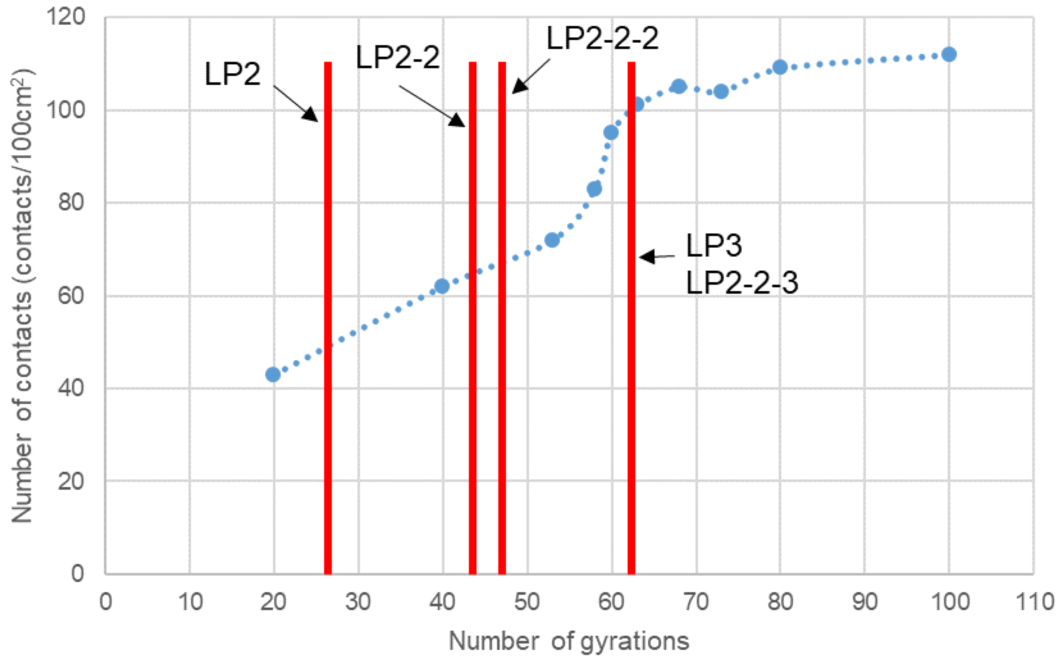

Figure 9.13. Number of contacts vs. number of gyrations for D mix

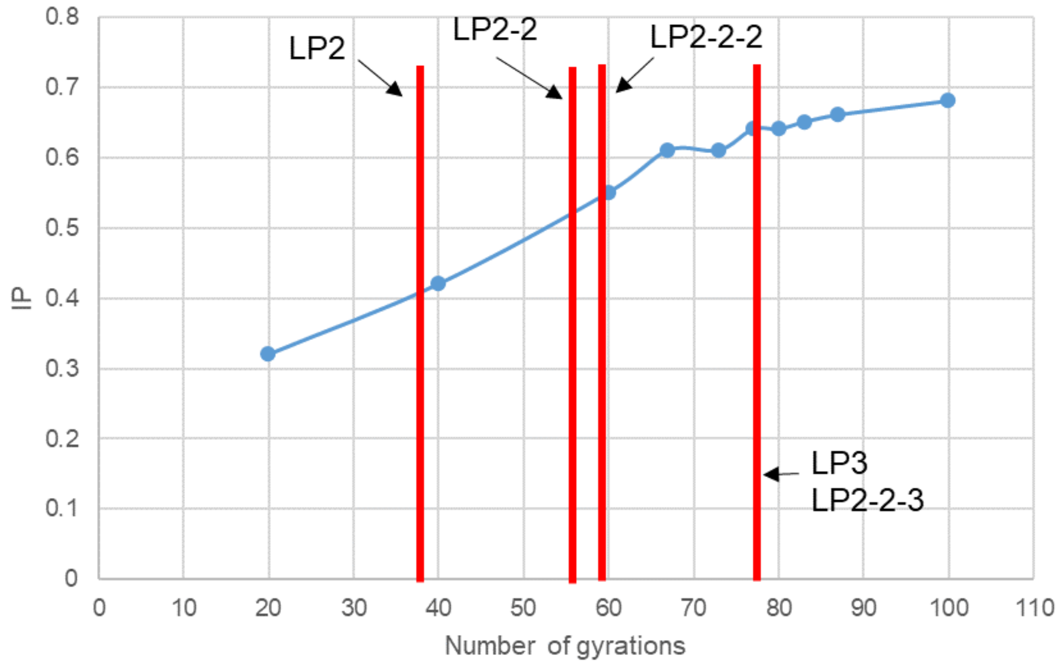

Figure 9.14. Interlocking parameter vs. number of gyrations for BM2 mix

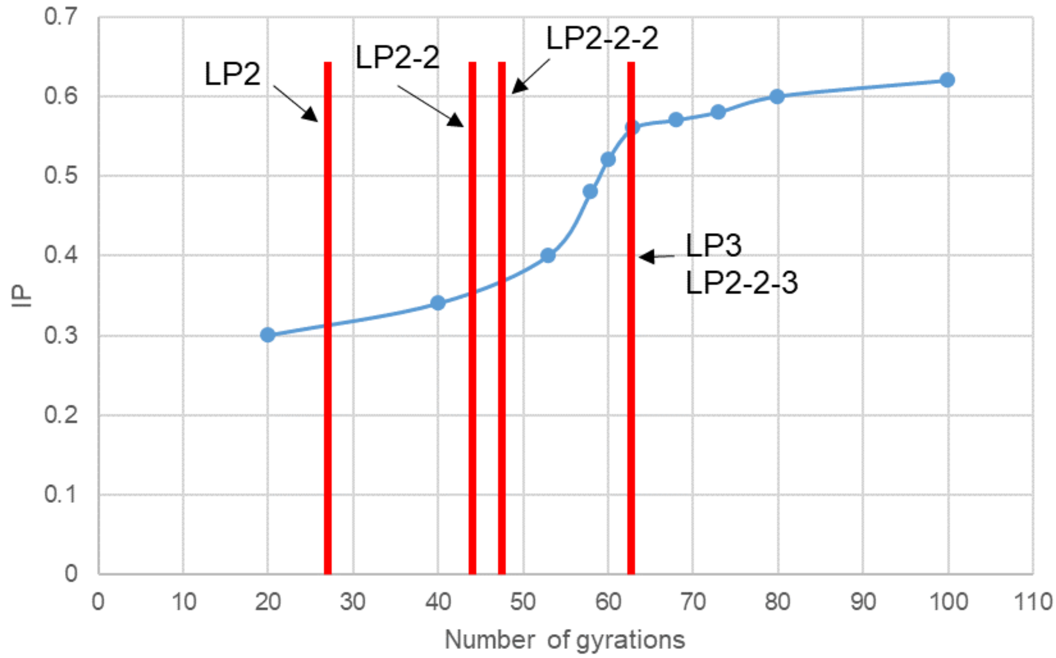

Figure 9.15. Interlocking parameter vs. number of gyrations for D mix

parameter. For D-mix, the LP3/2-2-3 definitions are located at the exact point where the interlocking parameter increase is considerably reduced.

Figure 9.16 presents the relation between compaction energy and the contact length for BM2-mix. There has been a constant increase in the contact length, while more compaction energy was applied, until 83 gyrations. After reaching 83 gyrations, there was no more increase. The locking point LP3/2-2-3 was the closest to the 83rd gyration with a difference of 6 gyrations.

Figure 9.17 presents the relation between compaction energy and the contact length for D-mix. Similarly to two previous parameters, there is a pronounced change in the contact length when different compaction energy is applied. There was a linear increase from 20 to 53 gyrations, then increase accelerated until 58 gyrations, and after 63 gyrations, there was no significant increase. Again, the locking point definitions LP3/LP2-2-3 were near the point where there was no more significant increase in the contact length.

Conclusions

This study investigated the possibility of quantifying the interlocking properties of hot mix asphalt by 2D and 3D image processing and correlating the results to the locking point concept. Based on the results of this study, the following conclusions were reached:

- 3D and 2D image processing is a promising non-destructive method to quantify the interlocking properties of asphalt mixtures.

