EFFECT OF WARM MIX ADDITIVES ON COMPACTABILITIY OF MIXTURES

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ABSTRACT

EFFECT OF WARM MIX ADDITIVES ON COMPACTABILITIY OF MIXTURES

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Warm Mix Asphalt (WMA), the technology that allows significant reduction in the mixing and compaction temperatures of asphalt mixtures, has been commonly used globally since the early 2000s. This study evaluates the effect of compaction temperature (CT) on WMA and Hot Mix Asphalt (HMA) mixtures volumetrics, degradation, stability, and compactability properties. Although both Superpave Gyratory Compactor (SPGC) and Marshall hammer are used for sample preparation, the focus of this study is to develop compactability parameters for mixtures compacted with Marshall hammer, since SPGC is not sensitive to temperature changes. Besides, current compactability related studies are not capable of assessing the influence of temperature changes. Therefore, in this study, an image-based method and a testing setup are developed to obtain the densification/compaction curves. In order to analyze the effect of CT, the test matrix includes one HMA and four different WMA mixtures; prepared with a non-foaming additive (Sasobit) and a foaming additive (Advera) at two different dosages. CT's are selected as the typical CT of HMA (140 °C), 15, 30, 45 °C lower than this temperature. It was concluded that pavements constructed with WMA additives at lower temperatures could meet the performance of HMA pavements constructed at traditional temperatures. In addition, the degradation patterns are similar for WMA and HMA mixtures. Finally, the compactability parameters calculated from Marshall densification curves meet the known field behavior of WMA and HMA mixtures, whereas it is not possible to drive the same relations from the parameters calculated from SPGC compaction curves.

Keywords: Warm Mix Asphalt, Compactability, Image Process, Volumetric Properties, Degradation

ÖZ

ILIK KARIŞIM ASFALT KATKILARININ KARIŞIMLARIN SIKIŞTIRILABİLİRLİĞİ ETKİSİNİN İNCELENMESİ

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Karıştırma ve sıkıştırma sıcaklıklarında önemli düşüşlere izin veren Ilık Karışım Asfalt (IKA) teknolojisi 2000'li yıllardan bu yana dünya genelinde yaygın olarak kullanılmaktadır. Bu çalışma, sıkıştırma sıcaklığının IKA ve Bitümlü Sıcak Karışımların (BSK) hacimsel, degradasyon, stabilite ve sıkıştırılabilirlik özellikleri üzerindeki etkisini incelemektedir. Her ne kadar Superpave Gyratory Compactor (SPGC) ve Marshall çekici numune hazırlama için kullanılsa da, SPGC sıcaklık değişimlerine duyarlı olmadığından, bu çalışmanın odağı Marshall çekiciyle sıkıştırılan karışımlar için sıkıştırma parametreleri geliştirmektir. Ayrıca, sıkıştırılabilirlik ile ilgili mevcut çalışmalar sıcaklık değişikliklerinin etkilerini değerlendirememektedir. Bu nedenle, bu çalışmada, yoğunlaştırma/sıkıştırma eğrilerini elde etmek üzere görüntü tabanlı bir yöntem ve test düzeneği geliştirilmiştir. Sıkıştırma sıcaklığının etkisini analiz etmek için test matrisi BSK ve dört farklı IKA numunelerinden oluşmaktadır. IKA numuneleri köpürmeyen katkı maddesi (Sasobit) ve köpüren katkı maddesinin (Advera) 2 farklı dozajda kullanılmasıyla hazırlanmıştır. Sıkıştırma sıcaklıkları BSK'nın tipik sıkıştırma sıcaklığı olan 140 °C ve 125 °C, 110°C, 95 °C olarak belirlenmiştir. Düşük sıcaklıklarda IKA katkı maddeleri ile yapılan kaplamaların, geleneksel sıcaklıklarda yapılan BSK kaplamaların performansını karşılayabileceği sonucuna varılmıştır. Ek olarak, degradasyon oluşumu IKA ve BSK karışımları için benzerdir. Son olarak Marshall yoğunlaşma eğrilerinden elde edilen sıkıştırma parametreleri, IKA ve BSK'nın bilinen saha davranışını yansıtmaktadır. Aynı ilişkilerin SPGC sıkıştırma eğrilerinden hesaplanan parametrelerden elde edilmesi mümkün olmamıştır.

Anahtar Kelimeler: Ilık Karışım Asfalt, Sıkıştırılabilirlik, Resim İşleme, Asfalt Parametreleri, Degradasyon

To My Parents, Family and Best Friends

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LIST OF ABBREVIATIONS

AASHTO: American Association of State Highway and Transportation Officials

AC: Asphalt Concrete

AR: Asphalt Rubber

ASTM: American Society for Testing Materials

CDI: Compaction/Construction Densification Index

CEI: Compactability Energy Index

CR: Compactability Ratio

FHWA: Federal Highway Administration

G_{mb}: Bulk Specific Gravity

G_{mm}: Theoretical Maximum Specific Gravity

G_{sb}: Bulk Specific Gravity of Aggregates

HMA: Hot Mix Asphalt

LDVT: Linear Variable Differential Transformer

MDOT: Michigan Department of Transportation

METU: Middle East Technical University

NAPA: National Asphalt Pavement Association

NCAT: National Center of Asphalt Technology

PG: Performance Grade

RAP: Reclaimed Asphalt Pavement

RAS: Recycled Asphalt Shingles

SPGC: Superpave Gyratory Compactor

TDI: Traffic Densification Index

TUBITAK MAM: The Scientific and Technological Research Council of Turkey-Marmara Research Center

V_a: Air Voids

VFA: Voids Filled with Asphalt

VMA: Voids in Mineral Aggregates

VTM: Voids in the Total Mix

WMA: Workability Energy Index

WMA: Warm Mix Asphalt

CHAPTER 1

INTRODUCTION

1.1. Research Objectives

In recent years, there have been new technological developments in the pavement industry due to global economic and environmental concerns. Warm Mix Asphalt (WMA) is a relatively new technology that is prepared and laid at lower temperatures in order to save energy, provide economic gains and reduce environmental impacts compared to Hot Mix Asphalt (HMA). WMA has been widely used since the early 2000s. In addition, its usage increases day by day worldwide.

HMA mixtures are typically mixed at an average temperature of 155 °C and laid and compacted around 145 °C. On the other hand, these temperatures depend on the environment and production conditions. Due to these variables, in some cases, it is not possible to make mixing and compaction at the desired temperatures. When mixing and compacting are performed with conventional methods at low temperatures, the desired properties such as air void percentage, stability, etc. cannot be reached, and thus, time-dependent deformations increase. In some cases, the mixtures are even overheated to meet the volumetric requirements. In this case, the energy required for production increases, environmental pollution occurs, and the mixture is damaged (aging) even before laying. In order to eliminate these problems, WMA technologies are widely used in today's practice. WMA technologies have been developed in the last 20 years to overcome the problems related to temperatures. The main philosophy behind the WMA technology is reducing the viscosity of asphalt by various methods and allowing production up to 30 °C lower than HMA. When WMA applications are examined, it is concluded that WMA performs better or similar compared to traditional HMA. In addition, considering life-cycle cost assessment and sustainability; the development of WMA technologies can provide environmental benefits. Moreover, in some applications, WMA technology solely used as a compaction aid without lowering mixing temperature.

Although WMA technology gets significant attention in the current practice, there are no complete specifications and standards. The important properties like mixing, compaction temperatures, and proportions are still determined based on the manufacturer's suggestions based on limited experience. However, since the usage of this technology increases globally, a more solid approach is needed.

In this study, the effects of warm mix additives on compactability of asphalt mixtures are investigated with respect to compaction temperature. Two types of additives were used at two different dosages and samples were compacted at four different compaction temperatures. Four compaction temperatures are determined as the compaction temperature of asphalt cement determined based on the Asphalt Institute method, 15, 30, and 45 °C lower than the determined temperature. Besides, samples were compacted with two different compactors; Marshall Hammer and Superpave Gyratory Compactor (SPGC). Since SPGC is not sensitive to temperature changes, compaction with Marshall Hammer was the main focus of this study. At the end of this study, an image-based method is developed for Marshall Hammer to extract the densification curves to determine the optimum compaction temperatures of WMA mixtures. Accordingly, new compactability parameters are proposed or modified from the ones in the literature for Marshall compaction. Additionally, change in volumetrics, the stability of the mixtures and gradation/degradation during compaction are studied.

1.2. Scope

This study performed by the following steps:

1- Analyzing the temperature-dependent volumetric properties of WMA and HMA mixtures compacted with Marshall Hammer and Superpave Gyratory Compactor.
2- Analyzing the influence of compaction temperature on degradation susceptibility of WMA and HMA mixtures
3- Understanding the effect of compaction temperature on the Marshall Stability of WMA and HMA mixtures
4- Developing a new method to extract densification/compaction curves of asphalt mixtures compacted with Marshall Hammer
5- Establishing modified compactability parameters for Marshall compacted samples and comparing with the parameters provided by Superpave compaction.

1.3. Outline of Research

The flow of the thesis is structured as follows:

- The current literature on the WMA technologies and studies on compactability are separately discussed in Chapter 2.
- The material and mixture properties, experimental procedures, sample preparation methods, experimental setups, and procedures are explained detail in Chapter 3.
- The results and discussion of the experiments were presented in Chapter 4, in which the volumetric properties the stability, and gradation/degradation changes of WMA and HMA mixtures were compared with respect to compaction temperature. As well, the compaction parameters are calculated and the Marshall hammer and gyratory compactor based compaction are compared.

- In Chapter 5, the major findings of this research are summarized by taking into account the limitations of the study. In addition, the future work plan of this study is established.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The pavement industry is developing day by day with the concerns of time and cost as well as the environmental concern. In this chapter, the current literature about the relationship between Warm Mix Asphalt (WMA) technology, and compactability parameters is presented briefly.

2.2. Warm Mix Asphalt

2.2.1. History of Warm Mix Asphalt

Warm mix asphalt (WMA) is the term that is used for asphalt mixtures prepared and laid at lower temperatures compared to Hot Mix Asphalt (HMA) in order to save energy, reduce environmental impacts and provide economic gains. In other words, WMA was developed for the pavement industry to overcome the various drawbacks of HMA (Ozturk, 2013).

Over the past 20 years, WMA technologies have been developed to overcome temperature-related problems. The first WMA studies started in Europe in 1995-96, and between 1997-99, test sections were built. In 2002, the USA conducted a tour under the leadership of National Asphalt Pavement Association (NAPA) to monitor WMA technology (B. D. Prowell et al., 2012). In 2005, the first field trials were done successfully in the USA. National Center of Asphalt Technology (NCAT) published research results on WMA in 2007 (Brian. D. Prowell, 2007). Since then the use of WMA technologies in the asphalt industry is increasing day by day (De Groot et al., 2001;Larsen et al., 2004; Cervarich, 2003; Brian. D. Prowell, 2007). In 2012, WMA's share in the USA asphalt industry was 24% (Hansen & Copeland, 2013). Some European countries such as Turkey, Sweden, France, Denmark initiated researches on WMA and constructed test sections (EAPA, 2014). In cooperation with Turkey General Directorate of Highways and TUBITAK MAM, a local WMA additive was developed, and the trial section was built in 2013 (Ertan et al., 2015). According to European Asphalt Pavement Association, when the data between 2013 and 2015 was analyzed, it was observed that the amount of production of WMA has significantly increased from year to year (EAPA, 2015).

2.2.2. Benefits of Warm Mix Asphalt

The use of WMA can provide environmental, economic and engineering benefits. As the WMA technologies become more and more popular throughout the world their properties, as well as their comparison with the traditional HMA mixtures, are investigated by several researchers. Although it is point of interest due to its benefits, there is limited knowledge about WMA. Since there are no complete specifications and standards, research is still needed on WMA technologies in terms of volumetrics, material performance, stiffness, etc. On the other hand, there were many completed studies and, in the following, some of them were briefly summarized in order to emphasize the benefits of WMA usage.

2.2.2.1. Environmental Aspects

Gandhi (2008) studied reduction in mixing and compaction temperatures with WMA additives, aiming to reduce emissions related to global warming. According to the study, additives decreased the viscosity of samples, which lowered the mixing and compaction temperatures. In addition, WMA additives increased the rutting resistance of mixtures. West et al. (2014) suggested that the use of WMA can provide indirect benefits such as reducing the pollution of the atmosphere and reducing the effects of road construction on climate change. Reducing the fuel used in asphalt production helps to reduce non-renewable fuel consumption, thereby reducing the carbon footprint caused by fuel production and transportation. Although there was a 20% -

35% reduction in fuel consumption in WMA use, 15 projects using 6 different WMA technologies referred to in the NCHRP 9-47 report showed that the energy consumption range can vary from 15.4% increase to 77% reduction.

2.2.2.2. Economical Aspects

Arega & Bhasin (2012) investigated the effects of chemical WMA additives on permanent deformation, stiffness, viscosity, etc. The study concluded that samples prepared with WMA additives had similar or slightly less viscosity values compared to control samples. This indicated that mixtures prepared with WMA additives could be stored longer in silos and hauled for longer distances. Meanwhile, the temperature drop caused by the WMA technology allows reductions in mixing and compaction temperature in the application. This reduces fuel costs in production. Prowell (2009) reported an average of 23% fuel savings in WMA applications. In addition, D'Angelo (2008) reported that WMA technology could provide fuel savings ranging from 20% to 35%.

2.2.2.3. Engineering Aspects

WMA technology allows preparation, transportation, mixing and placement at temperatures lower than conventional temperatures (Moreno et al., 2011). WMA technologies allow the production of 15-40 ° C lower temperatures compared to HMA by reducing asphalt viscosity by various methods. In other words, WMA technologies reduce the viscosity at lower temperatures, which increase the compactability. The decrease in the viscosity increases the compactability and it results in a decrease in the roller passes to targeted density (Hossain et al., 2009; D’Angelo et al., 2008). Ozturk (2013) developed a new foam-based WMA technique. As a result of the study, it was observed that WMA additives decreased the viscosity of the mixtures, utilized a better coating of the aggregates, increased workability and provided better compaction at lower temperatures. Hence, there are various field and laboratory studies that investigates the performance of WMA technologies in recent years. In this section, the results of the studies utilizing similar WMA technologies (additives) in this study are briefly shared.

Behl et al. (2013) studied the field performance of WMA pavements in India. Two WMA pavements and one HMA as control pavement were placed. All of them were evaluated after considerable exposure to traffic and weather. After 13-31 months of monitoring, the authors reported that there were no visible cracks and deformations in these sections. In addition, according to performance tests such as Marshall stability, resilient modulus and, static creep tests, the results indicated that WMA pavements were stiffer, denser and resistant against displacement, distortion, rutting and shearing stresses under exposure of static and dynamic loads. Similar to field studies, the properties of WMA technology were examined in the laboratory. Vaitkus et al. (2016) studied WMA technologies utilizing several additives that might be used to improve the physical and mechanical properties of asphalt mixtures. They tried to optimize the asphalt mixing temperature by lowering the additive proportions. It was reported that the use of organic additives increased asphalt pavement stability. Asphalt pavement tensile strength was increased by additives, Sasobit and Rediset. However, excessive usage of them i.e. 2.0% by mass of the bitumen were not suggested because it may result with a decrease in asphalt pavement resistance on low temperature cracking. In another study, Wu & Li (2017) studied the effect of curing time on dynamic modulus, flow number, moisture resistance, fatigue and thermal cracking resistance for both HMA and WMA samples with Advera. Following the preparation of mixtures, specimens were tested after 2-week, 1-month and 2-months periods of curing time. The authors reported that curing time had a positive influence on samples prepared with WMA based on the dynamic modulus (i.e. stiffness). Curing time may reduce the possibility of foam decaying which Advera provides over time. The rutting resistance and fatigue resistance of Advera mix (WMA) also increased with curing time, whereas no significant effect of curing observed on HMA control mixtures.

Additionally, WMA technology has benefits on recycling in addition to engineering contributions. Valdes-Vidal et al. (2018) studied the mechanical behavior of WMA prepared with natural zeolite and Reclaimed Asphalt Pavement (RAP) with different amounts. Five different WMA specimens were evaluated and compared with respect to HMA samples. According to test results, the addition of natural zeolite slightly increased stiffness modulus value. In addition, rutting resistance of WMA mixtures showed better behavior than HMA control samples. WMA mixtures with natural zeolite were similar to HMA mixtures with respect to cracking resistance.

When WMA applications are examined in the literature, it could be concluded that WMA performs better or the same compared to traditional HMA (West et al., 2014).

2.2.3. Warm Mix Asphalt Additives

WMA technologies are divided into (i) Chemical Additives (surfactants), (ii) Foaming Processes and (iii) Non-foaming Additives. There are various methods and materials for each technology. For briefness, each technology discussed with one or two examples in this section.

2.2.3.1. Chemical Additives or Surfactants

Evotherm (Figure 2.1), developed in the USA, is a chemistry package designed to improve workability and adhesion at low temperatures. Evotherm Emulsion Technology (ET) was introduced in 2004. Evotherm Dispersed Asphalt Technology (DAT) was developed in 2005. Evotherm 3G (Third Generation), developed in partnership with Paragon Technical Services and Mathy Technology and Engineering. This additive is mixed with the hot aggregates and resulting mix temperature between 85 ° to 115 °C. Typical usage dosage is 5% of by weight of the binder.

Figure 2.1. Evotherm chemical additive (EVOTHERM)

The use of Evotherm is beneficial for several reasons. With the use of Evotherm, more RAP and Recycled Asphalt Shingles (RAS) can be used and less binders can be applied. Due to temperature drops, longer hauling distances and less emission can be achieved. In addition, as the compaction improvement occurs, longer life pavements can be constructed since the performance of the pavement increase (Brian D. Prowell et al., 2011).

2.2.3.2. Foaming Process

Advera (Figure 2.2) is a kind of synthetic zeolite, composed of aluminosilicates and alkali metals that contain about 20% crystallized water, supplied by PQ Corporation. Crystallized water is released by increasing temperature above the boiling point of water. This release creates a controlled, prolonged foaming effect that leads to a slight increase in binder volume. By this volume change the viscosity of the binder decrease and workability of the mix increases (B. D. Prowell et al., 2012). Advera is, classified as an odorless material, very fine additive (passing No. 200 sieve) and, insoluble in the water with a melting point over 100˚C. Typical usage dosages are 0.20-0.25% by weight of the mix. The limit proportions are 0.1% and 0.3%, respectively. Higher additive dosage is suggested for the mixtures having more than 7% binder content (B. D. Prowell et al., 2012). Advera provides approximately 28˚C less mixing and compaction temperatures compare to HMA mixtures. Between 2006-2012, more than 1 million tons of WMA was used with Advera in the USA and Canada (B. D. Prowell et al., 2012). In addition, Advera is commonly used in Europe and Asia (Mohd Hasan et al. 2013; PQ Corporation 2015).

Figure 2.2. WMA foaming additive (ADVERA)

Aspha-min (Figure 2.3) is also a foaming additive. It was developed by Aspha-min GmbH in Hanau, Germany in 2006 (B. Prowell et al., 2011). Similar to Advera, Aspha-min contains 20% water by weight and is also a synthetic zeolite. It's foaming process, same as the Advera, starts with the boiling water above the 100 ˚C. However, it provides a longer working period compare to Advera (up to 7 hours). 0.3% by weight of the total mixture is the suggested proportion. Compare to Advera, its particle size (around 0.3mm) is coarser. It can be also used as a compaction aid in HMA (The Hubbard Group, 2006).

Figure 2.3. WMA foaming additive (Aspha-min)

2.2.3.3. Non-foaming Additives

Sasobit (Figure 2.4) is a common non-foaming additive. It is a paraffin wax supplied by Sasol Wax North America Corporation. Sasobit is obtained by the Fischer-Tropsch process by steam-treated hot coal or natural gas in the presence of a catalyst. It is long-chain aliphatic hydrocarbon waxes with a congealing point of more than 100 °C. Below their melting point, it has higher viscosity and above the melting point, it has lower viscosity (Figure 2.5). They harden in asphalt from 65 to 155°C into regularly distributed, microscopic stick-shaped particles. The typical Sasobit dosage is 1.5% by weight of the binder, also the dosage can vary from 0.8%-4% depending on the application (B. D. Prowell et al., 2012). Dosages directly affect the bitumen viscosity and performance grades (PG). According to Shaw, (2007), if Sasobit dosage is increased from 1.5% to 2% by weight of binder, the high and low PG increases 4-6 °F and 0-3 °F, respectively. This viscosity and PG affects provides more workable mixtures above the melting point and more durable pavements after cooling.

Sasobit, organic additive, can directly add to the mixtures with several methods since it added prior to mixing (Qin et al., 2015). There is no need for high shear blending. Due to its wider molecular weight distribution, it enhances the workability of RAP and RAS addition (B. D. Prowell et al., 2012).

Sasobit usage reached 2.5-3 million tons in the USA between 2005- 2012 (B. D. Prowell et al., 2012).

Figure 2.4. WMA non-foaming additive (Sasobit)

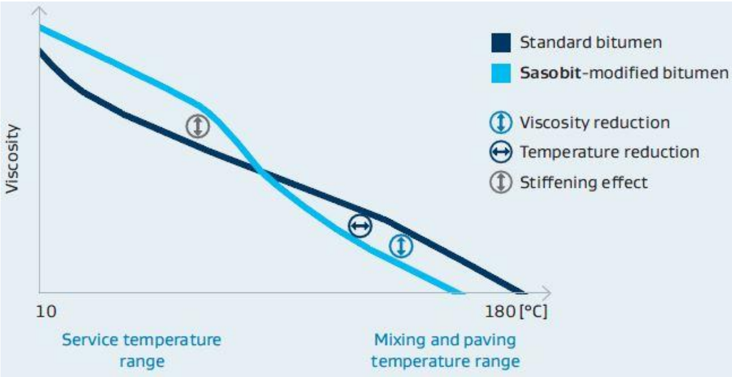


Figure 2.5. Sasobit viscosity effect (SASOL, 1997)

2.3. Marshall Mix Design

The Marshall mix design was first developed by the Mississippi Highway Department in 1939 (Pavement Interactive (a), 2019). It's named after its developer, Bruce Marshall. In the following years, during World War 2, the US Army improved the method in order to meet the needs of airport runways. The Marshall method seeks to select the asphalt binder content at the desired density that satisfies minimum stability and range of flow values (White, 1985).