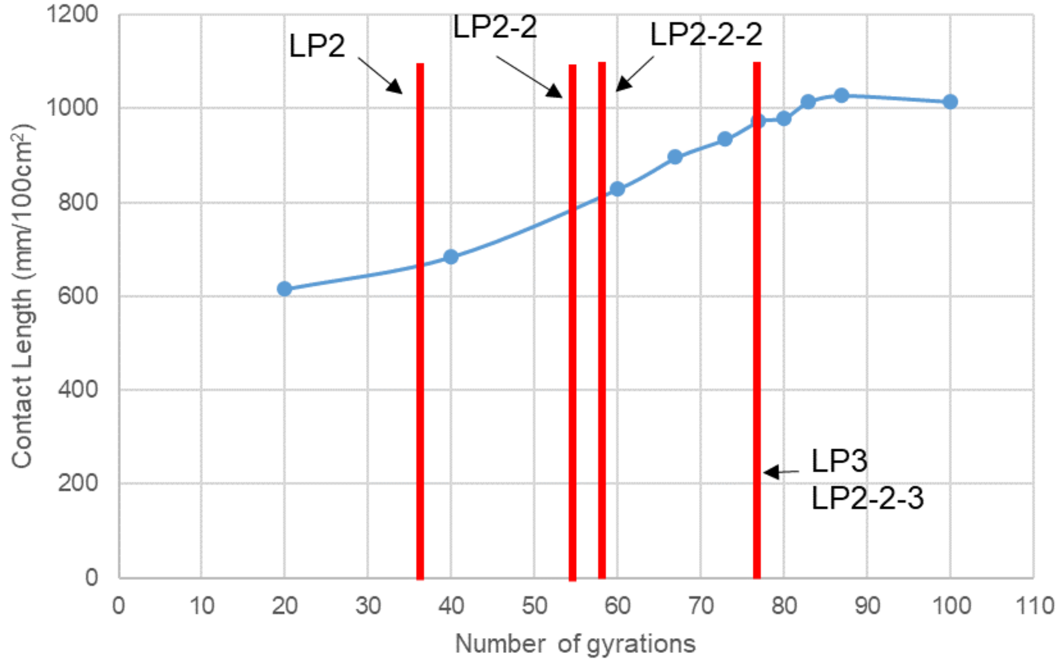

Figure 9.16. Contact length vs. number of gyrations for BM2 mix

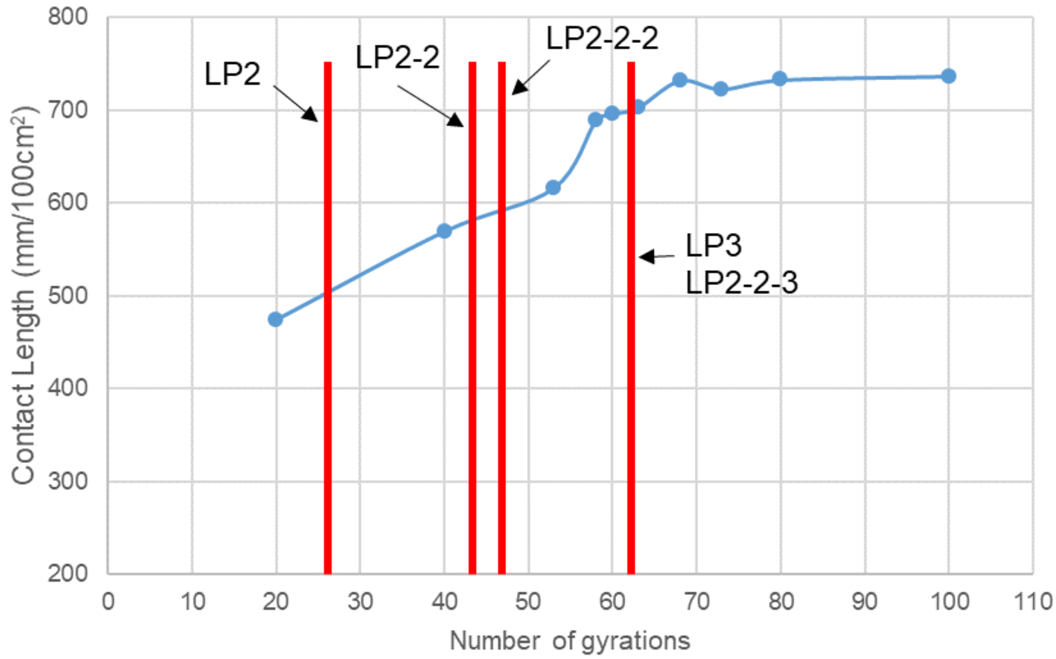

Figure 9.17. Contact length vs. number of gyrations for D mix

- Based on the parameters included in this study, the locking point definitions LP3/2-2-3 are the most appropriate to quantify the interlocking of asphalt mixture.
- The LP3/LP2-2-3 has less dispersed data concerning the mean than LP2, which is confirmed by standard deviation and variance.
- Mixtures with larger aggregates size seem to have a higher number of contacts and contact length. However, in the present study, two different mixtures types were prepared with different aggregate types. Gravel has less fractured faces, which might influence the results.
- This research was limited by the number of samples (3D), type of mixtures (2), type of aggregates (limestone and gravel), and type of binder (1). Further study is necessary to: confirm the finding obtained from the 3D analysis, increase the number of mix and aggregate types.
- The analysis included in this work involves compacted samples without applied loading (inherent condition). Once the loading (traffic) is applied, there is a change in the structure (induced condition). Further work is needed for analyzing the skeleton of the asphalt mixture under the loading condition.

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CHAPTER TEN

CONCLUSIONS AND RECOMMENDATIONS

Summary of Conclusions

This dissertation addressed the compactability and interlocking of the asphalt mixtures. This work's major contribution is developing the method to determine the locking point when impact compaction is applied. Until now, there was no available such a method. Since the Marshall mix design utilizes the impact compaction and this method is still dominating the asphalt paving world, this new method can be further correlated with field compaction and provide feedback to better schedule the construction planning process. Including impact locking point in the mix, the design would benefit the process by detecting the over-compaction, especially for finer mixes, and prevent possible errors during mix design caused by aggregate breakage. Another major contribution is an in-depth investigation of factors affecting the gyratory locking point. The Superpave mix design can be improved by implementing a gyratory locking point and preventing the mixture fro over-compaction or insufficient compaction. The results obtained in this study can help modify various parameters of the asphalt mixtures to improve the performance.

Based on the results of this study, the following detailed conclusions were reached:

- The impact locking point can be determined with an accelerometer attached to the Marshall hammer. For researchers, it can be used to evaluate the compactability of the asphalt mixture. It can provide an easy way for contractors to determine the effort required to compact asphalt mixture in the field.