Marshall Mix Design has six main steps:

a) Selection of aggregates and gradation: Although there is no specifically developed an aggregate evaluation and selection procedure for Marshall mix design, the batch must meet some aggregate parameters. Firstly, physical properties of aggregates such as durability and soundness, toughness and abrasion, particle shape and surface texture, cleanliness and deleterious materials are determined according to related standards. Then, gradation is determined within the limits of specifications. Finally, the specific gravity and absorption of the aggregate are determined. This process continues by changing gradation until the mixture reaches its targets.

b) Evaluation of asphalt binder: There is no common generic asphalt binder selection and evaluation procedure for Marshall mix design. Binder evaluation can be based on local experience, previous performance or a set procedure. To identify bitumen, penetration, ductility, softening point, etc. tests are done. Viscosity test is also performed to determine mixing and compaction temperatures.

c) Sample preparation: The optimum binder ratio is assumed for the predetermined aggregate blend and bitumen. Three replicates for each five different bitumen ratios, assumed ratio and two different proportions above and below with the 0.5% change, are prepared.

Samples are compacted in an automatic or manual Marshall Hammer (Figure 2.6). The sample diameter is 102 mm and the height after compaction is aimed to be 64 mm. The weight of the hammer used in the compaction is 4536 gr and it is allowed to fall free on the sample from a height of 457.2 mm. 35, 50, 75 blows can be applied to the top and bottom surfaces of the sample according to the traffic load. Many studies have shown that 75 blows are necessary to obtain densities equivalent to Superpave compaction (Rushing et al. 2010; Christensen & Bonaquist 2006). The sample temperature should be monitored during compaction. The Marshall method is known to be temperature sensitive (Hurley et al. 2006; Brian D. Prowell et al. 2011).

Figure 2.6. Automatic Marshall Compactor

d) Determination of Marshall stability and flow (Figure 2.7 and 2.8): The Marshall stability and flow test provide performance estimation for the Marshall mix design method. The stability test measures the maximum load that the sample at 60 °C can carry under a load of 50.8mm/min. During loading, the plastic flow of the sample is also recorded. The flow value is the total deformation from the intersection of projected tangent of the linear part of load-displacement curve with the x-axis (deformation) to the maximum load value. If failure condition is different than expected maximum load point can be found by shifting projected tangent 1.5 mm right (Figure 2.8).

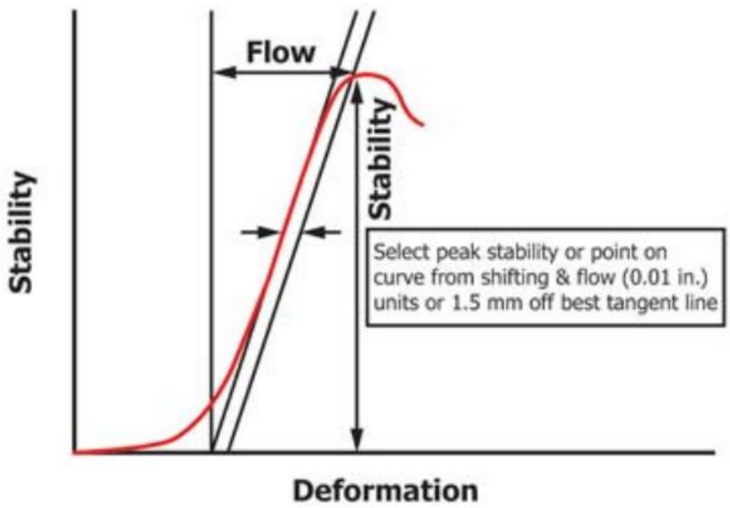


Figure 2.7. Marshall Stability and Flow (ASTM D6307-19, 2015)

e) Determination of Volumetric properties: With the purpose of determining the physical characteristics of samples, density and voids are determined. Theoretical maximum specific gravity (G_{mm}) and Bulk specific gravity (G_{mb}) are determined according to related standards in order to calculate Air Voids (V_a), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA).

f) Optimum asphalt binder selection: Optimum binder ratio is determined according to the results of air voids, VMA, VFA, stability and, flow. The main parameter for determining the ratio is air void. Firstly, the asphalt binder content that corresponds to the specified air void content (typically this is 4 percent) is determined and the other parameters corresponding to related bitumen content are checked with the limits. If these parameters don't satisfy the limitations, design needs to be changed (Roberts et al., 1996).

Figure 2.8. Marshall Stability Apparatus

2.4. Superpave Mix Design

Superpave mix design procedure was developed by the Strategic Highway Research Program (SHRP) in 1993 to replace Marshall Method (Pavement Interactive (b), 2019). This method considers traffic loading and environmental conditions. Also, aggregate selection and asphalt binder evaluation are the main parameters of this method. Aggregate selection is based on availability and specification criteria such as mechanical and shape properties. The binder evaluation is done according to Performance Grade (PG) considering the environmental conditions such as climate and traffic level. Mixing and compaction temperatures are typically determined according to viscosity test based on Asphalt Institute Method.

In this method, samples are compacted with the SPGC (Figure 2.9). SPGC simulates field conditions better due to shear force occurrence provided by the gyration. The compaction effort (number of gyrations applied) is determined with respect to equivalent single axle loads (ESAL). The compaction effort is controlled by vertical pressure, gyration angle and number of gyrations. The Superpave gyratory compactor targets three different gyration numbers as N_{ini}, N_{des} and, N_{max}. Initially, N_{ini} is the number gyrations that represent the mixture compactability during construction. N_{ini} can be defined as the gyration number corresponding to 11% air void. Then, N_{des} is the number of cycles that provide the density to be achieved after the compaction according to the estimated traffic in the field. Finally, N_{max} is the number of gyrations corresponding to the density that should never be exceeded in the field. The corresponding air void of N_{max} is 2%.

Although AASHTO limits are universally set, each state according to their experience has verified limits for their applications. Since the specifications of Michigan Department of Transportation (MDOT) are used in this study, these are presented from Table 2.1 to Table 2.4.

Table 2.1. *L.A. Abrasion Maximum Criteria* (MDOT, 2007)

Estimated Traffic (million ESAL)	Mix Type	Top & Leveling Courses	Base Course
< 0.3	LVSP	45	45
< 0.3	E03	45	45
< 1.0	E1	40	45
<3.0	E3	35	40
< 10	E10	35	40
< 30	E30	35	35
<100	E50	35	35

Table 2.2. *Superpave Mix Design Criteria* (MDOT, 2007)

Design Parameter	Mixture Number				
	5	4	3	2	LVSP
Percent of Maximum Specific Gravity (%G_{mm}) at the design number of gyrations, (N_d) (See Note)	96.0 % (a)				96.0% (a)
%G_{mm} at the initial number of gyrations, (N_i)	See Table 9				
%G_{mm} at the maximum number of gyrations, (N_m)	98.0%				
VMA min % at N_d (based on aggregate bulk specific gravity, (G_{sb}))	15.00	14.00	13.00	12.00	14.00
VFA at N_d	See Table 8 (b)				
Fines to effective asphalt binder ratio (P_{No200}/P_{be})	0.6 - 1.2				
Tensile strength ratio (TSR)	80 % min				

a. For mixtures meeting the definition for base course: Mixtures shall be designed to 96.0% of Maximum Specific Gravity (%G_{mm}) at the design number of gyrations, (N_d). During field production Percent of Maximum Specific Gravity (%G_{mm}) at the design number of gyrations, (N_d) may be increased to 97.0%.

b. For base course or regressed shoulder mixtures the maximum criteria limits do not apply.

Note: Target Air Voids will be lowered by 1.0 percent if used in a separate shoulder paving operation unless noted otherwise on the plans.

Table 2.3. *VFA Minimum and Maximum Criteria* (MDOT, 2007)

Estimated Traffic (million ESAL)	Mix Type	Top & Leveling Courses	Base Course
< 0.3	LVSP	70-80	70-80
< 0.3	E03	70-80	70-80
< 1.0	E1	65-78	65-78
< 3.0	E3	65-78	65-78
< 10	E10	65-78(a)	65-75
< 30	E30	65-78(a)	65-75
<100	E50	65-78(a)	65-75

a. For mixture Number 5, the specified VFA range shall be 73% - 76%.

Table 2.4. *Superpave Gyratory Compactor (SGC) Compaction Criteria* (MDOT, 2007)

Estimated Traffic (million ESAL)	Mix Type	%G_{mm} at (N_i)	Number of Gyrations		
			N_i	N_d	N_m
< 0.3	LVSP	91.5%	6	45	70
< 0.3	E03	91.5%	7	50	75
< 1.0	E1	90.5%	7	76	117
< 3.0	E3	90.5%	7	86	134
< 10	E10	89.0%	8	96	152
< 30	E30	89.0%	8	109	174

Figure 2.9. Superpave Gyratory Compactor

The optimum bitumen content is determined according to the target air void (4%) when the samples are compacted to N_{des} gyrations. The mixture should also satisfy volumetric limits like VFA and VMA.

Although Superpave Gyratory Compactor represents field compaction better and accounting the traffic and environmental conditions, it was proven that it is not sensitive to compaction temperature (Roberts et al., 1996). Initially, Hunter & Brown (2001) investigated the effect of compaction temperature on the volumetrics of HMA samples. According to the study, gyratory compaction had no effect on volumetric properties in the range of ±14°C. Then, Bahia et al. (2001) stated similar findings on HMA mixtures prepared with modified binders. Furthermore, (Hurley & Prowell, 2005) conducted study with the WMA additives by using SPGC. They were concluded that additives have no influence on the temperature sensitivity.

2.5. Degradation

Compaction is affected by various factors such as environmental, mix property and construction factors (Kassem, 2008; U.S. Army Corps of Engineers, 2000). Degradation analysis is performed to demonstrate how mix property and construction factors affect samples during the compaction process. In degradation analysis, changes in gradation are examined for each sieve size. Airey et al. (2008) described degradation according to Equation 2.1. In this equation, RET_{before} represents the original retained percentage for a specific sieve fraction and RET_{after} represents the retained percentage for that specific sieve fraction after the compaction.

$$Percent\ Change(Total\ Aggregate) = \frac{(RET_{before} - RET_{after})}{100} \quad (3.4)$$

When the previous studies are examined, it is concluded that degradation is affected by three main issues. Firstly, the gradation type affects degradation. Densely graded mixtures expected to be less degraded. Secondly, aggregate stiffness is a major subject that affects degradation. Los Angeles Abrasion test is the most commonly used test to understand stiffness. Although there is no specification for Los Angeles abrasion, most states in the USA give a maximum range of 40-45% (Y. Wu et al., 1998). Lastly, compaction method affects degradation. Impact based compactors (Marshall Hammer) causes more degradation (Moavenzadeh & Goetz, 1963; Amirkhanian et al., 1991; Button et al., 1994; Collins et al., 1997; Airey et al., 2008). Additionally, Airey's study concluded that an increase in compaction energy slightly increase degradation but did not affect the degradation pattern.

2.6. Compactability

Compaction effort is one of the most important parameter which affects the quality and serviceability of asphalt pavement. Regardless of the quality of design and materials, the proper compaction of asphalt is critical for the success of flexible pavement. There are several research conducted in literature relating compaction, temperature, volumetric and mechanical properties of asphalt mixtures. After the Superpave design method was developed, researches were mostly focused on compaction curves to understand the compactability of asphalt mixtures.

In this context, Bahia et al. (1998) developed two new parameters. The parameters are Construction Densification Index (CDI) and Traffic Densification Index (TDI). CDI defines the effort required for compaction from the void ratio of the asphalt laid on the site before compaction to the desired void ratio. According to Bahia's study, the void ratio of the first laid asphalt in the field is equal to the void ratio obtained in the first 8 cycles of Superpave Gyratory Compactor. However, according to Superpave design method and studies, many states in the USA accept initial compaction level as 89% G_{mm}. The other limit of the CDI parameter is 92% G_{mm}, which is the maximum acceptance requirement in most states in the United States. CDI represents the area between 89% and 92% G_{mm} in the compaction curve. Lower CDI values are more desirable as they represent less effort required for compaction. TDI represents the continued compression under traffic loads after compaction. According to the Superpave design method, the maximum limit that samples can be allowed to compact is 98% G_{mm} (N_{max}). TDI represents the area between 92% and 98%. CDI and TDI parameters are shared visually in Figure 2.10. In addition, in this study, the energy transferred to the system for desired void ratios was calculated by multiplying the force applied to the system with the resulting displacement.

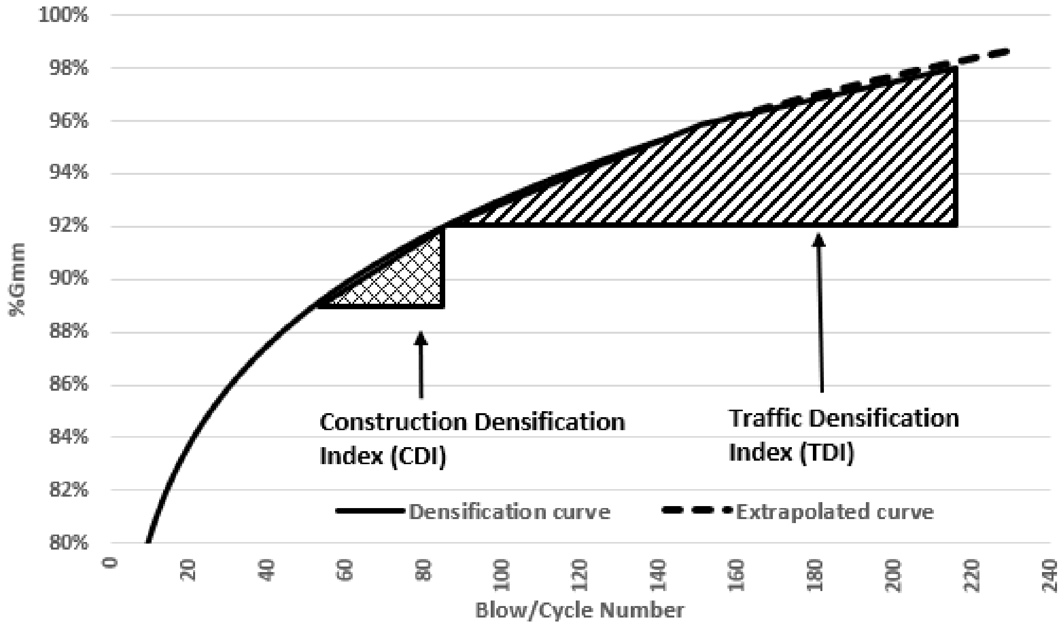


Figure 2.10. Densification indices according to H. Bahia et al., 1998

Dessouky et al. (2013) obtained two parameters related to compactability by modifying the energy parameters found by H. Bahia et al. (1998). The parameters they found were the Workability Energy Index (WEI) and the Compactability Energy Index (CEI). These parameters calculate the amount of energy per cycle. WEI represents energy per cycle from beginning of the compaction to 92% G_{mm} in order to represent workability, CEI represents energy per cycle between 92% and 96% G_{mm} to represent compaction. The development stages of these parameters are shared in Table 2.5.

Table 2.5. *Development stages of compactability parameters (Dessuky et al 2013)*

	Index	Formula	Abbr.	Reference
Workability Indices	Porosity Index	100/a	PI	Cabrera and Dixon (1994)
	Volumetric Energy Index from intercept to 92% G_{mm}	$EI_{(92\%)} = P + \frac{\pi d^2}{4} + \sum_{N=1}^{N_{92}} \Delta h$	$EI_{(92\%)}$	Bahia et al. (1998)
	Workability Energy Index from intercept to 92% G_{mm}	$WEI = EI_{(92\%)} / N_{92}$	WEI	
Compactability Indices	Linear compaction slope + Air voids(%) at N_{des}		K+AV	Anderson et. Al (2002)
	Shear Energy Index (EI) from 92-96% G_{mm}	$EI_{(92-96)} = P + \frac{\pi d^2}{4} + \sum_{N_{92}}^{N_{96}} \Delta h$	$EI_{(92\text{-}96\%)}$	Bahia et al. (1998)
	Compactability Energy Index from 92 to 96% G_{mm}	$CEI = EI_{(92\text{-}96\%)} / N_{92\text{-}96}$	CEI	

Compactability ratio is another parameter developed in 2011 that can be used to examine the compaction. It compares the number of cycles applied in the Superpave to reach 92% G_{mm} at the determined compaction temperature and the number of cycles required to reach the same G_{mm} at a temperature 30 °C lower than the previous one. The 30 °C difference simulates the temperature loss between production and compaction. It is calculated by dividing the number of low-temperature cycles by the number of high-temperature cycles. Compactibility ratios less than 1.25 mixtures are called as compactable (Advanced Asphalt Technologies, 2011).

Many researchers attempted to analyze the compactability of WMA mixtures. Some of these researches were briefly discussed, as follows:

Prowell et al. (2007) studied the field performance of Warm-Mix Asphalt on a test track. The test section was 2.7 km in length and had 45 different flexible pavement sections. Despite the significant decrease in ambient compaction temperatures (8 °C to 42°C), WMA sections showed equal or better performance than HMA sections in terms of in-place densities. Both laboratory and field performance for rutting resistance of WMA and HMA layers showed similar behavior. However, laboratory tests indicated that WMA sections were worse in terms of moisture damage potential.

Mocelin et al. (2017) investigated the workability of WMA mixtures by evaluating CDI obtained from compaction curve of SGC. Test results indicated that higher temperatures lead to reduction in CDI values which means better compaction performance may be accomplished. The authors suggested that the addition of surfactant to the binder also improved compaction behavior. They also pointed out that although significant air void values were achieved for WMA mixtures around 100°C and CDI values were similar to HMA, below this temperature, densification starts to decrease which may lead to undesired collateral effects.

Pereira et al. (2018) investigated the compactability behavior of WMA mixtures prepared with different chemical additives. Two different chemical additives were mixed with three different bituminous binders. According to the test results, although chemical additives did not decrease the viscosity of the binders, they tended to increase the compactability of the mixtures and thus, reduced the compaction energy and the temperature.

According to the discussed studies, compactability significantly affected by the WMA additive type and dosage, though SPGC is not capable of wholly simulating the compaction in the laboratory. In a recent study, Polaczyk et al. (2018) used an accelerometer placed on the falling plate of the Marshall hammer to investigate the compactability of Hot Mix Asphalt. According to the test results, a locking point, which could be defined as the blow number that peak acceleration and the impact time become stable, can be identified. Beyond this point, decrease in air voids were minimized and further compaction effort had significantly lower effect. This critical point in respect of compaction can be seen in Figure 2.11. Locking point was observed to be occurring between 108^{th} and 146^{th} blow according to their majority of test results.

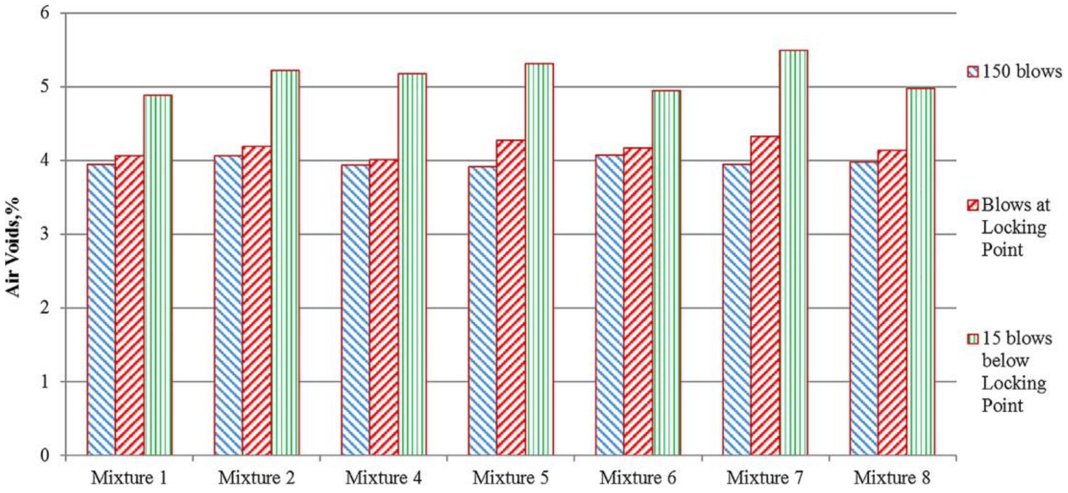


Figure 2.11. *Air voids immediately before, during and after the locking point (Polaczyk et al., 2018)*

This recent study indicated that the compactability concept takes significant attention and Marshall hammer is still the only compactor that is temperature sensitive in the laboratory. Therefore, the proposed method, which is discussed in Chapter 3 in detail, is novel and have potential to be used widely.

CHAPTER 3

MATERIALS AND METHODS

3.1. Introduction

This chapter covered material properties, sample preparation procedures, test matrix, and analysis methods. All experiments were carried out at the METU transportation laboratory according to ASTM, AASHTO standards and Turkish General Directorate of Highways specifications.

3.2. Materials

The properties of major components (i.e. aggregates, asphalt binder, WMA additive) of asphalt mixtures were presented in this section as follows:

3.2.1. Aggregates

3.2.1.1. Aggregate Gradation

In this study, an E1 asphalt mixture satisfying the requirements of the Michigan Department of Transportation Special Provision for Superpave HMA mixtures was used (MDOT, 2007). To determine the compaction characteristics of Marshall and Superpave samples, the gradation was kept constant throughout the study. The fine aggregate ratio was relatively high, and the gradation was dense-graded. The gradation consisted of 36.2% of coarse aggregates, 59.4% of fine aggregates and, 4.4% of filler. The gradation was presented in Table 3.1 and plotted in Figure 3.1.

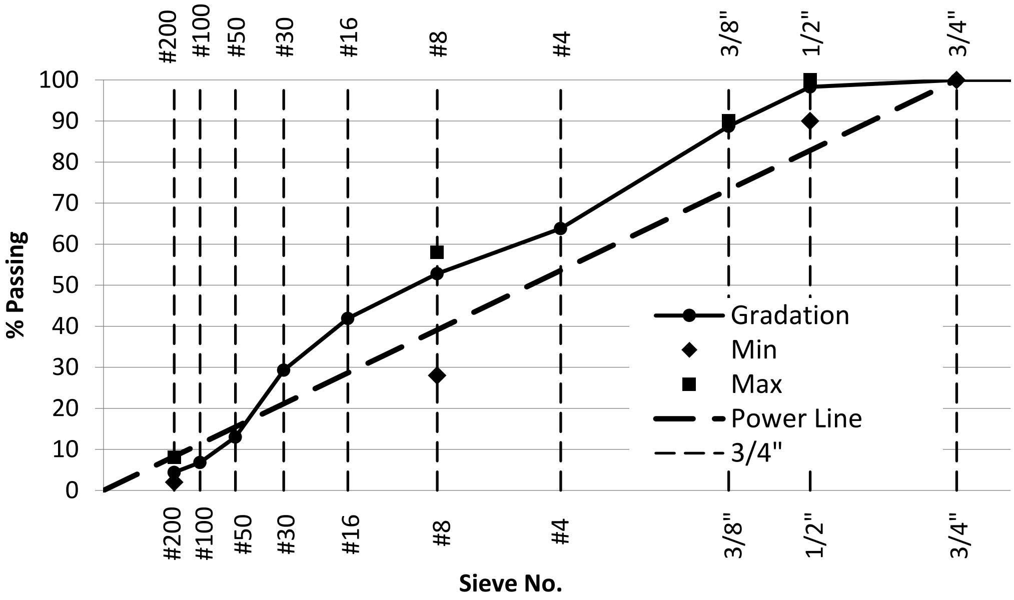


Figure 3.1. Aggregate gradation

Table 3.1. Aggregate gradation

Sieves	% Passing Aggregate
¾”	100
½”	98.3
3/8”	88.7
#4	63.8
#8	52.8
#16	41.9
#30	29.3
#50	13.0
#100	6.8
#200	4.4

3.2.1.2. Aggregate Properties

Aggregate properties were determined with respect to the ASTM standards. In this study, aggregates were provided from the local (Yapracık) basalt quarry. The physical properties such as specific gravity, water absorption capacity, Los Angeles abrasion and flakiness index tests were performed according to the standards. It was observed that the absorption capacity of aggregate was high due to the fact that basalt is a volcanic rock (2.12% for coarse aggregate and 3.35% for fine aggregate). However, the aggregate type was relatively stiff. It is assumed that it prevented excessive degradation during compaction. Los Angeles abrasion loss is measured as 17.28%, and the other aggregate properties are given in Table 3.2 together with the test methods.

Table 3.2. *Aggregate properties*

Property (Unit)		**Standard**	**Result**
Water Absorption (%)	Coarse	ASTM C127	2.121
Water Absorption (%)	Fine	ASTM C128	3.349
The Specific Gravity of Coarse Aggregate	Bulk	ASTM C127	2.547
	SSD	ASTM C127	2.601
	Apparent	ASTM C127	2.692
The Specific Gravity of Fine Aggregate	Bulk	ASTM C128	2.461
	SSD	ASTM C128	2.544
	Apparent	ASTM C128	2.683
Los Angeles Abrasion Loss	Gradation B	ASTM C131	17.28%
Flatness Index	Coarse	BS 812	22.82%

3.2.2. Asphalt Binder

In this study, one type of binder was used obtained from the local refinery (Kırıkkale) with bitumen grade of 50/70. In order to determine the physical properties of bitumen, penetration, ductility, softening point, flash and fire point and specific gravity tests were performed. The test results were presented in Table 3.3.

Table 3.3. *Asphalt binder properties*

Property (Unit)	Standard	Result
Binder grade	-	Pen 50/70
Penetration (25˚C, 0.1mm)	ASTM D5	64
Softening Point	ASTM D6090	53.5
Ductility (cm)	ASTM D113	>100
Flash point (˚C)	ASTM D92	246
Fire point (˚C)	ASTM D92	283
Specific gravity G_b (g/cm^3)	ASTM D70	1.024

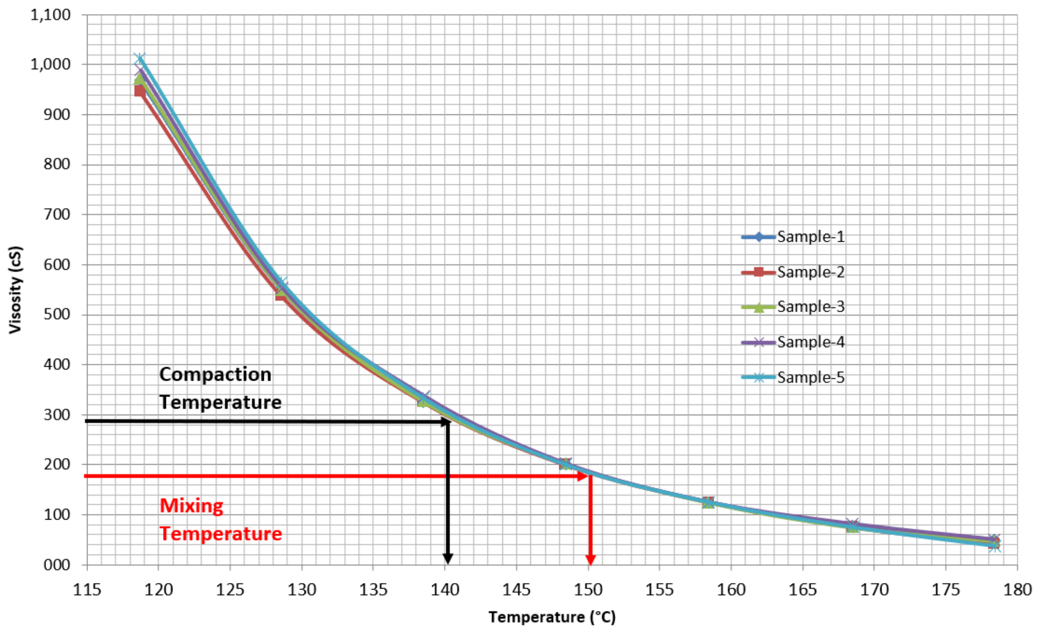


Figure 3.2. Viscosity - Temperature Graph for Asphalt Bitumen

Bitumen viscosity was determined according to ASTM D4402: Viscosity Determination of Asphalt Binder Using Rotational Viscometer Test. Temperatures corresponding to the viscosity values of 0.17 ± 0.02 Pa-s (170 cS) and 0.28 ± 0.03 Pa-s (280 cS), respectively, 150 °C and 140 °C were determined as mixing and compaction temperatures (Figure 3.2). Subsequently, 4 different compaction temperatures were determined with 15 °C intervals (decrease) to determine the temperature influence on various mixture properties. The compaction temperatures applied throughout the project were 140 °C, 125 °C, 110 °C, and 95 °C, respectively.

3.2.3. WMA Additives

In this study, two types of additives, foaming, and non-foaming were used to examine the effects of additive type. Sasobit, non-foaming additive, and Advera, foaming additive, were preferred because of their high share in the market and also because of their ease of access. Two types of additives were added at two different dosages to examine the effects of the additive proportion on the mixture. Additive dosages were determined based on the supplier's suggestions.

The typical Sasobit dosage is 1.5% by weight of binder, also the dosage can vary between 0.8%-4% depending on the application (B. D. Prowell et al., 2012). In this study, 2% and 3% Sasobit dosages were determined in order to limit the change in the performance grade of the binder. The performance grades of the binders were not determined since it was out of the scope of this study.

Advera is generally used in the range of 0.20% to 0.25% by weight of the mixture. However, it is suggested to be used in between 0.1 to 0.3%. Also, higher additive dosages are recommended for high binder content mixtures (B. D. Prowell et al., 2012). For this reason, the specified additive dosages were determined as 0.25%, the highest typical dosage, and 0.3%, the highest suggested dosage, by weight of the mix since the optimum binder content of the mixture used in this study was high.

3.3. Design Properties

At the beginning of the study, the Marshall method was determined as the design method. This preference was due to the fact that the Superpave design method is not temperature-sensitive (H. U. Bahia et al., 2001; Delgadillo & Bahia, 2008; Huner & Brown, 2001; Hurley & Prowell, 2005; Roberts et al., 1996). In addition, many researchers have stated that the Marshall Design Method is temperature sensitive (Hurley & Prowell, 2005; B. Prowell et al., 2011). Since the Superpave gradation was used in the study, the blow number of the Marshall design was determined as 75 in order to provide a comparison with Superpave design. Many studies showed that 75 blows meet the necessary density equal to Superpave gyration (Christensen & Bonaquist, 2006; Rushing et al., 2010). Superpave experiments were also included later in the study. Details related to Superpave samples were also described in the test matrix part.

3.3.1. Determination of the Optimum Bitumen Content

In order to determine the optimum bitumen content, HMA samples with different bitumen content were prepared with the materials mentioned in section 3.2 according to Marshall Design Method. Four different bitumen contents (6.5, 7.0, 7.5, 8.0% by weight of the total mixture) were tried in order to determine the optimum bitumen content. Three replicates for each binder content were fabricated. Subsequently, Voids in Total Mixture (VTM), Voids in Mineral Aggregates (VMA), Voids Filled with Asphalt (VFA), density, stability, and flow values were determined. The results for each content were presented in Table 3.4 and plotted from Figure 3.3 to Figure 3.9. With respect to the results and Marshall Design Method, optimum bitumen content was determined to be 7.5% which corresponds to the air void of 4.10% (Table 3.5). The theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}) of HMA mixture were determined to be 2.310 and 2.218, respectively.

As compared to traditional HMA mixtures, it was obvious that binder content was relatively high. There were two main reasons for high bitumen content. Firstly, the gradation consists of relatively high fine aggregate content. Since aggregate sizes getting smaller their surface area increased, and it increased the area that needed to be covered by bitumen. Secondly, the high absorption capacity of aggregates increased the bitumen content. Absorption capacities were determined to be 2.121% for coarse aggregates and 3.349% for fine aggregates.

Table 3.4. *Marshall design properties for HMA*

Asphalt Content (%)	**VTM (%)**	**VMA (%)**	**VFA (%)**	**Density (g/cm³)**	**Flow (mm)**	**Corrected Stability (kgf)**	**G_{mb}**
6.5	6.7	18.0	62.8	2.016	2.95	1157	2.191
7.0	5.4	18.0	70.1	2.168	2.87	1131	2.203
7.5	4.1	18.0	77.3	2.174	3.12	1066	2.215
8.0	2.9	18.2	83.9	2.187	3.91	1001	2.222

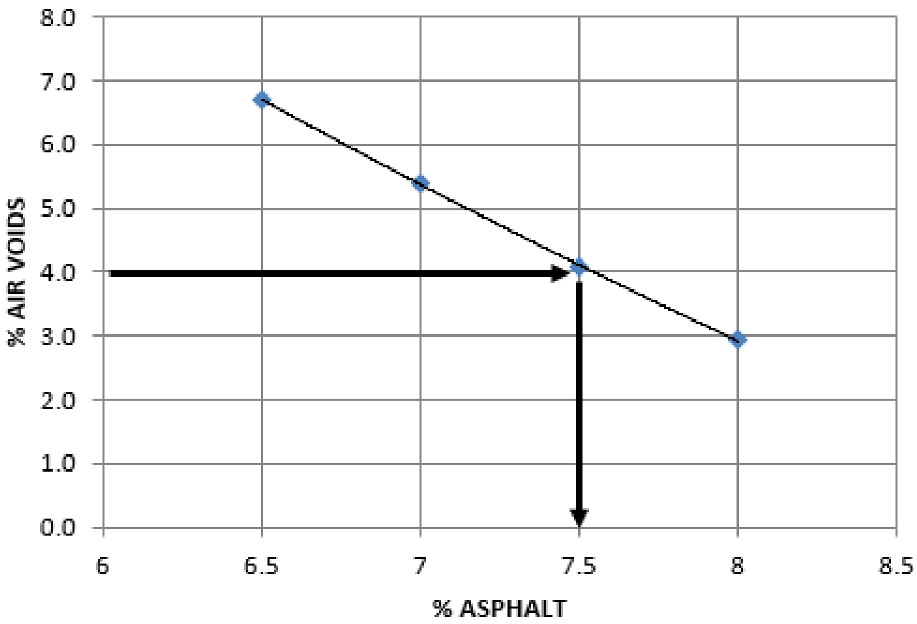


Figure 3.3. Air Voids - Asphalt Content

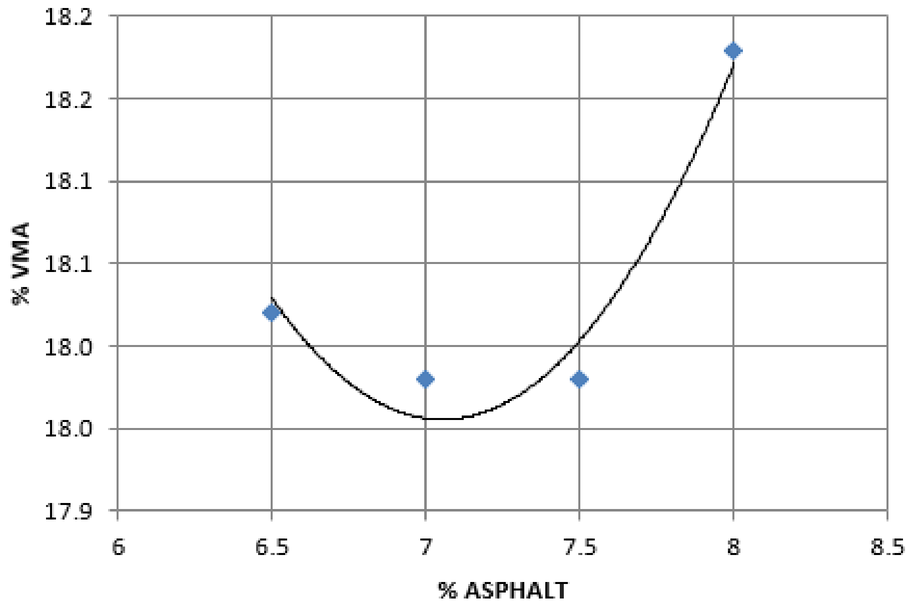


Figure 3.4. VMA - Asphalt Content

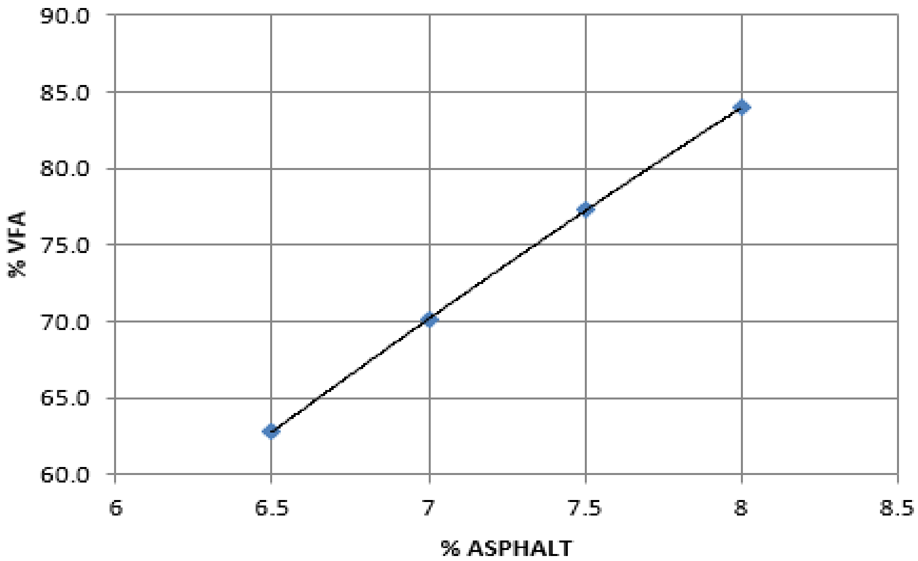


Figure 3.5. VFA - Asphalt Content

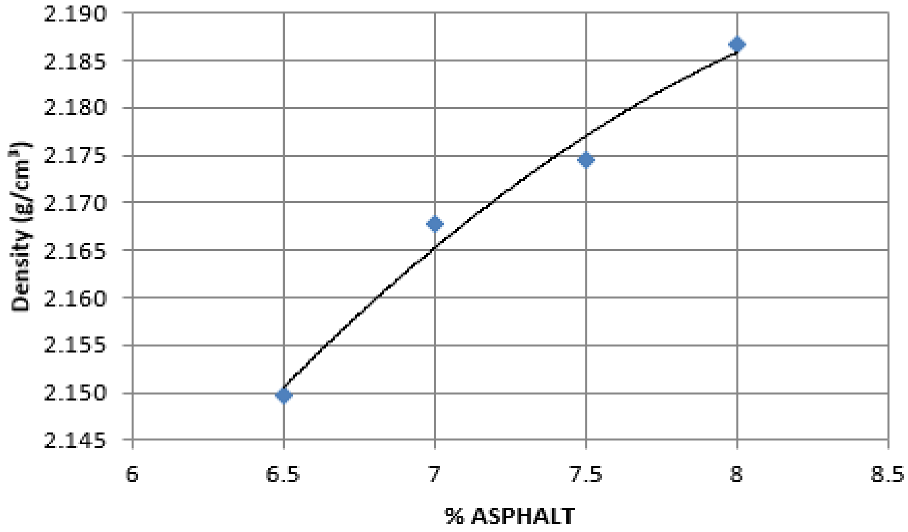


Figure 3.6. Density - Asphalt Content

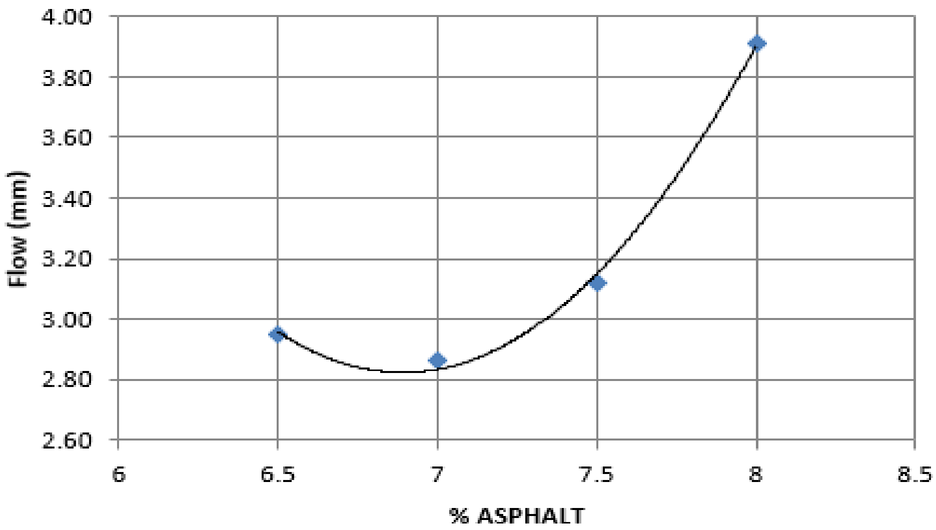


Figure 3.7. Flow - Asphalt Content

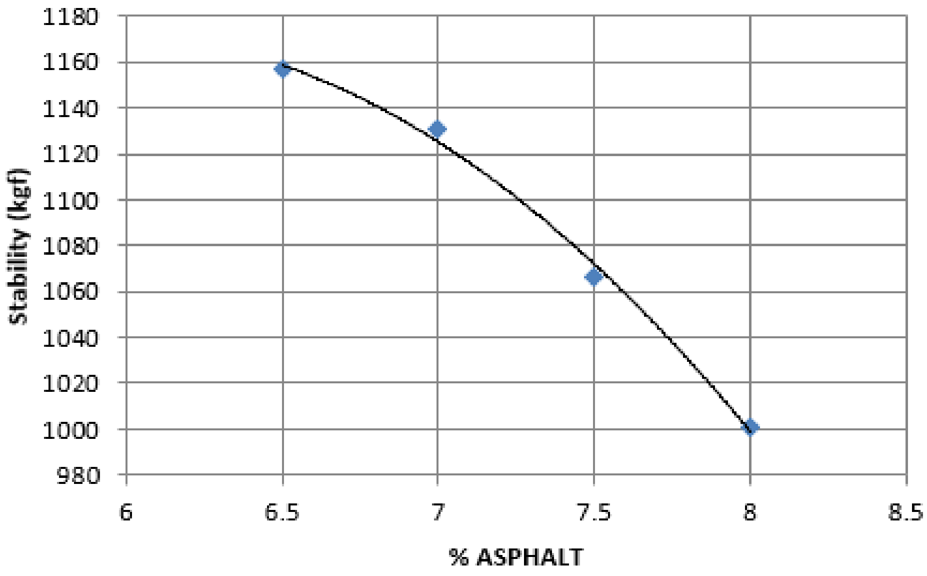


Figure 3.8. Stability - Asphalt Content

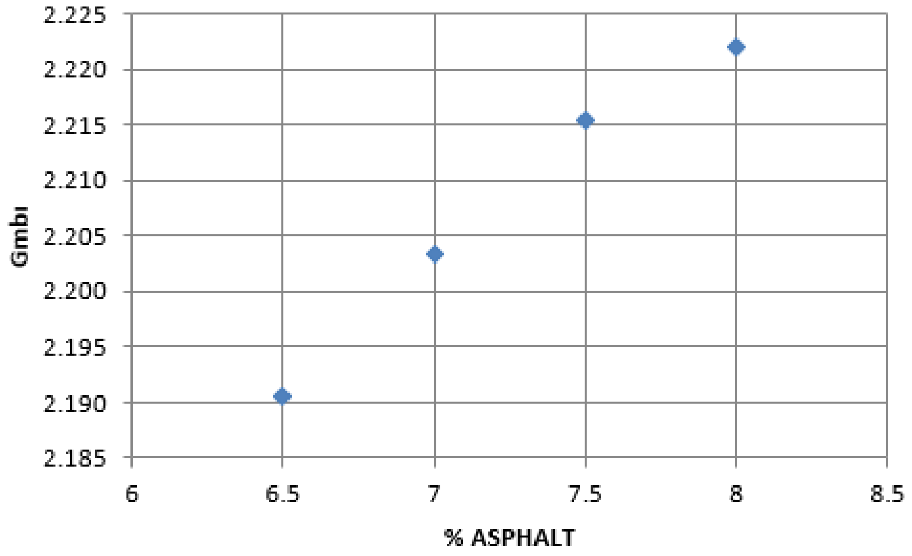


Figure 3.9. G_{mb} - Asphalt Content

Table 3.5. *Optimum Design Properties*

%Air Voids	*%A.C*	*%VMA*	*%VFA*	*Density (gr/cm^3)*	*Flow (mm)*	*Stability (kgf)*	*G_{mb}*
4.10%	7.50%	18.00	77.3%	2.174	3.12	1066	2.215

3.4. Experimental Design and Test Matrix

This test matrix of this study consisted of 8 different mixtures, in which the compaction apparatus, type of WMA additive and amount of the additive were varied. (details in part 3.4.1). Aggregate type and gradation, bitumen type, optimum bitumen content, and mixing temperature were kept constant throughout the study in order to limit the variables.