- The locking point is related to the full gradation of the blend consisting of coarse and fine aggregates. Dense-graded mixtures show a broader range in locking points than SMA mixtures. This difference may be attributed to granulometric variation. Dense-graded mixtures vary in both coarse and fine aggregates, whereas SMA mixtures vary mostly in coarse aggregate.
- Dense-graded mixtures with smaller maximum aggregate size had a lower locking point. This finding may be attributed to the fact that these mixtures generally contain more asphalt binders, which serve as a lubricant and make compaction easier and faster.
- The locking point of base mixtures was slightly under 150 blows, the common number of blows in the Marshall Mix Design. The SMA had the impact locking point just above 100 blows, again the mix design's common number. In contrast, surface mixtures showed an impact locking point far below 150 blows. This finding indicates that surface mixtures may suffer over-compaction and aggregate breakage when 150 blows are used for mix design.
- The gyratory locking points for the 150-mm specimens were significantly higher than those for 100-mm specimens, but the ranking is maintained regardless of mold size. This finding allows comparing the locking points for different mixtures if the mold's same size is utilized.
- The different gradation inside each type of asphalt mixture strongly influences the locking point, regardless of the compaction method.

- The fine aggregate mixture combined with high asphalt content can be unstable and requires more energy to develop a stable skeleton.
- Aggregate angularity had a significant influence on the locking point of asphalt mixtures. As aggregate angularity increased, the locking point of asphalt mixtures decreased. More angular aggregates not only made asphalt mixtures more challenging to compact but also increased the possibility for aggregate particles to interlock with each other at the early stage of compaction, resulting in a lower locking point.
- The locking point could not be determined for the mixture with only uncrushed aggregates compacted by the impact, even with an increased number of blows. The reason can be attributed to the lack of interlocking between spherical aggregates.
- Mixtures with high participation of crushed aggregates may suffer a significant aggregate breakage during impact compaction. Aggregate breakage required additional compaction effort, resulting in a higher locking point.
- Mixtures made with different aggregate angularities need different compaction efforts to develop a stable aggregate skeleton and reach their locking points.
- The mixing sequence significantly influences the asphalt mixtures' lab compactability regardless of the compaction method. The alternative mixing alters traditional mixing and permits improvement in the film thickness of coarse aggregates, which may be translated in the asphalt mixture's homogeneity.