3.4.1. Test Matrix

The test matrix in this study consisted of 8 different sample types. As presented in Figure 3.10, 5 different mixtures with different additive types and/or amounts were compacted by Marshall Hammer. In other words, there were one HMA and four WMA mixtures two of which were prepared with two different dosages of non-foaming additive and the rest was prepared with two different dosages of foaming additive. In addition, 3 different mixtures, one HMA and two WMA mixtures with foaming additive at different dosages, were also compacted with Superpave Gyratory Compactor. WMA additive dosages and selection procedures were discussed in detail in section 3.2.3.

Due to the high variability between the replicates prepared by Marshall apparatus, 4 replicates for each set were prepared. On the other hand, 2 replicates were prepared due to the small deviations in the Superpave samples.

All mixtures, summarized in Figure 3.10, were compacted at 4 different temperatures, as explained in Section 3.2.2

As a summary, the test matrix for the Marshall Design Method consisted of five different mixtures compacted at four different temperatures. The number of samples prepared by the Marshall test method was 80 (5 mixtures x 4 CT x 4 replicates). In addition, the test matrix for the Superpave Design Method consisted of 3 different mixtures prepared at four compaction temperatures. The number of samples prepared by the Superpave method was 24 (3 mixtures x 4 CT x 2 replicates). The total number of samples produced in the whole study was 104. The test matrix is summarized in Figure 3.10.

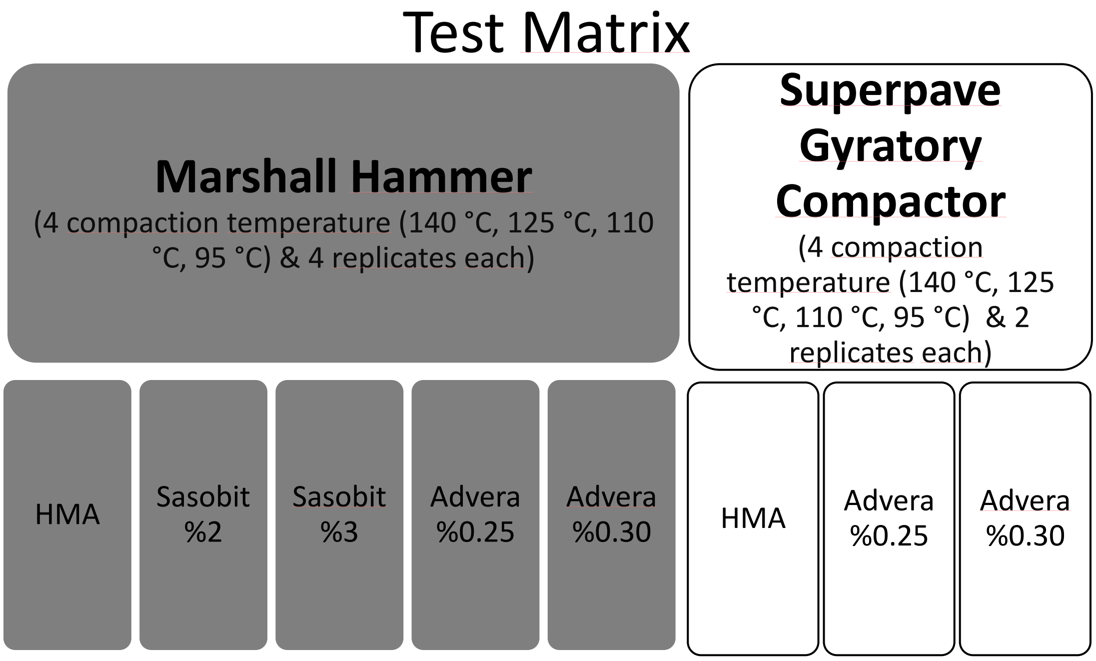


Figure 3.10 Test matrix

3.4.2. Specimen Identification

Specimen identification technique has been developed for the ease of the following of the study. The naming sequence was made according to the compaction apparatus, type, additive type and ratio, compaction temperature and sample number (if necessary), respectively. Since Marshall hammer is the major compaction apparatus, it is not identified with a letter in the identification, but Superpave samples are named as "S". Mixture type is classified as "H" and "W" respectively, depending on whether it is a hot or warm mixture. "A" was used for Advera and "S" was used for Sasobit. Specimen identification technique is explained with three examples.

For example, the name H-140 symbolizes a sample compacted at 140 degrees with no additive (HMA) and compacted with a Marshall Hammer. Similarly, the name W-A-0.25-110 symbolizes a sample compacted with Marshall Hammer, prepared with

Advera (WMA) at a proportion of 0.25% by weight of the mix and compacted at 110 °C. Lastly, the name S-W-S-3-95 symbolizes a sample compacted with Superpave Gyratory Compactor, prepared with Sasobit (WMA) at a proportion of 3% by weight of the binder and compacted at 95 °C.

3.5. Sample Preparation

According to the test matrix, there were eight different types of mixture. Differences between the additive proportions didn't affect the sample preparation method. Therefore, sample preparation methods were divided into three main groups. These groups could be summarized as HMA samples preparation, WMA with non-foaming additive preparation and WMA with foaming additive preparation. In addition, mixtures divided into two groups according to the compaction apparatus. Therefore, Superpave samples preparation was also explained as the fourth group of preparation section.

3.5.1. HMA Preparation

All Marshall Samples were prepared according to Marshall mix design procedure. The steps of HMA samples preparation are as follows:

Initially, preheated aggregates were placed into a preheated mixing bowl and a crater was formed in the middle of an aggregate batch. The binder was poured into the crater. Then, the bowl was placed to a mixer equipped with a heater and mixture was mixed for 2 minutes at a constant rate and mixing temperature. Afterwards, the mixture was spreaded into the trays to reach the desired compaction temperature. The mixture homogenously cooled through mixing with a spatula to the desired compaction temperature. During the cooling process, temperature was controlled simultaneously with the help of an infrared temperature gun. Subsequently, the cooled mixtures were poured to the molds, which were preheated in the oven at the desired compaction temperature. Both sides (top and bottom) of the samples were compacted with 75 blows of Marshall Hammer. After the compaction, samples were cooled at room temperature to be removed from molds.

3.5.2. WMA with Non-Foaming Additive Preparation

Preparation of the WMA samples with the non-foaming additive procedure is similar to HMA preparation but it has only an additive adding difference. Preparation of WMA samples with non-foaming additive are as follows:

Initially, preheated aggregates were placed into a preheated mixing bowl and pre-weighted additives (Sasobit) were directly added and mixed with the aggregate batch. Afterwards, a crater was formed at the middle of aggregate batch. The binder was poured into the crater. Then, the bowl was placed to the heater coupled mixer and mixture was mixed for 2 minutes at a constant mixing temperature. Followingly, the mixture was spreaded into the trays to reach the desired compaction temperature. The mixture homogenously cooled through mixing with a spatula to the desired compaction temperature. During the cooling process, temperature was controlled simultaneously with the help of an infrared temperature gun. Subsequently, the cooled mixtures were poured to the molds, which were preheated in the oven at the desired compaction temperature. Both sides (top and bottom) of the samples were compacted with 75 blows of Marshall Hammer. After compaction samples were cooled at room temperature. Finally, totally cooled mixtures were removed from molds.

3.5.3. WMA with Foaming Additive Preparation

Preparation of the WMA samples with foaming additive procedure is similar to HMA preparation but it has only additive adding difference. Preparation of WMA samples with foaming additive are as follows:

Initially, preheated aggregates were placed into a preheated mixing bowl and a crater was formed at the middle of an aggregate batch. The binder was poured into the crater until the optimum bitumen rate was achieved. Afterward, pre-weighted foaming additive (Advera) was added to the binder. The additive was mixed with the binder by the help of a glass rod. Then, the bowl was placed to the heater coupled mixer and mixture was mixed for 2 minutes with a constant mixing temperature. Afterwards, the mixture was spreaded into the trays to reach the desired compaction temperature. The mixture homogenously cooled through mixing with a spatula to the desired compaction temperature. During the cooling process, temperature was controlled simultaneously with the help of an infrared temperature gun. Subsequently, the cooled mixtures were poured to the molds which were preheated in the oven at the desired compaction temperature. Both sides (top and bottom) of the samples were compacted with 75 blows of Marshall Hammer. After compaction samples were cooled at room temperature. Finally, totally cooled mixtures were removed from molds.

3.5.4. Superpave Samples Preparation

All Superpave samples were also prepared according to the aforementioned procedures and compacted using a gyratory compactor. Other than compaction all Marshall sample preparation steps are valid for Superpave samples. Although mixtures should be compacted up to N_{des} number, samples were compacted to N_{max} with the purpose of obtaining more data for compaction curves. According to MDOT (2007) specification, N_{des} and N_{max} values are 76 and 117 cycles, respectively. In this scope, samples were compacted under 600 kPa pressure, 1.25° gyration angle and, 30 rev/min through the 117 cycles. It should be noted that the samples were not subjected to short term aging.

3.6. Test and Analysis Methods

According to Figure 3.11, samples compacted with two different compactors (Marshall-SPGC) were analyzed to observe the change in their physical and performance related properties with respect to compaction temperature.

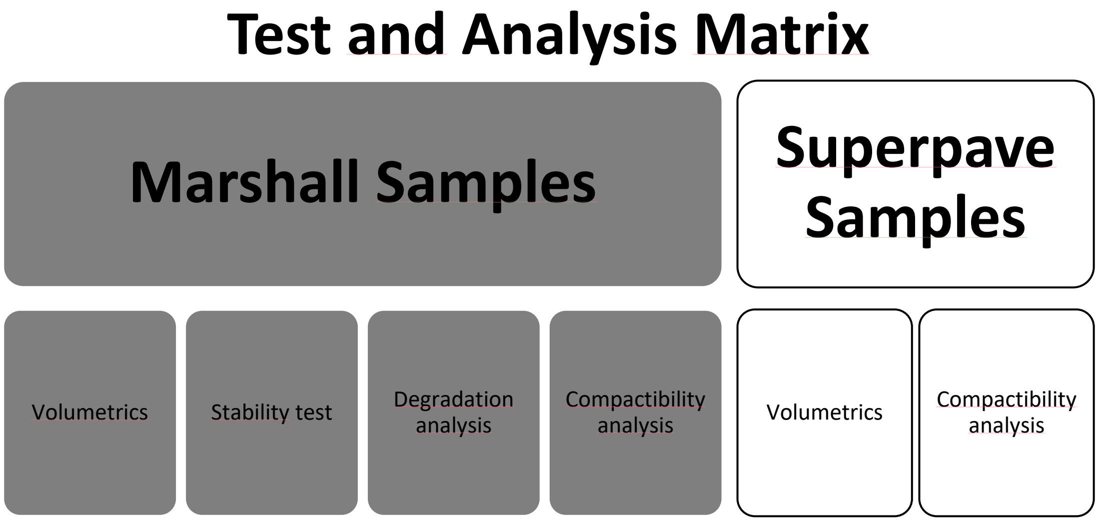


Figure 3.11. Test and analysis methods

3.6.1. Volumetrics

In order to determine the volumetric properties of mixtures, the maximum theoretical specific gravity (G_{mm}) at optimum bitumen content was determined according to ASTM D2041 standard. Then, the volumetric properties of the mixtures (Figure 3.12) were determined according to ASTM D2726 standard.

Voids in the total mixture (AV%) was determined according to Equation 3.1.

$$AV\% = 1 - \frac{G_{mb}}{G_{mm}} \qquad (3.1)$$

G_{mb}: *Bulk specific gravity of the sample*

Voids in mineral aggregates (VMA%) was determined according to Equation 3.2.

$$VMA\% = 1 - \frac{G_{mb} * (1 - P_b)}{G_{sb}} \qquad (3.2)$$

P_b=Bitumen content, G_{sb}=Specific Gravity of Aggregate

The voids filled with asphalt (VFA%) was determined according to Equation 3.3.

$$VFA\% = \frac{VMA\% - AV\%}{VMA\%} \tag{3.3}$$

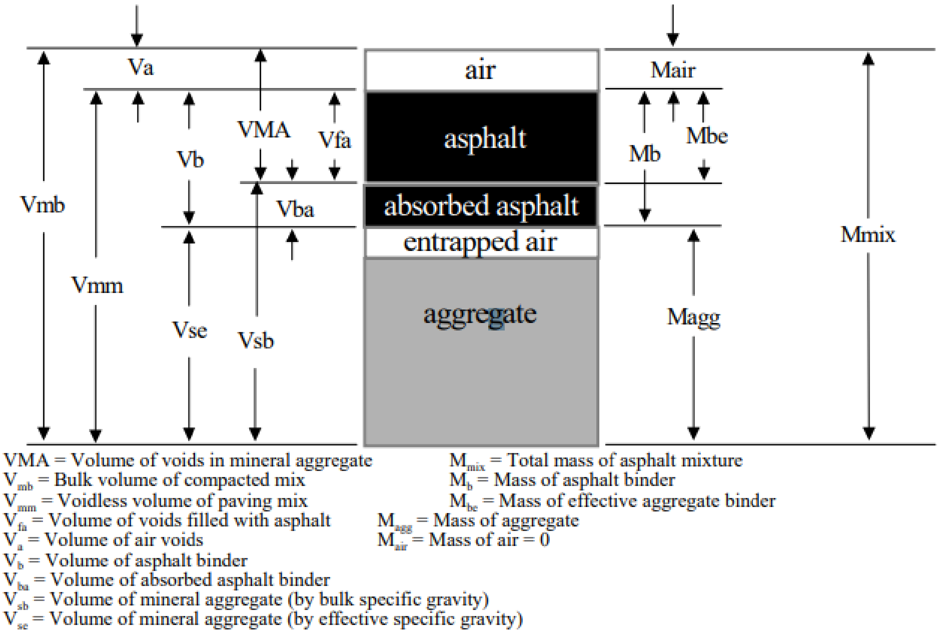


Figure 3.12. Volumetric parameters (Huner & Brown, 2001)

Volumetric tests were applied through all samples.

3.6.2. Stability Test

Half of the Marshall samples (40 samples) were subjected to a Marshall stability test to give insight to their performance with respect to change in compaction temperature and, in addition to the change in WMA additive type and amount. Although stability and flow parameters are not sufficient to understand the performance of the mixtures, they give hints about their resistance to traffic loads. Marshall Stability test was performed according to ASTM D6307: Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures standard. According to the procedure, the samples were conditioned in a water bath at 60˚C for 30 to 40 minutes. After conditioning samples were loaded under the automatic Marshall stability test apparatus. The stability and, flow values were determined in the units of kgf and mm, respectively. Before testing samples, sample heights were measured in order to make Marshall stability correction (Figure 3.13).

Figure 3.13. Height measurement by caliper for correction

3.6.3. Degradation Analysis

Workability and compactability are not fully defined parameters in the literature. The Marshall compactor is an impact base device. As the workability and compactability increase, aggregate breakage is expected to increase in impact-based compactions. Half of the Marshall samples were subjected to degradation analysis to determine aggregate fracture rates to give insight into workability and compactability with respect to compaction temperature, as well with respect to WMA additive type and amount.

In order to determine degradation samples were burned at 538 °C for 12 hours according to ASTM D6307-19: Standard Test Method for Asphalt Content of Asphalt

Mixture by Ignition Method. The samples with the highest and the lowest void ratios, where void ratios were in a narrow range, of each quartet group, were subjected to degradation test in order to observe the critical gradation change. Since gradation is fixed in this study, sample gradation before compaction is known. After burning, gradations after compaction were determined according to ASTM C136 (sieve analysis). In this study, percentage change as a function of Total Aggregate is calculated according to Equation 3.4 (Airey et al., 2008):

$$Percent\ Change(Total\ Aggregate) = \frac{(RET_{before} - RET_{after})}{100} \quad (3.4)$$

RET_{before} represents the original retained percentage for a specific sieve fraction and RET_{after} represents the retained percentage for that specific sieve fraction after the compaction. Because of the formula, plus signs indicate a decrease in related aggregate size and negative signs indicate an increase in related aggregate size.

3.6.4. Compactability Analysis

The compactability of the samples was analyzed to examine the effect of compaction temperature and additives. Compactability is a concept defined by various parameters depending on the instantaneous air voids of samples during compaction.

SPGC is a compaction apparatus capable of supplying instantaneous sample heights at the moment of compaction and consequently instantaneous sample air voids. However, Marshall Hammer is an impact-based and relatively old device that cannot show instant air voids. In this study, a new image-based method was developed to capture instant sample air voids for Marshall Hammer.

Compactability parameters in the literature have been developed for SPGC. The compactability data obtained from the new method (developed for Marshall Hammer) and obtained from SPGC were compared with the parameters developed for SPGC. Accordingly, new parameters were proposed or modified for Marshall Hammer based on previous SPGC parameters.

3.6.4.1. Data Acquisition

Unlike SPGC, Marshall Hammer cannot supply instantaneous sample heights during compaction. For this reason, an image-based method was developed for Marshall Hammer to extract the densification curves in this study. The new method measures the reduction in the height of the compacted mixtures during compaction via image analysis.

A number of modifications were made to the Marshall apparatus to implement the new method. The Marshall apparatus was equipped with a u-shaped phone holder, phone for video recording, light source and white dots on a black background to observe height changes (Figure 3.14). The u-shaped phone holder was fixed to the wall which stands behind the Marshall apparatus in order to minimize vibration effects that occurred during compaction. Non-industrial camera (iPhone) was used for recording compaction due to its ease of access. The camera was placed perpendicular to the Marshall apparatus and parallel to the ground surface to prevent any computational error. Phone light was used as a light source with the purpose of preventing any reflections and shadows in the images. Two pieces of white dot on a black background were stuck to the Marshall apparatus. The first piece was stuck to the compactor surface which stands stable during compaction and the other one was stuck to the hammer shaft with the intention of observing movement.

a) Camera, Light Source, Black Paper & White Dots

b) U shape rod

Figure 3.14. Image process modification to Marshall apparatus

All the Marshall samples compaction were recorded separately for the top and bottom side compactions by the camera. During the compaction, a camera captured the movement of two white dots by video recording.

Recorded videos were subjected to the image process analysis by the help of Matlab code, prepared within the scope of this study. The video capture speed of the mobile phone was 30 frames per second. The working speed of Marshall Hammer was 60-66 blows per minute. When the videos were taken during the experiment were examined, it was seen that every 29-30 frames in the video images corresponded to 1 blow of Marshall Hammer. Therefore, the use of non-industrial camera was accurate to catch the blows per minute. From the videos taken with the help of Matlab code, the frames corresponding to one blow of Marshall Hammer was determined. These frames were sequentially combined to produce a new compaction video (extracted video).

Extracted videos were analyzed in a program written in Matlab to obtain compaction curves. In the image analysis, the center coordinates of the two white dots (D1 and D2) were determined to utilize morphologic labeling operation for all consecutive frames. D1 represents the fixed-point during compaction and D2 represents the compaction of the mixture since it was attached to the hammer shaft. Although D1 should be stable in each frame, due to the vibration of the floor because of the impact of the hammer, the location of D1 slightly varies from frame to frame in the captured video. In order to eliminate this vibration effect, the movement of white dots (D1 and D2) relative to each other was used in the analysis. The coordinate change between the frames of the two white dots was calculated and the motion was obtained in the manner of the pixel (Figure 3.15). Then, pixel data were converted to length units (mm) using the actual dimensions of the white dots. The Matlab analysis steps are shared in appendix A.

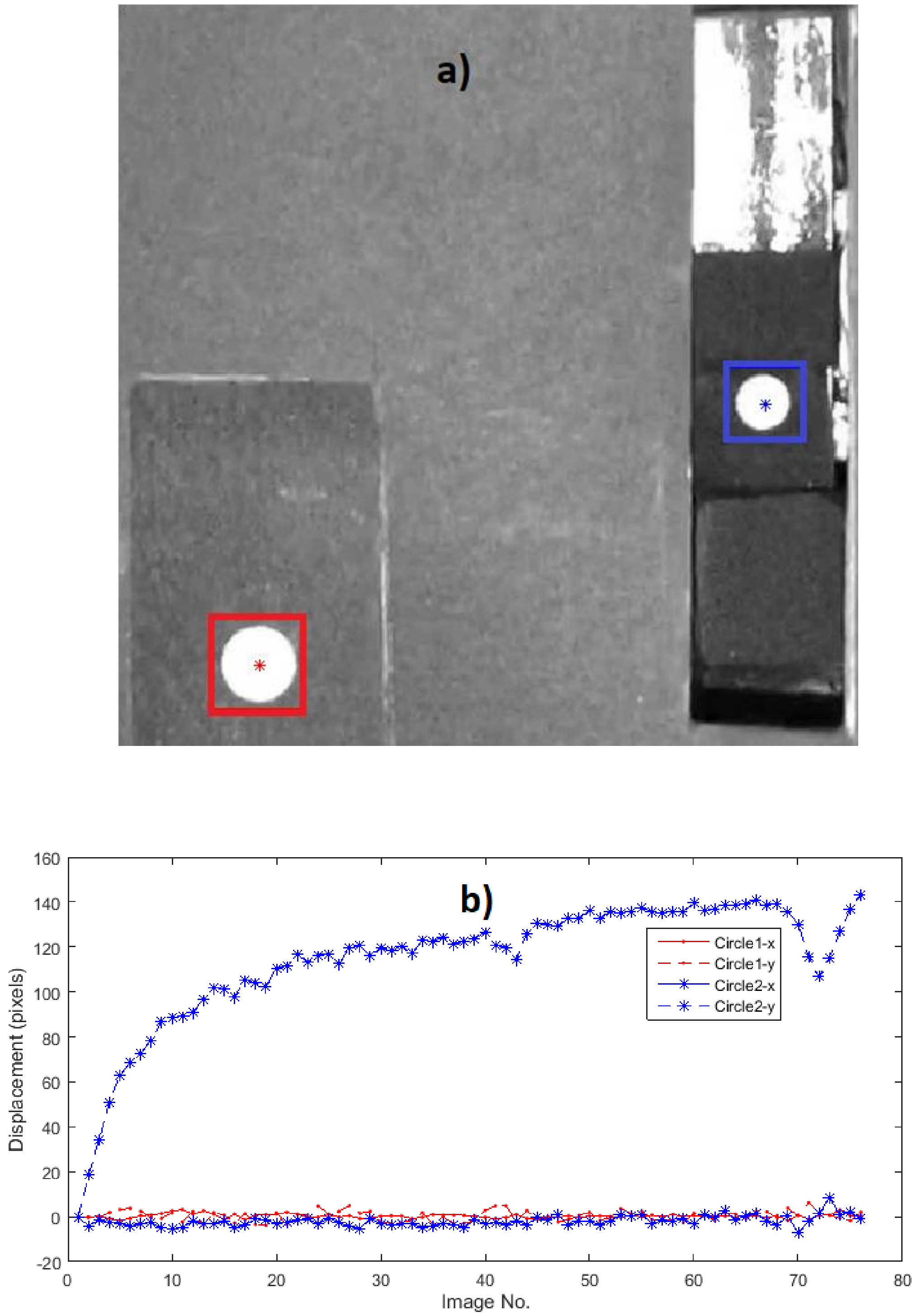


Figure 3.15. White dots & change in pixels location a) White dots, b) Displacement per frame

3.6.4.2. Densification Curves

Various computations were made to obtain densification curves. The SPGC automatically provides compaction heights per cycle. However, a number of adjustments were required to obtain the displacement data from Marshall Hammer. First, the height data obtained from the top and bottom compaction videos of each sample were combined (displacement curves). Bottom compaction data was added to the upper compaction data in accordance with the compaction sequence. When the combined displacement curves examined, it is clear that the compaction process is logarithmic, decreasing displacement as the number of blows/cycles increases. Because of the discrepancy between the Marshall Hammer blow frequency (60-66 blow/minute) and frame per second in the videos (30 fps), it could be seen that some pre-blow frames were included in the Marshall displacement curves analysis. Furthermore, the vibration in the system could not be completely prevented. A number of adjustments were made to the received data to eliminate errors related to blow mismatch and vibration. These steps are as follows:

- The closest logarithmic equation to displacement curves is established by mathematical methods. The regression values of the first logarithmic curves were over 90%.
- If the obtained displacement values deviate 1.2 mm from the displacement value from the curve, the displacement value in the curve equation was considered correct.
- No displacement values were changed during the first 10 blow since the compaction was high.
- The values that appear to have higher displacement than the final displacement value due to vibration were replaced with the value from the curve equation.

A second logarithmic curve was fitted to the error-free vibrating data. The regression values of the second fitting curves were generally above 98%. The sample raw data, edited data and the fitted curve (second fitting curve) are shared in Figure 3.16.

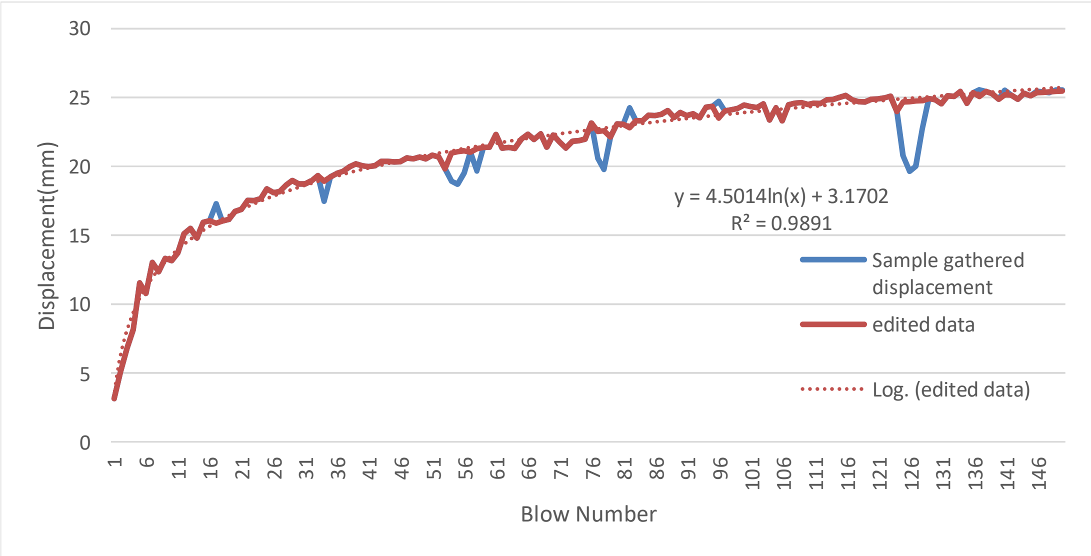


Figure 3.16. Sample displacement data

Due to the high regression values, the analyzes were continued with the second logarithmic curve values. The second reason for using the logarithmic equation is some parameters in the further steps of the analysis, depending on the values more than the compaction blow number.

The densification curves were obtained from the instantaneous air voids during the compaction process. Instantaneous air voids are the height depended parameter during the compaction. Since the displacement amount (Δ_{hi}) is known in each blow (i), the initial height of the sample ($H_{initial}$) is calculated by adding total displacement to the final compacted height (H_{final}), as given in Equation 3.5. Similarly, the instantaneous height (H_{ins}) at n_{th} blow is calculated by subtracting the total displacement till n_{th} blow from the initial height, as given in Equation 3.6. Instantaneous air void percentage (AV_{ins}%) is calculated as follows in Equation 3.7. Finally, the densification values (G_{mm}%) were calculated according to Equation 3.8.

$$H_{final} + \sum_{i=1}^{i=150} (\Delta h_i) = H_{initial} \tag{3.5}$$

$$H_{ins} = H_{initial} - \sum_{i=1}^{i=n} (\Delta h_i) \tag{3.6}$$

$$\%AV_{ins} = \left[1 - \left(\frac{G_{mb} * H_{final}}{G_{mm} * H_{ins}}\right)\right] * 100 \tag{3.7}$$

$$\%G_{mm} = 100 - \%AV_{ins} \tag{3.8}$$

The sample densification curve is shared in Figure 3.17. It should be noted that this data is extrapolated for further analysis, which is discussed in the following section.

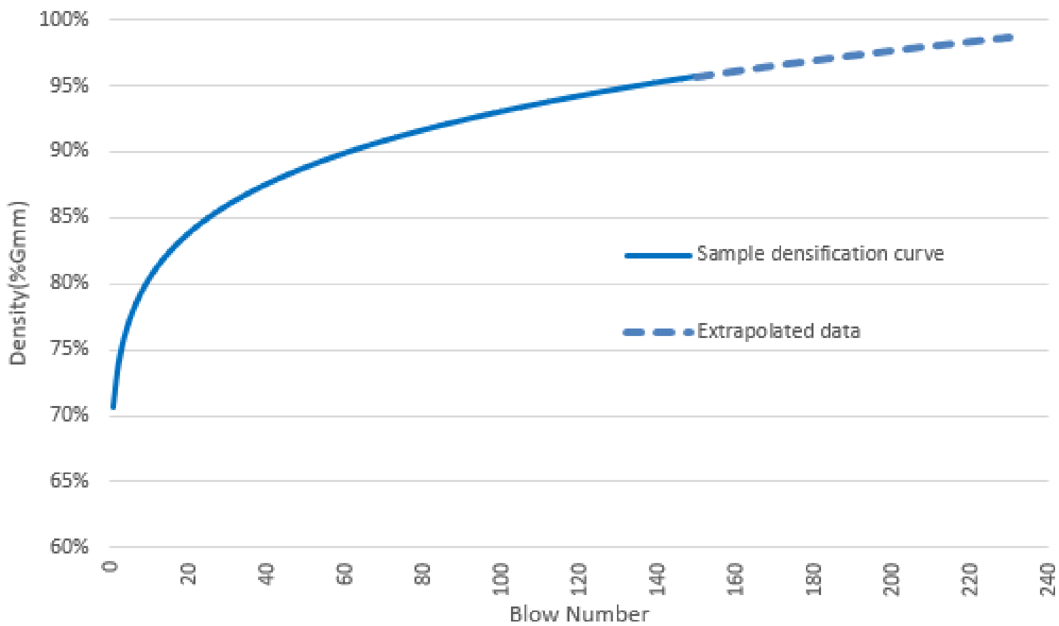


Figure 3.17. Typical densification curve

3.6.4.3. Compactability Metrics

Compactability parameters are based on the Superpave compaction curves in the literature. Since there is no compactability parameter for Marshall compaction, all samples were analyzed according to Superpave compactability metrics. For Marshall incompatible parameters, some modifications were made, and modified parameters were proposed.

The parameters developed to understand compactability depend on the energy required for compaction and densification curves. When literature is reviewed, some parameters related to compactability are prominent.

The number of cycles or blows required for samples to reach certain void ratios (92%, 96%, 98%) gives an idea of compactability. Since the energy supplied to the system increases with each cycle or blow, the effort required to reach certain void ratios generates roughly comparable data.

Compaction/Construction Densification Index (CDI) represents the cylinder effort during road construction. Studies have concluded that CDI represents the area between 89% and 92% Gmm under the densification curve. The schematic representation of CDI is made in Figure 3.18.

Traffic Densification Index (TDI) indicates the compaction under traffic loads to the plastic failure. This parameter is determined according to the triangular area under the densification curve from 92% to 98% G_{mm}. The schematic representation of TDI is made in Figure 3.18.

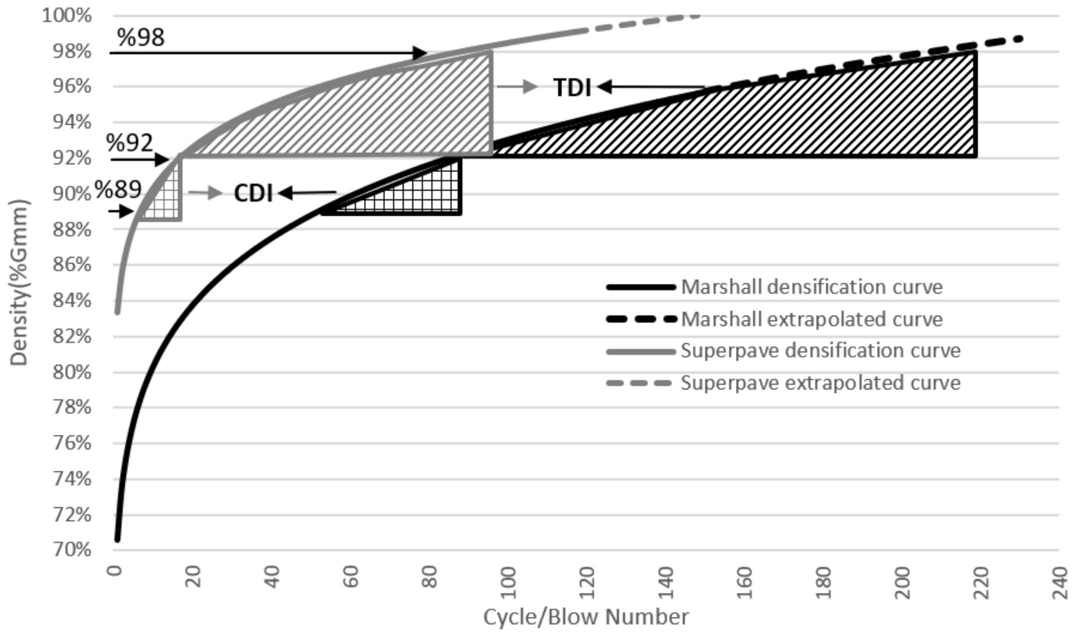


Figure 3.18. Densification indices (CDI & TDI)

Other parameters related to compactability are workability energy index (WEI) and compactability energy index (CEI). WEI and CEI are energy parameters that describe the energies required for switching between certain void ratios in the literature. SPGC makes compaction under constant pressure. Since the surface areas of the samples produced in the SPGC remain constant during compaction, the applied constant pressure corresponds to a constant force. When the displacement of the sample during compaction is multiplied by the applied force, the energy transferred to the system for the compaction process can be calculated. In the literature, energy parameters (WEI, CEI) are defined as the energy used per cycle in the relevant region. WEI and CEI calculated according to Formula 3.9 and Formula 3.10 respectively.

$$WEI\ (N.m) = \frac{\frac{\pi d^2}{4} * P * (h_0 - h_{92})}{N_{92}} \tag{3.9}$$

$$CEI\ (N.m) = \frac{\frac{\pi d^2}{4} * P * (h_{92} - h_{96})}{N_{96} - N_{92}} \quad (3.10)$$

Where; d is mold diameter in terms of mm, P is compaction pressure in terms of (kPa), h values are specimen heights at the related $\%G_{mm}$ in terms of mm, N values are the number of cycles to reach related $\%G_{mm}$.

When the energy parameter formulas are examined, it is seen that the area and pressure parameters used to obtain the force and they enter the equation as a constant multiplier. The remaining parameters correspond to the amount of displacement per cycle between the respective air gaps. The amount of displacement per cycle can be expressed as a slope in mathematics.

The total energy transferred to the system in Marshall Hammer cannot be determined with certainty. However, by the help of the obtained displacement curves displacement amount per blow can be determined independently from the force unit for Marshall samples. These slopes, similar to those in SPGC, gives an idea of the relationship between the two compaction devices and the sample behavior. Displacement-dependent slopes are indicated by WEI(h), CEI(h). These parameters are calculated according to Equation 3.11 and Equation 3.12 and shown in Figure 3.19.

$$WEI\ (h) = \frac{(h_0 - h_{92})}{N_{92}} \quad (3.11)$$

$$CEI\ (h) = \frac{(h_{92} - h_{96})}{N_{96} - N_{92}} \quad (3.12)$$

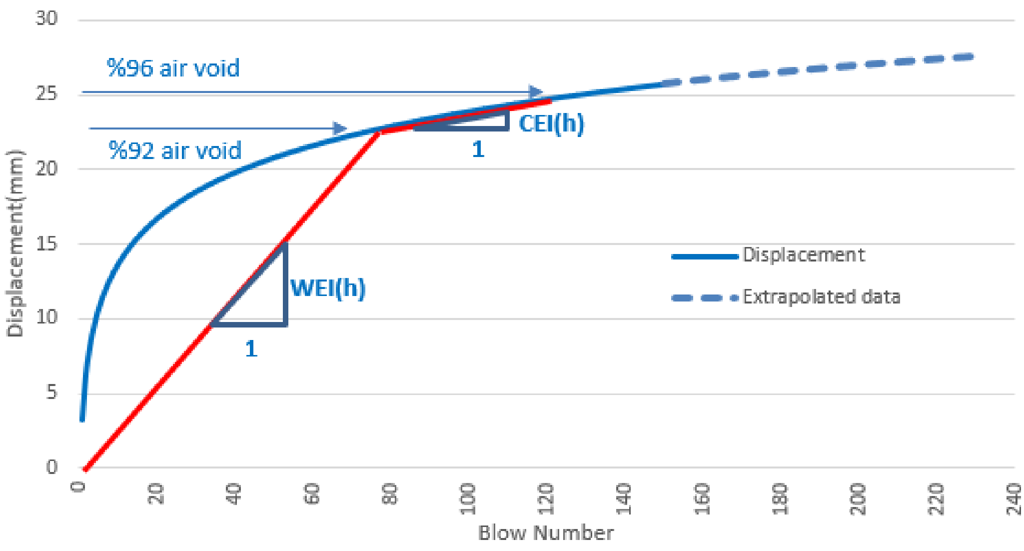


Figure 3.19. Compactability energy parameters (WEI(h) & CEI(h))

Compactability Ratio (CR) is another parameter developed for WMA. CR compares the number of gyrations to reach 92% G_{mm} at compaction temperature(T) and 30°C lower than this temperature. 30 °C temperature difference simulates the temperature loss between production and construction. For Marshall samples gyrations numbers replaced by the number of blows. CR formula can be seen in Equation 3.13.

$$CR = \frac{N92_{T-30°C}}{N92_{T}} \tag{3.13}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Introduction

As indicated in the previous sections, various tests and analyses were performed on WMA and HMA mixtures to understand the compactability with respect to compaction temperature, WMA additive type and amount. Volumetric, Marshall stability and flow, degradation and, compactability analysis were performed in this context. The results of the studies were analyzed and discussed in this section.

4.2. Volumetrics

In this study, the effects of WMA additives on volumetric properties were investigated depending on temperature. Volumetric results were presented based upon the average of at least four replicates due to the low variability between the samples. The maximum standard deviation of air voids per mix was approximately 0.20%. Since the other parameters (VMA and VFA) depended on the air void (AV), only air void-compaction temperature graphs were plotted in Figure 4.1 to Figure 4.3. All volumetric parameters were presented separately in Table 4.1 and Table 4.2 for Marshall and Superpave samples.

4.2.1. Marshall Samples Volumetric

As the AV-CT graphs (Figure 4.1 and Figure 4.2) were examined, clear trends were observed for samples prepared with Marshall Hammer. For all samples, as the compaction temperature increased, the void ratios decreased. In HMA samples, 2% air void decrease was observed between 95-140 °C, whereas this decrease was in the range of 1-1.5% in WMA samples. Depending on these air void variations, it was clear that WMA was less susceptible to temperature changes.

The WMA additives significantly reduced the void ratios at any temperature. Below 140 ° C, Advera samples had lower air voids than Sasobit samples. According to the volumetric results, in this case, the foaming additives contributed to the compaction more than the non-foaming additives. Although the increase in Sasobit dosages did not affect the air voids significantly in compaction, it was seen that high dosage at 95-110 °C causes lower air voids. It was observed that the increase of Sasobit at low temperatures increased the compaction, and at high temperatures (125-140 °C) the increase of Sasobit decreased the compaction. For Advera, the dosage increment improved compactability a little bit up to 110 °C. At temperatures above 110 °C, Advera samples were not affected by temperature and dosage changes significantly.

According to MDOT specifications, E1 mixtures should meet a minimum 14% for VMA and 65-78% for VFA criteria (MDOT, 2007) and target 4% air void. The target air void achieved at 140 °C in HMA mixtures. With ± 0.5% accuracy WMA mixtures met the target air void at 110 °C (highlighted in Table 4.1). Almost all samples met the VMA and VFA criteria. Volumetric properties indicated that 30 °C less compaction temperature than the conventional compaction temperature could be applied to WMA mixtures.