- The mixing sequence influences the mixtures with larger stones since it is more challenging to get an adequate coating on the largest particles when traditionally mixed. Alternative mixing allows the coarse aggregate to be mixed in the first stage with asphalt binder and good coating before filler and fine aggregate are added.
- The mixing sequence affects mixing efficiency. On average, the alternative mixing permitted around 35% faster coating of aggregate particles than traditional mixing.
- Decreasing viscosity (increasing temperature of asphalt binder) increases the lubricative properties of asphalt binders. There is a linear relationship between the temperature of the mixture and the locking point for gyratory compaction. For impact compaction, there is a 4^{th} order polynomial relation between temperature and the locking point. At higher temperatures, the lubricative properties do not improve as fast as at the lower temperature.
- The lab compactability of asphalt mixture is improved by higher asphalt content. There is a linear relation between asphalt content and the locking point for both gyratory and impact compaction. For gyratory compaction, the mixtures with larger stone are more susceptible to change in asphalt content. For impact compaction, there is no significant difference in susceptibility regardless of the maximum aggregate size.
- Most of the dense-graded mixtures failed in the range of +20 to +30 gyrations over the locking point. These mixtures were mainly made with crushed stones.

Gravel seems to be most resistant to damage because most of the samples failed in the range of +30 to +40 gyration. The surface gravel mixture has not failed even after reaching +40 gyrations. It may suggest that gravel resists better over-compaction, or due to the low angularity, it never wholly interlocks.

- The LP2-2-3 and LP3 are the most indicated to define the locking point based on axial strain from the Flow Number test and CT_{index} from the IDEAL CT test.
- For most of the cases, LP2-2-3 and LP3 definitions provide the same results. However, for some coarser mixtures, it is not possible to detect the LP2-2-3 pattern, so LP3 seems a better choice than LP2-2-3. There was no similar problem for the LP2-2-2 pattern as it appeared in the case of all the samples.
- The LP3/LP2-2-3 has less dispersed data concerning the mean than LP2, which is confirmed by standard deviation and variance.
- As indicated by the axial strain and the flow number, the compaction process should reach the interlocked stage to achieve the best rutting resistance. However, further uncontrolled compaction may compromise earlier archived rutting performance.
- 3D and 2D image processing is a promising non-destructive method to quantify the interlocking properties of asphalt mixtures.
- Based on the parameters included in this study, the locking point definitions LP3/2-2-3 are the most appropriate to quantify the interlocking of asphalt mixture.

- Mixtures with larger aggregates size seem to have a higher number of contacts and contact length. However, in the present study, two different mixtures types were prepared with different aggregate types. Gravel has less fractured faces than limestone, which might influence the results.

Recommendations for Future Work

- In this study, the 4" diameter Marshall mold was utilized. However, most of the current performance tests require 6" diameter samples. Further research should be conducted to evaluate the impact compaction method when 6" mold is utilized and correlate the results with performance tests.
- In this study, the over-compaction was evaluated for gyratory compaction. Further study is necessary to address the impact of compaction. Also, a variety of mixtures types should e included.
- In this study, the effect of aggregate angularity was evaluated. Further study should be conducted to evaluate the influence of the plane and elongated particles, especially over-compaction.
- 2D and 3D image processing have enormous potential to be used in the asphalt mixture interlocking characterization. In this study, a limited number of samples were utilized. Further study should include more types of asphalt mixtures and new parameters such as number and length of contact chain and aggregate orientation. The analysis included in this work involves compacted samples without applied loading (inherent condition). Once the loading (traffic) is applied, there is a change in the structure (induced condition). Further work is

needed for analyzing the skeleton of the asphalt mixture under the loading condition.

VITA

Pawel Andrzej Polaczyk was born in Warsaw, Poland, to the parents of Daniel and Marianna Polaczyk, and he has one younger brother Lukasz. He is married to Ana Margarita Hernandez de Polaczyk, and they have a daughter Estefania. After High School graduation, he attended the Warsaw University of Technology (College of Civil Engineering). In 2004 he obtained a Bachelor of Science degree in Civil Engineering with a concentration in Transportation. He worked in the road design and construction field in Poland and Guatemala for almost 10 years. In 2017 he got a Master`s in Civil Engineering degree with a concentration in Geotechnology and Materials Engineering at The University of Tennessee, Knoxville. Currently, he attends Civil Engineering Doctorate Program with a concentration in Geotechnology and Materials Engineering at The University of Tennessee, Knoxville. He works as a Graduate Research and Teaching Assistant under the supervision of Dr. Baoshan Huang.