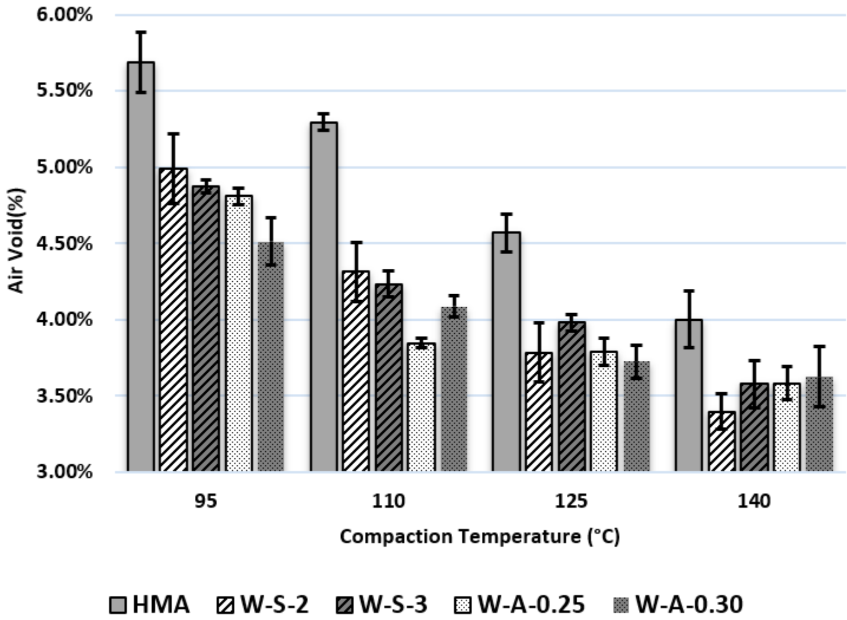


Figure 4.1. Air voids of mixtures with respect to compaction temperature (Marshall)

Table 4.1. *Volumetric results for Marshall Samples (Ozturk & Pamuk 2018)*

Mix. Type	**Additive Content**	**CT (°C)**	**AV (%)**	**VMA (%)**	**VFA (%)**
HMA	NONE	**140**	**4.00**	**17.42**	**77.04**
		125	4.57	17.91	74.49
		110	5.30	18.54	71.43
		95	5.69	18.87	69.88
Sasobit	2% by weight of binder	140	3.40	16.90	79.90
		125	3.79	17.24	78.04
		110	**4.31**	**17.69**	**75.62**
		95	4.99	18.27	72.70
Sasobit	3% by weight of binder	140	3.58	17.06	79.02
		125	3.98	17.40	77.13
		110	**4.23**	**17.62**	**75.98**
		95	4.87	18.17	73.18
Advera	0.25 % by weight of mix	140	3.58	17.06	79.01
		125	3.79	17.24	78.02
		110	**3.85**	**17.29**	**77.75**
		95	4.81	18.12	73.45
Advera	0.30 % by weight of mix	140	3.63	17.10	78.80
		125	3.73	17.18	78.32
		110	**4.09**	**17.49**	**76.64**
		95	4.51	17.86	74.75

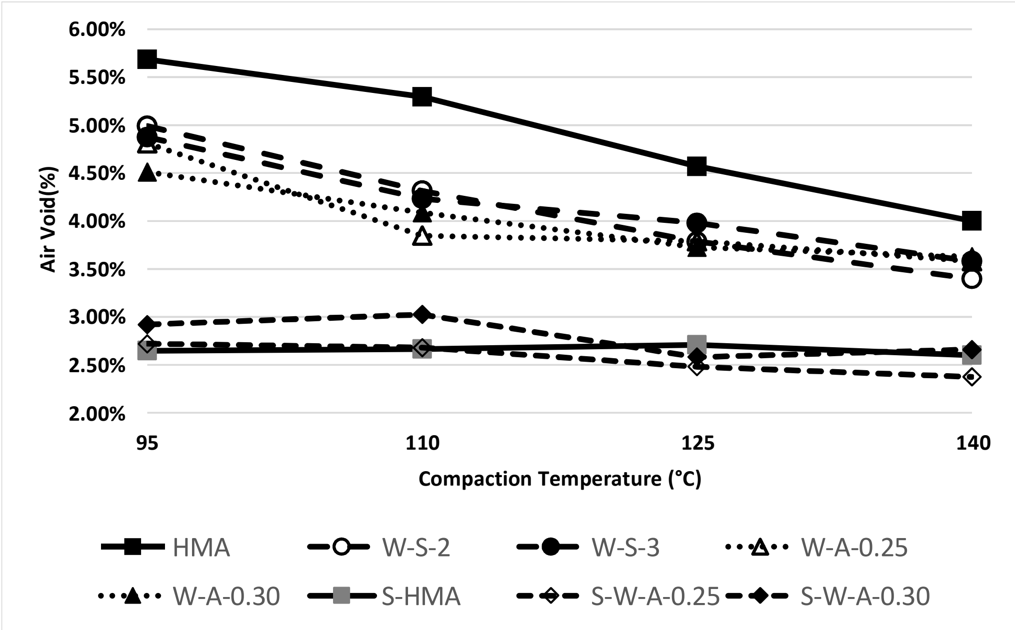


Figure 4.2. Air voids of mixtures with respect to compaction temperature (all types)

4.2.2. Superpave Samples Volumetric

Superpave samples were compacted to N_{max} (117 cycles) value. However, the volumetric properties should be investigated at the N_{des} (76 cycles) compaction level. The air voids at the N_{des} compaction level were calculated from the compaction (densification) curve data and presented in Table 4.2.

As given in AV-CT graph (Figure 4.3), there was no clear trend for Superpave mixtures with respect to temperature. For all Superpave mixtures, air voids changed in the range of ±%0.65. This revealed the fact that compaction with a gyratory compactor is insensitive to temperature changes. As presented in Figure 4.2, in which Marshall and Superpave mixtures were presented together, the decrease in the air voids with respect to increase in compaction temperature was clear in Marshall samples, though Superpave samples were not affected by temperature change. For HMA samples there was only air void variation in the range of %0.10 by the compaction temperature change (Figure 4.3). Above the 110 °C by the effect of additive WMA samples compacted slightly better (0.4% less air void low temperatures) than HMA samples. Although the increase in Advera dosages decreases compactability (Figure 4.3), this change is not significant within the standard deviations of the samples. Dosage increase in Superpave samples had a neglectable effect on void ratios. According to Figure 4.2, all Superpave samples compacted more than Marshall Samples (more than 1% low air voids). Due to this extreme compaction, VFA criteria for all Superpave samples had exceeded the limits. The extreme compaction was and the applied high-pressure during the gyratory compaction. Because of this high compressive strength, the mixtures were not affected by temperature and additive change. Eventually, it could be stated that Superpave mixtures were affected by neither the change of compaction temperature nor the additive amount.

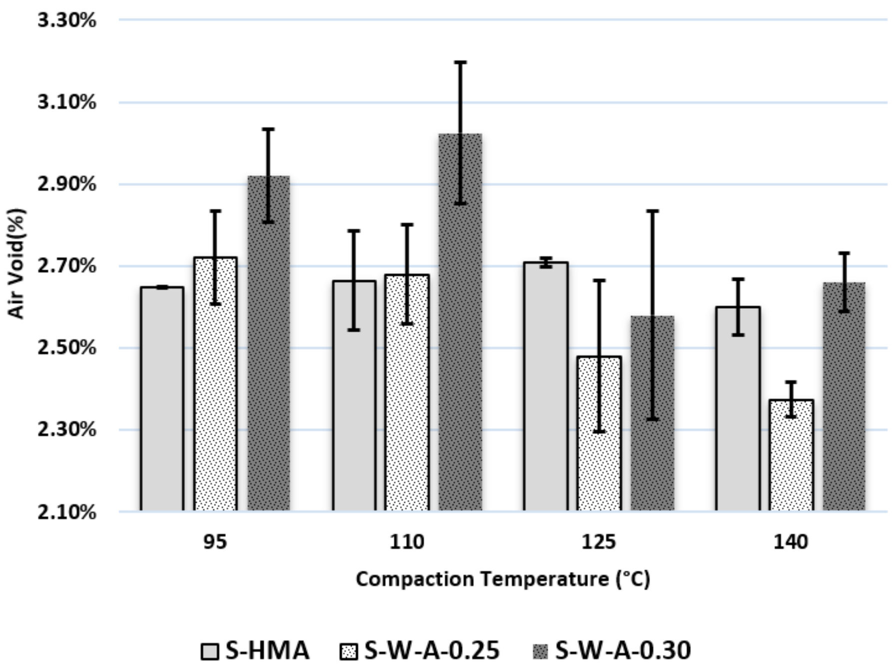


Figure 4.3. Air voids of mixtures with respect to compaction temperature (Superpave)

Table 4.2. *Volumetric results for Superpave Samples (N_{des})*

MİX. Type	Additive Content	CT (°C)	AV (%)	VMA (%)	VFA (%)
HMA	NONE	140	2.60	15.74	83.49
		125	2.71	15.84	82.90
		110	2.66	15.80	83.14
		95	2.65	15.79	83.23
Advera	0.25 % by weight of mix	140	2.37	15.55	84.73
		125	2.48	15.64	84.16
		110	2.68	15.97	83.39
		95	2.72	16.08	83.16
Advera	0.30 % by weight of mix	140	2.66	16.03	83.59
		125	2.58	15.96	83.86
		110	3.02	16.73	79.24
		95	2.92	16.25	82.28

4.3. Marshall Stability and Flow

The effects of WMA additives on Marshall stability were investigated depending on the temperature in order to get indirect estimates on the performance of the different mixtures. Although stability and flow parameters are not sufficient to understand the performance, they reflect the behavior. Therefore, the stability values should be high enough for the traffic loads. The limits according to Asphalt Institute (2014) for stability and flow are 817 kgf (8010 N) and 2-3.5 mm respectively for heavy traffic samples (75 blows). As presented in Table 4.3, stability and the flow values are within the specified limits for all the mixtures.

As mentioned before two out of four replicates were subjected to stability test. The results are presented in Figure 4.4. According to results, as the compaction temperature decreases, the stability of the samples decreases, and it is related to the AV change. Therefore, stability of the HMA samples at 140 °C is approximately equal to the stability of WMA mixtures compacted at 110 °C. At higher temperatures, WMA stability results are higher than HMA. Besides, %1 increase in Sasobit dosage increase in the stability of mixtures about 10% for all temperatures. However, the increase in the Advera dosage does not affect the stability significantly, but still, the increase is visible. Comparing the types of additives, Sasobit samples have equal or higher stability values than Advera. In addition, the flow values of all samples are within the specified limits.

It can be revealed that WMA performs as good as HMA or better at the same compaction levels (aid voids). Hence, by using WMA, compactions can be done with lower efforts at higher temperatures or productions can be done at lower temperatures.

Table 4.3. *Marshall stability and flow*

	Mix. Type	**CT (°C)**			
		140	**125**	**110**	**95**
Stability (kgf)	HMA	**1020**	1026	906	822
	Sasobit (2 %)	1105	1014	**949**	872
	Sasobit (3 %)	1230	1112	**1001**	989
	Advera (0.25%)	1044	1028	**995**	796
	Advera (0.30%)	1100	1043	**976**	873
Flow (mm)	HMA	**3.40**	3.21	3.14	3.66
	Sasobit (2 %)	3.15	2.97	**3.08**	2.95
	Sasobit (3 %)	2.77	2.90	**2.67**	2.80
	Advera (0.25%)	2.96	2.76	**3.10**	3.14
	Advera (0.30%)	2.85	3.00	**2.73**	3.24

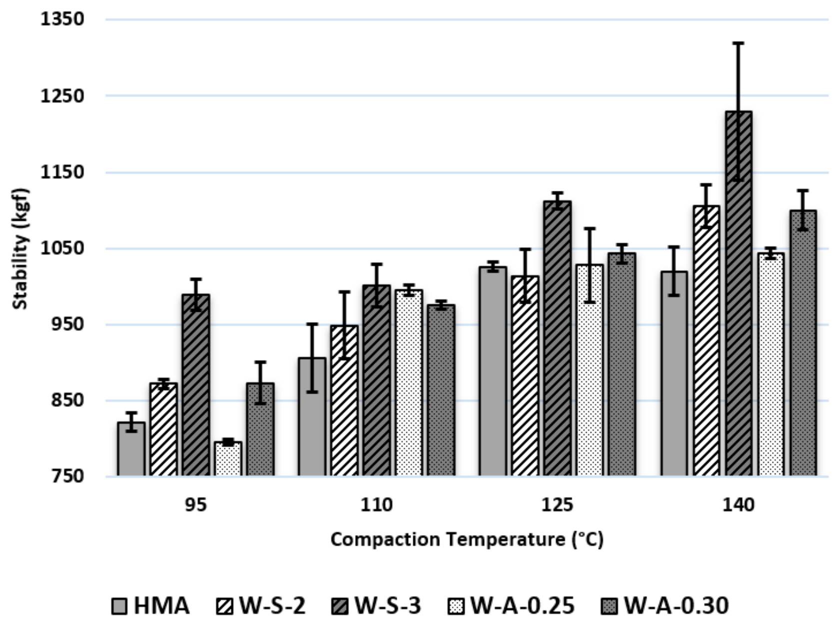


Figure 4.4. Stability-Compaction temperature

4.4. Degradation Analysis

As mentioned in the previous sections, half of the Marshall samples were separated for degradation analysis in order to analyze the influence of compaction temperature change to aggregate breakage. Therefore, the degradation of the samples was examined according to both the compaction temperature and the type of mixture. Degradation results were shared in Figure 4.5. When the results were examined, changes in certain sieve sizes (3/8”, #4, #30, #50, #100, #200 and pan) were observed. However, these variations did not significantly differ according to sample types and compaction temperature, in other words, similar degradation paths were roughly observed for all samples. As expected, in all mixture types, coarse aggregates decreased (+ sign corresponds to decrease) and fine aggregates increased (- sign corresponds to increase). The change in retaining sieves of 1/2", #8 and #16 was less than 0.5%. It could be said that there was no change in these sieve sizes for all samples and could be referred as sample-to-sample variability. It was observed that there was a decrease of 2.5% in retaining 3/8” sieve. Therefore, there was 2% increase in retaining #4 sieve. Considering the degradation of #4 aggregates, it was clear that the aggregates were degraded more than two sieve sizes. Materials in sieve numbers #30 and # 50 showed a reduction of approximately 1% and slightly more than 1%, respectively. Therefore, the amount of finer material increased and there was an approximately 1% increase as a function of total aggregates in No.100, No.200, and pan materials.

It should be noted that no significant change was observed when the degradation was examined with temperature. It was seen that the temperature changes had similar impacts in terms of degradation for all sample types and sieve sizes.

Although there is a weak connection, it could be said that more workable and compactable samples were obtained with the increase of dosages. Therefore, the fracture of coarse aggregates increased with increasing dosage. With the increase in Sasobit dosage, about 1% increment in degradation was observed (Figure 4.5 b to c). Similar results could be driven for Advera, workability, and compactability have increased with the increase in Advera dosage. As expected, more degradation was experienced with dosage increase in all type of additives. Furthermore, Sasobit samples showed about 0.5% more degradation than Advera samples. This shows that Sasobit samples were more workable but also has a negative effect on degradation compare to Advera.

Since the variation in degradation was not significantly different, the results of the analysis indicated that the degradation of HMA and WMA samples were similar. It was concluded that WMA additives did not have adverse effects on the aggregate breakage.

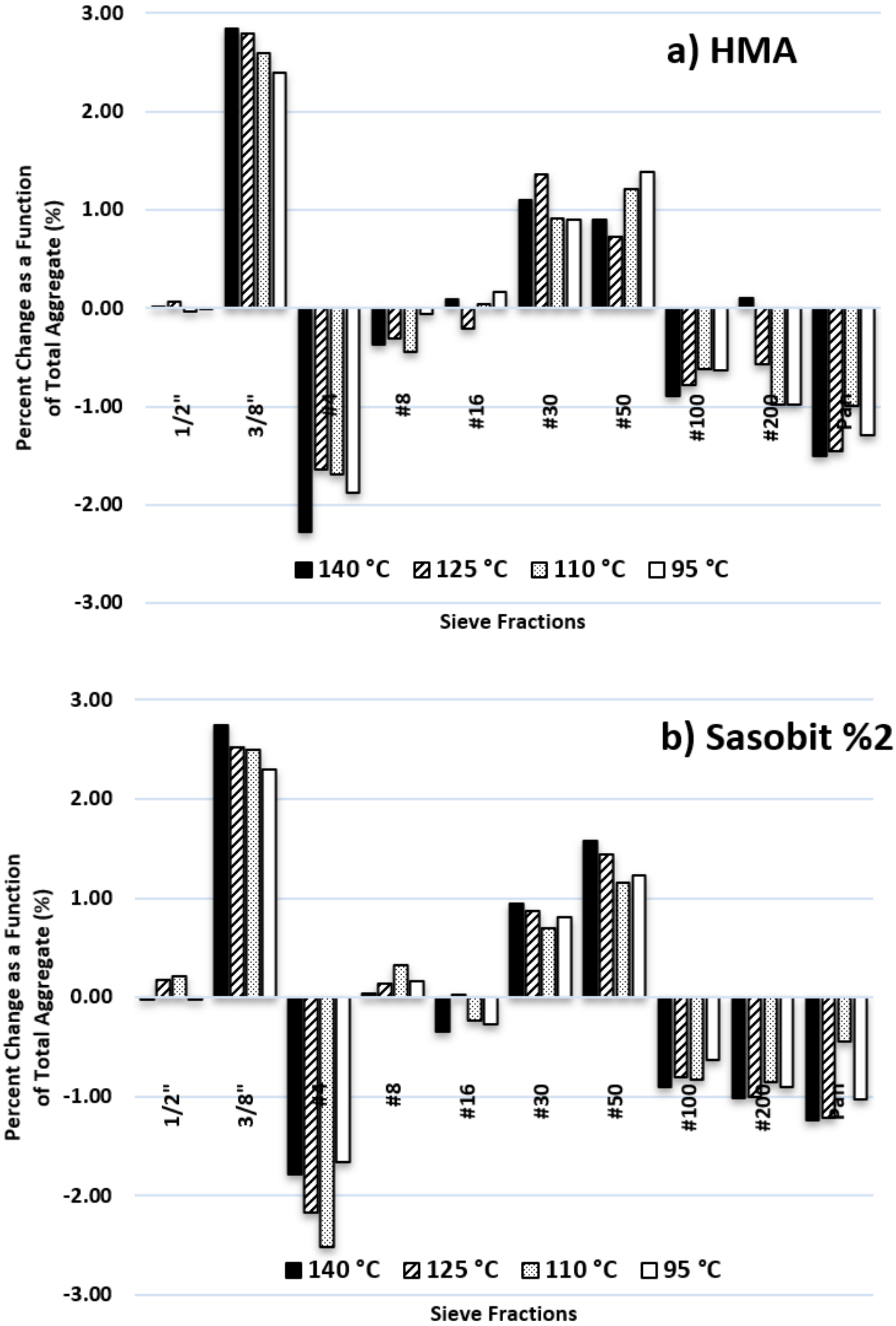


Figure 4.5. Average percentage change of individual aggregate sizes as a function of total aggregate percentage a) HMA, b) Sasobit 2%, c) Sasobit 3%, d) Advera 0.25%, e) Advera 0.30% cont.

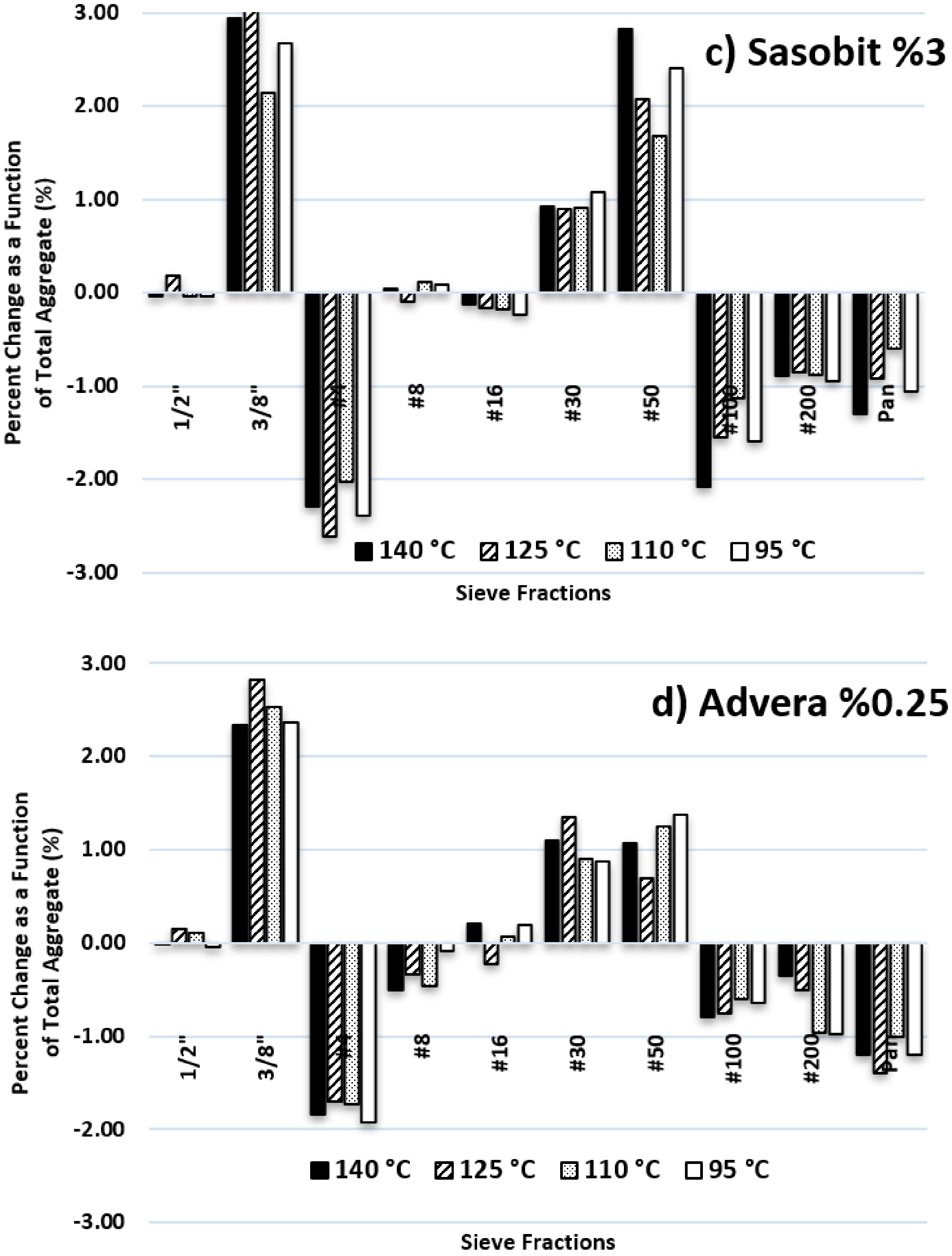


Figure 4.5.. Average percentage change of individual aggregate sizes as a function of total aggregate percentage a) HMA, b) Sasobit 2%, c) Sasobit 3%, d) Advera 0.25%, e) Advera 0.30% cont.

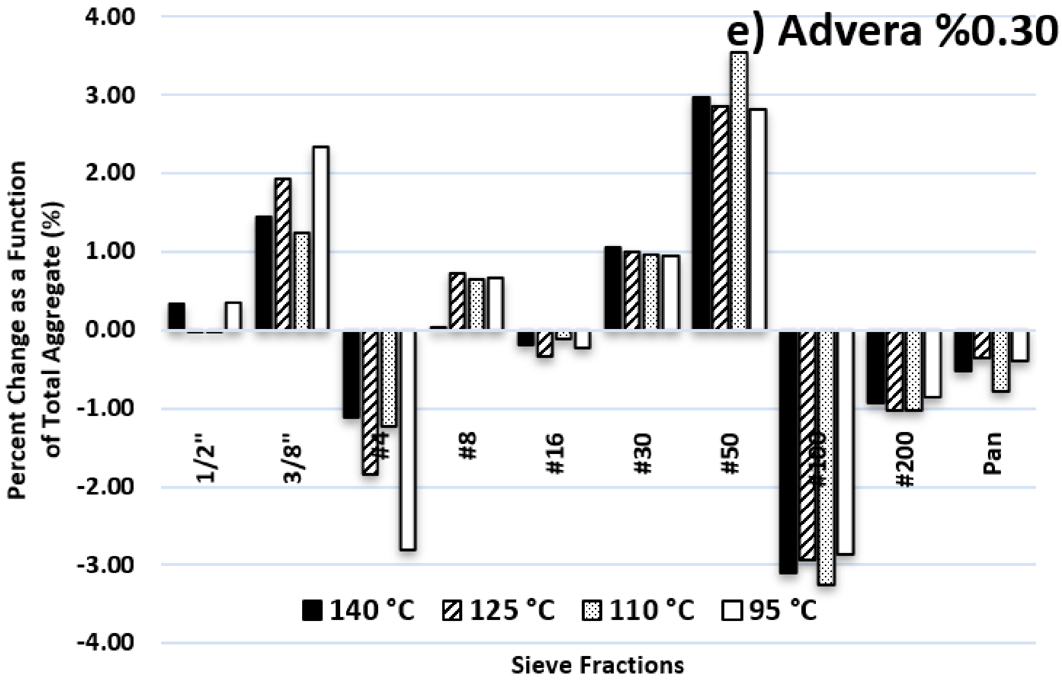


Figure 4.5. Average percentage change of individual aggregate sizes as a function of total aggregate percentage a) HMA, b) Sasobit 2%, c) Sasobit 3%, d) Advera 0.25%, e) Advera 0.30%

4.5. Compactability Analysis

In this study, the effect of WMA additives on compactability was investigated depending on temperature and mixture type utilizing compactability parameters (Number of blows or cycles, CDI, TDI, WEI, CEI and, CR). The parameters were required for analyzing the compactability of different mixtures with respect to temperature, as discussed in section 3.6.4.3. In this section, the results of these parameters were presented according to average values for all samples.

4.5.1. Blow or Cycle Numbers to the Aimed Air Voids

The number of blows/cycles required to achieve certain void ratios gave a perspective on compactability depending on the energy transferred to the system. The number of blows/cycles required achieving 89%, 92%, 96%, 98% of G_{mm}, which were the critical thresholds for compaction parameters, were plotted in Figure 4.6 and Figure 4.7 for

Marshall and Superpave samples, respectively. In order to achieve the same air void level, it was clear that HMA samples needed more compaction effort as compared to WMA samples, which was also revealed in many field studies (Behl et al., 2013; Brian D. Prowell et al., 2007). In addition, as the compaction temperature decreased, the compaction effort increased to meet the desired air void content. However, this statement could not be concluded from the samples compacted by Superpave gyratory compactor. Therefore, the results drawn from Figure 4.7 might be misleading for this study. As observed, the number of gyrations didn't show a significant difference within the samples compacted to the same level at different compaction temperatures. It was also clear that the number of blows versus number of cycles was significantly different due to the energy difference between the compaction methods. Thus, the Marshall samples were separately discussed in the following.

If the findings in Figure 4.6 were handled in detail, at low compaction temperature (95 °C), the influence of Sasobit amount decreased as compaction effort increased. On the other hand, the influence of Advera amount was significantly important at low compaction temperature (95 °C) as the compaction effort increased. At high compaction temperature (140 °C), the influence of the WMA additive type and amount was ignorable when the air void level was less than 4%. Therefore, contractors have also preferred WMA additives for only as compaction aid. In addition, it was possible to fit exponential trend lines to estimate the compaction effort (number of blows) at the desired compaction temperature for the target air void content. In addition, when Marshall samples were examined, HMA mixtures had high standard deviations as compared to WMA mixtures. It could be concluded that WMA additives could aid to provide more reliable production in the field applications.

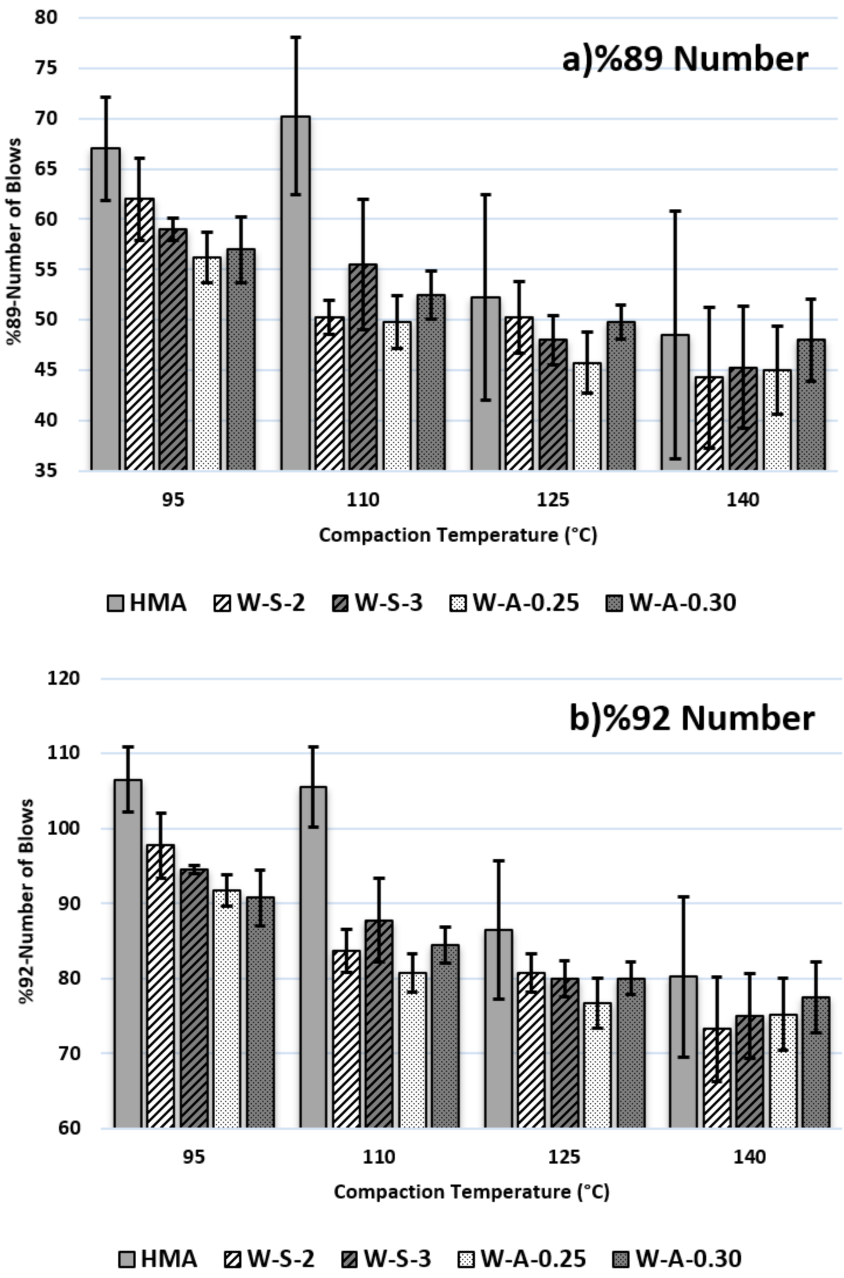
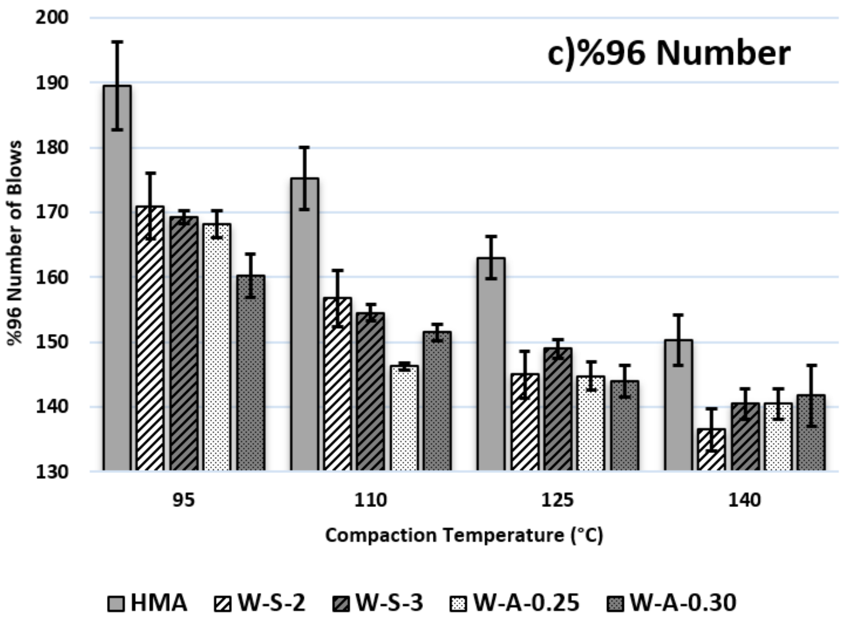


Figure 4.6. Marshall required blow number to the aimed air voids a) 89% number, b) 92% number, c) 96% number, d) 98% number cont.



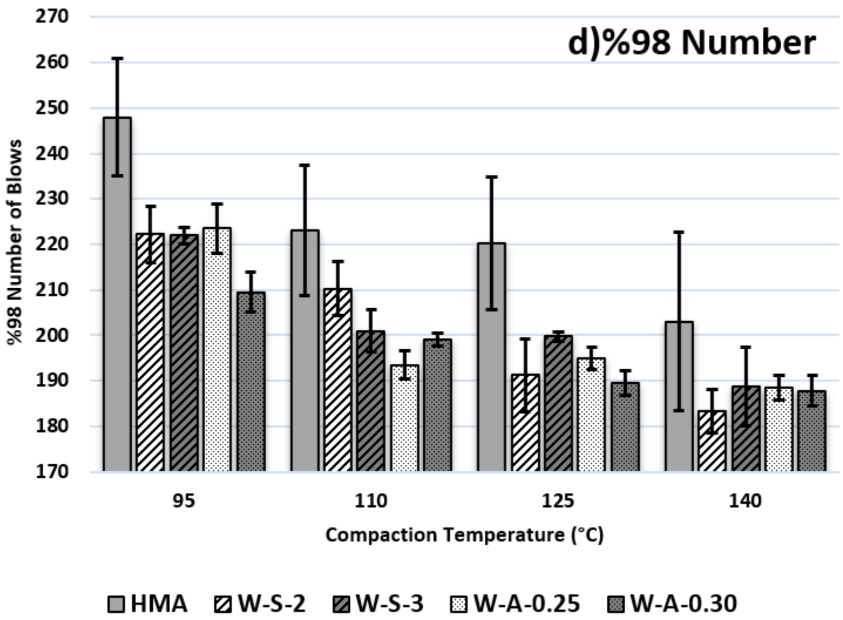


Figure 4.6. Marshall required blow number to the aimed air voids a) 89% number, b) 92% number, c) 96% number, d) 98% number

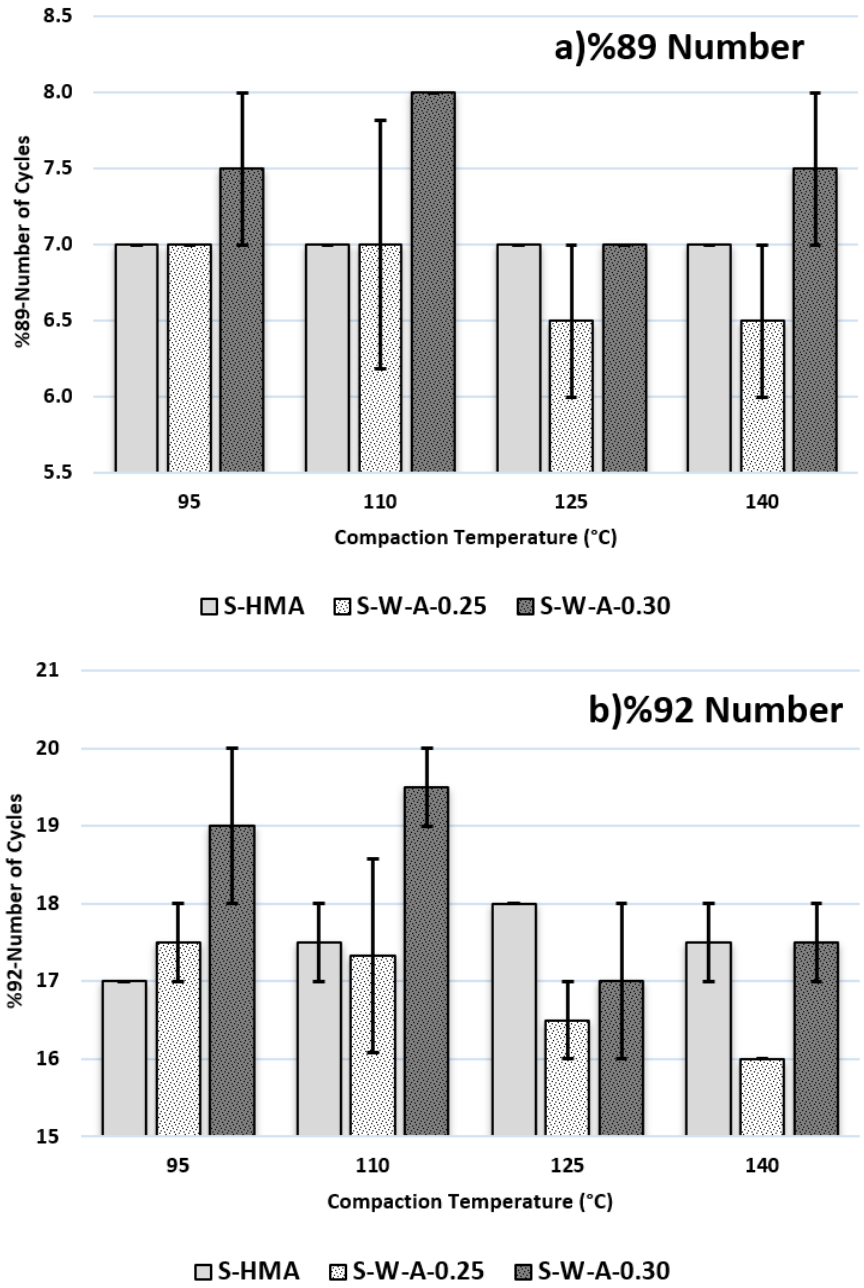


Figure 4.7. Superpave required cycle number to the aimed air voids a) 89% number, b) 92% number, c) 96% number, d) 98% number cont.

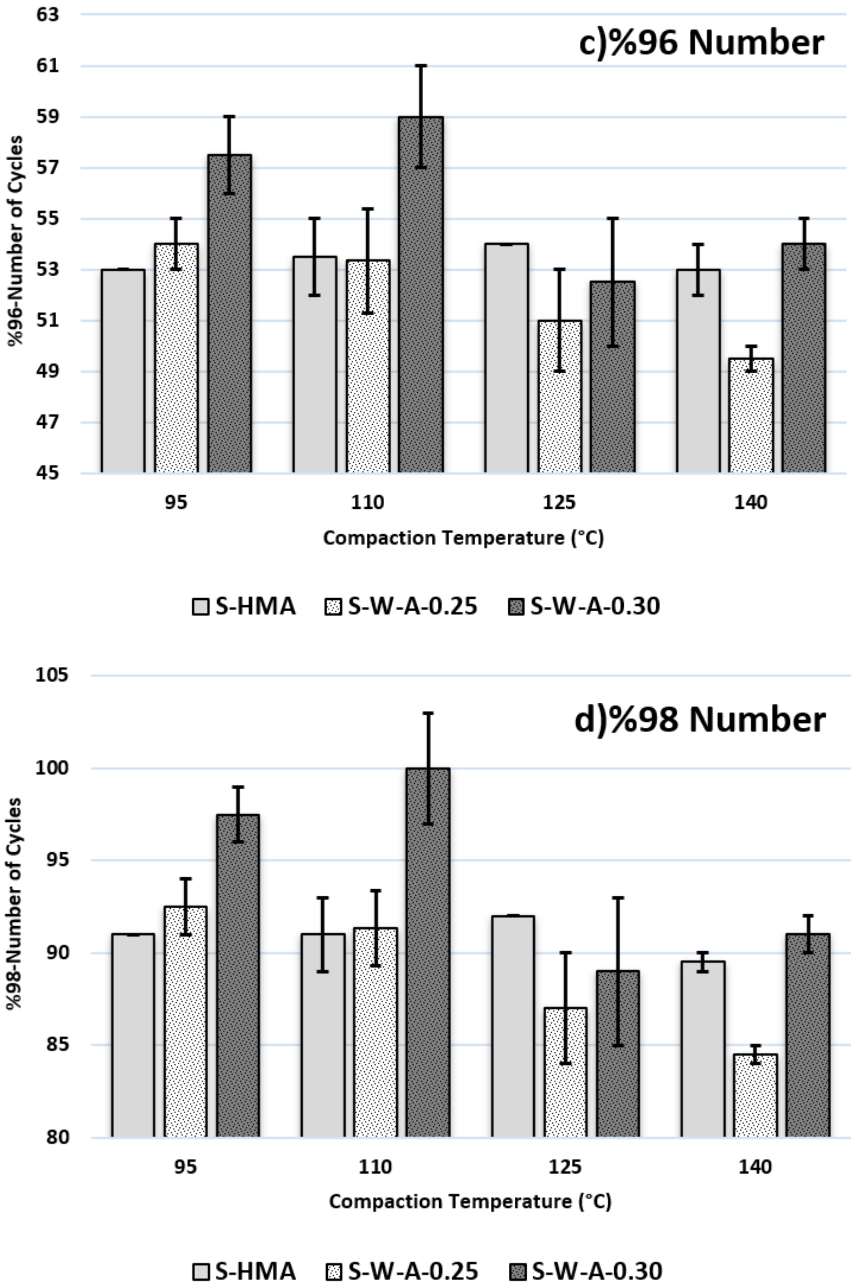


Figure 4.7. Superpave required cycle number to the aimed air voids a) 89% number, b) 92% number, c) 96% number, d) 98% number

4.5.2. Traffic and Compaction/Construction Densification Index

Densification indices represent the construction effort during laying down and compaction due to traffic loads during the life cycle of the pavement. Since these parameters are calculated from the areas under the densification curves, they are unitless. Since the blow and gyration numbers significantly differed for target air void levels, the difference in the magnitude of these parameters (TDI and CDI) was about four times. Therefore, these parameters were presented separately in the following.

CDI indicates the area under the densification curve in between 89% to 92% of G_{mm}. Low values indicated susceptibility to compaction. Thus; the low CDI indicated that there was less effort needed between two air voids (11% -8%). In all Marshall samples, WMA samples had CDI values lower than HMA samples (Figure 4.8). On the other hand, this change was only observed at high temperatures for Superpave samples. However, the influence was not statistically significant and thus it could not be generalized. According to CDI data gathered from Marshall samples, WMA was more compactable than HMA, as expected. The decrease in CDI observed by the increase in temperature in Marshall samples, due to the fact, the compactability increased with temperature. In addition, according to Marshall samples, the use of Sasobit at high dosages increased compactability in samples below 125 °C, and the use of Advera at high dosage appeared to increase compactability at all temperatures. At temperatures below 140 °C, Advera samples had lower CDI values than Sasobit. This indicated that Advera performed better than Sasobit in terms of compactability. It should be noted that this statement could not be generalized since WMA behavior depends on various factors (i.e. binder grade, chemical structure, etc.)

TDI indicates the area under the densification curve form 92% Gmm to 98% of Gmm. Thus, low TDI values were calculated as compactability increased, similar to CDI. The decrease in TDI values with the temperature drop in Marshall samples indicated that this parameter is also temperature sensitive (Figure 4.9). Although the TDI values of HMA samples appeared to be higher than WMA samples, the high standard deviations indicated that densification under traffic loading was similar for WMA and

HMA mixtures. It should be noted that WMA samples yield lower standard deviations than HMA samples. This indicated that WMA is more reliable and might increase the construction quality. For Sasobit, the use of additive at low dosage yielded favorable results for TDI. On the other hand, high doses of Advera positively affected TDI. Apart from the dosage effect, both additives had a similar effect on TDI compared to HMA.

Similar to the previous parameters discussed in the initial parts, for Superpave samples, there was no trend for TDI. For instance, no change was observed for HMA samples with respect to compaction temperature change. It could be stated that Advera usage decreased TDI values at high temperatures, though this statement could not be generalized solely analyzing the data from Superpave samples.

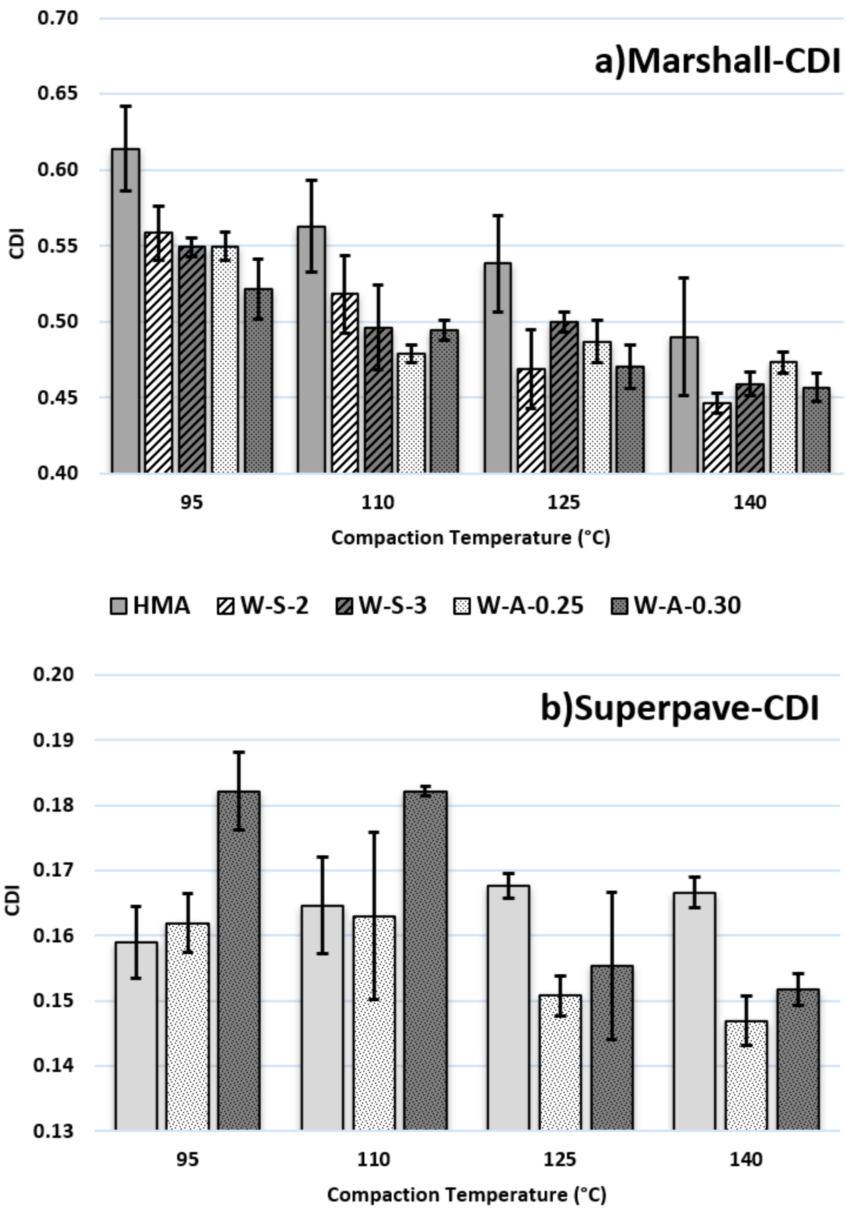


Figure 4.8. Compaction/Construction densification index-Compaction temperature a) Marshall CDI b) Superpave CDI

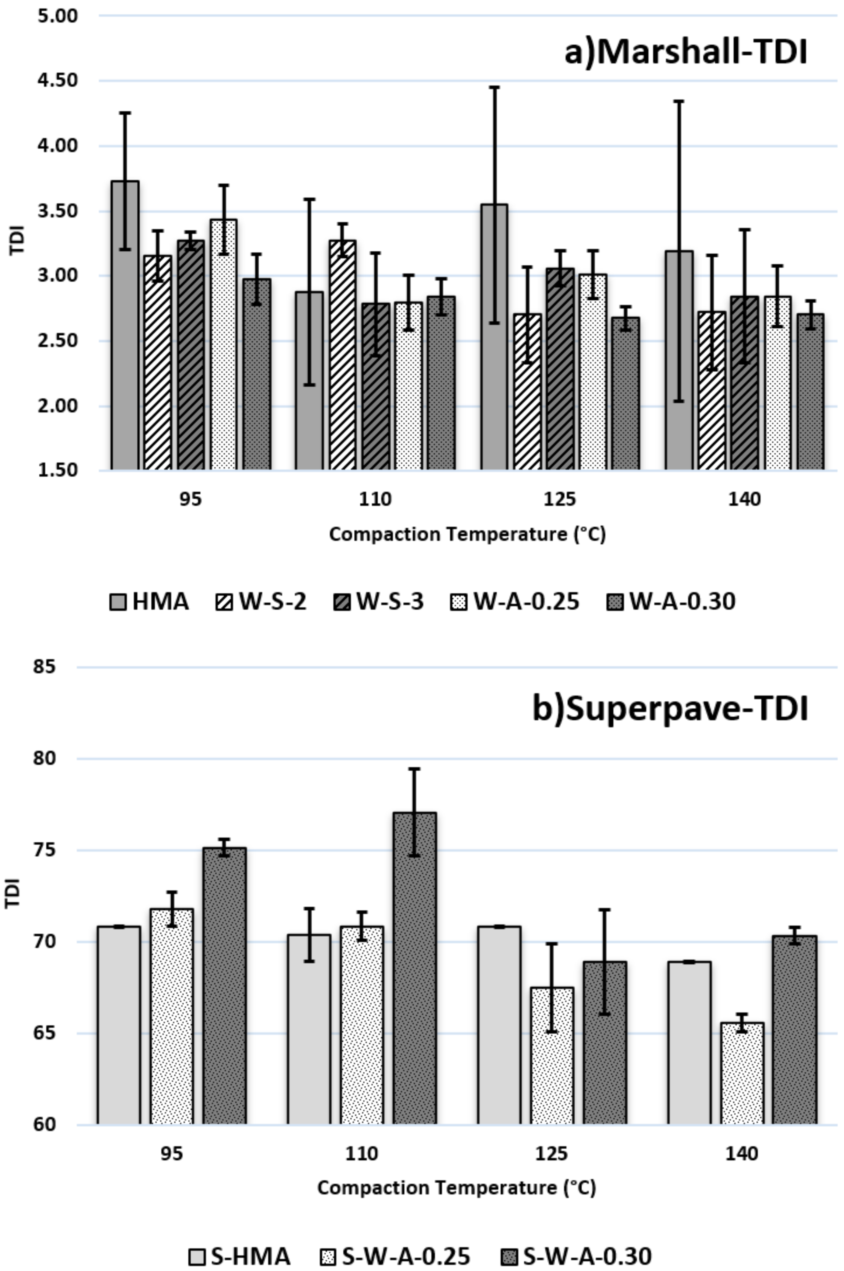


Figure 4.9. Traffic densification index-Compaction temperature a) Marshall TDI, b) Superpave TDI

4.5.3. Workability and Compactability Energy Index

Energy indices refer to the energy needs for compaction per cycle/blow in between desired air void levels. From the start of compaction up to 92% of G_{mm} simulates the workability of the mixture and compaction from 92% of G_{mm} to 96% of G_{mm} simulates the compactability of the mixtures on-site. Hence, rapid compaction (low number of blows or cycles) to desired levels under constant effort resembles high workability or compactability. In all samples prepared with Marshall hammer, it was reapproved that WMA increased compactability and workability. It was also concluded that there was no acceptable trend in Superpave samples. When the workability was examined (Figure 4.10), according to Marshall samples, usage of the high dosage of both additives minorly improved the workability. However, the influence of WMA additives on workability was clear when compared to HMA mixtures, approximately 20% more. On the other hand, according to HMA samples prepared with Superpave gyratory compactor, workability was not affected by temperature change. Besides, the content increase in WMA additive had an adverse effect on low temperatures (95-110 °C), in which this conclusion incompatible with reality.

When the compactability was examined in Figure 4.11, the rise in Sasobit dosage is seen to be increased the compactability of mixture at 110 °C. Advera also has minor increases in compactability with the dosage increment. As with workability, the results of the Superpave are not reliable.According to the energy parameters and Marshall samples, it could be concluded that Sasobit samples were more compactable than Advera samples at high temperatures (140 °C). However, Advera performed better at low temperatures (below 140 °C).

In summary, Marshall samples indicated its sensitivity to temperature and additive changes. As expected, workability and compactability increased with increasing temperature and dosage of additives according to energy parameters.

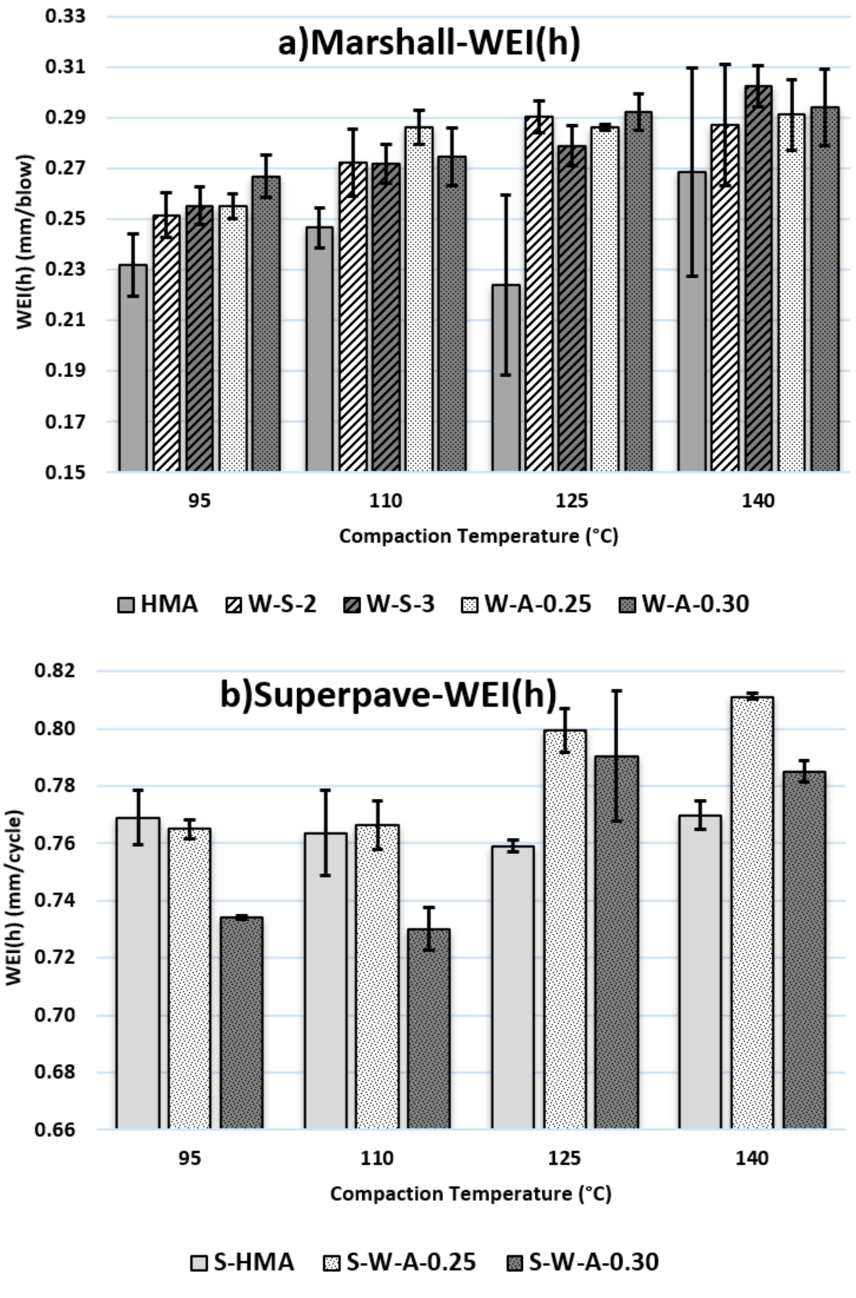


Figure 4.10. Modified workability energy index-Compaction temperature a) Marshall WEI(h), b) Superpave WEI(h)

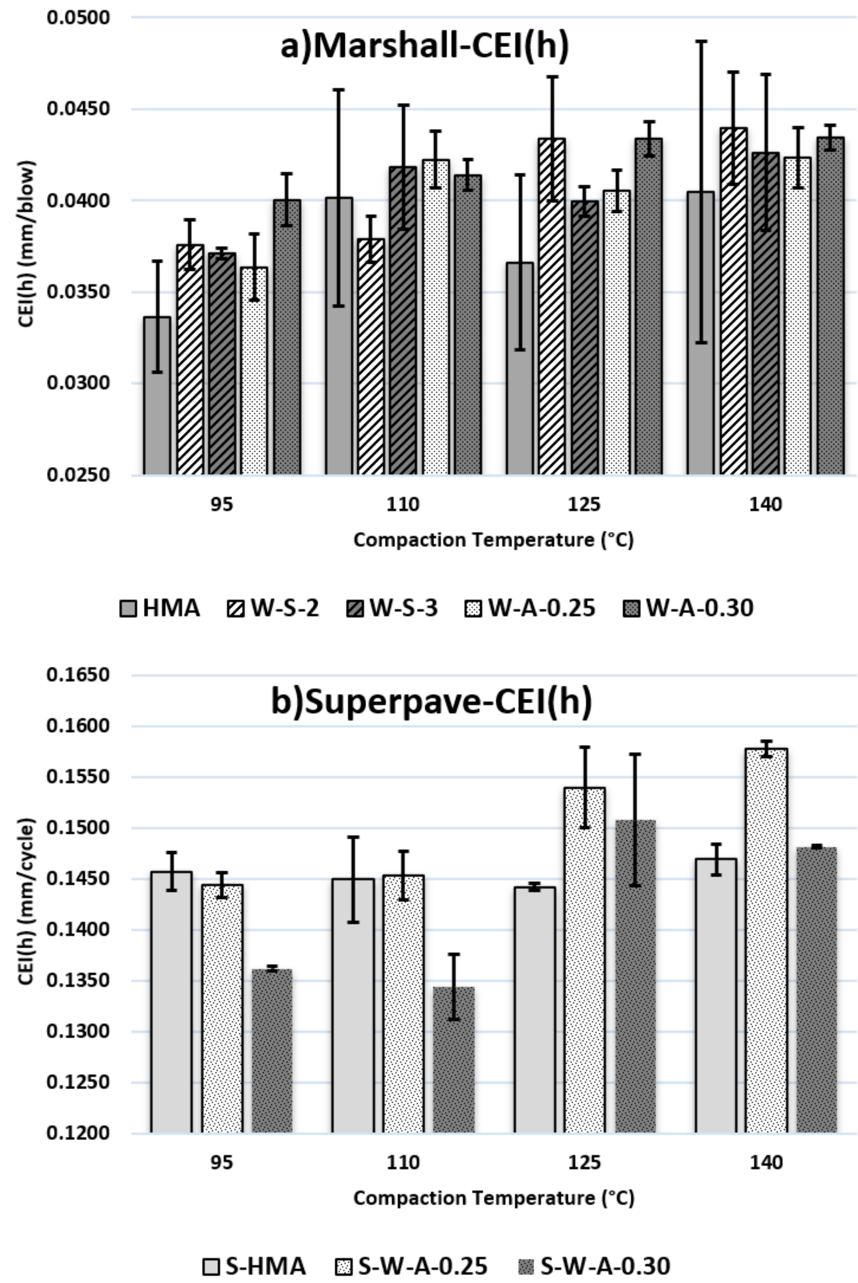


Figure 4.11. Modified compactability energy index-Compaction temperature a) Marshall CEI(h), b) Superpave CEI(h)

4.5.4. Compactability Ratio

The compactability ratio of the samples was calculated according to the types of additives (Figure 4.12). According to the NCHRP Report 673 and 691 (Advanced Asphalt Technologies, 2011; Bonaquist, 2011), mixtures with a compactability ratio below 1.25 are referred as compactable. When the results were examined, only Marshall HMA sample could not be defined as compactable. According to samples prepared by Marshall hammer, WMA additives increased the compactability and made the samples more compactable. Accordingly, samples prepared by Advera were more compactable than the samples prepared by Sasobit. On the other hand, according to this parameter, the amount of the WMA additive did not significantly indicate the difference in compactability though compactability decreased slightly as the amount of additives increased.

For the samples prepared with a gyratory compactor, the compactability ratio for HMA and WMA mixtures were about 1. Since SPGC was not temperature sensitive and misleading when the field studies were taken into account.

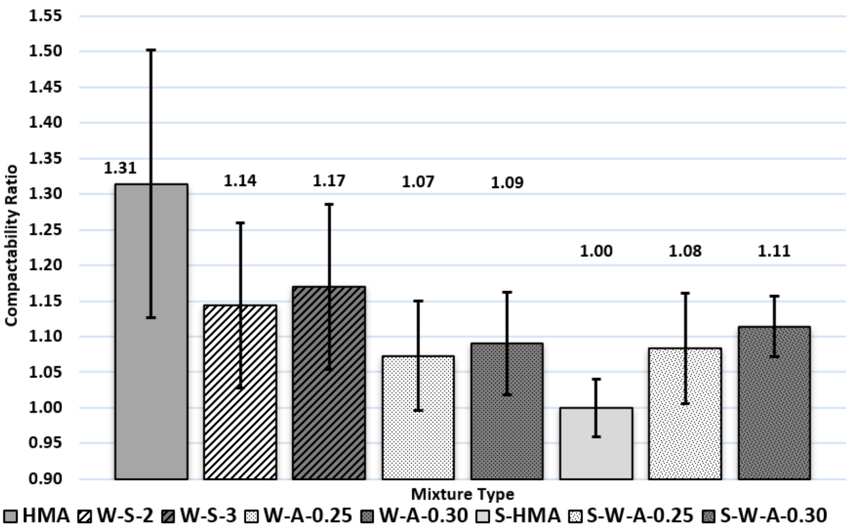


Figure 4.12. Compactability ratio

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary

In this study, the effect of warm mix additives and compaction temperatures on the compactability of mixtures were investigated according to image-based testing procedure developed for Marshall compaction. This study is the first attempt to develop compactability parameters for Marshall compaction. The need for this study emerged from the insensitivity of gyratory compaction to temperature changes. Although SPGC was developed to better represent the field conditions, it is senseless to temperature change. On the other hand, in the current practice, environmental and economic concerns force the pavement industry to lower production and laying temperatures. However, current laboratory approaches are not capable of responding this need. Thus, in this study, compactability was examined depending on compaction temperature, WMA additive type, and amount by utilizing the proposed image-based method. Throughout this study, aggregate origin, gradation, binder, and mixing temperature were kept constant and 104 samples were produced for 5 different mixtures. 80 of these samples were compacted with Marshall Hammer and the rest (24) was prepared with SPGC. Accordingly, the mixtures were analyzed in terms of the change in their volumetric properties, and Marshall stability and flow. In addition, their tendency to degradation was investigated to understand the impact of WMA additives under different compaction temperatures. Finally, compactability of mixtures was studied using the existing or modified versions of parameters (CDI,TDI,WEI,CEI, and compactability ratio) for WMA and HMA mixtures prepared with Marshall and SPGC.

5.2. Conclusion

This study associated many parameters with compactability. Based on the different type of mixtures following major conclusions were drawn:

- As the compaction temperature increased, mixtures were compacted easier. Therefore, air voids decreased by the increase in compaction temperature when compacted with Marshall Hammer. Although this finding reflected the behavior in the field, it was not possible to observe the air void change when compacted with SPGC.

- Between compaction temperature of 95 °C to 140 °C, HMA samples showed 2% decrease in air voids, whereas the air void of WMA samples decreased in the range of 1-1.5%. This indicated that WMA mixtures are less susceptible to compaction temperature changes than HMA mixtures. Therefore, it might be possible to limit the compaction variability in the field with WMA technologies.

- Additives had different effects on the behavior of WMA mixtures. The increase of the Sasobit dosage decreased the air voids at lower compaction temperatures and increased it at higher compaction temperatures (125-140 °C). On the other hand, Advera dosage was effective until 110 °C, beyond this value no significant change was observed by dosage variation. This revealed that the additive selection and optimum dosage depended on many variables (i.e. compaction temperature, mixture properties, field conditions, etc).

- According to volumetric analysis, it was proven that WMA samples could be laid and compacted 30 °C lower than HMA. In addition, this finding was also supported by Marshall stability and flow. It was indicated that pavements constructed with WMA additives at lower temperatures could meet the performance of HMA pavements constructed at traditional temperatures. In another perspective, as indicated in many laboratory and field studies, WMA usage could allow longer haul distances, extension of the construction season and improve working conditions in the field in terms of health and safety without compromising the performance.

- Marshall hammer, as an impact-based compacter, applies a significant amount of energy. In addition, the high compaction temperatures facilitate the ease of compaction and lower the air voids, which might lead the aggregates to break. Therefore, the degradation patterns of HMA and WMA mixtures at all compaction temperatures were analyzed. It was concluded that the patterns are roughly similar for WMA and HMA mixtures independent from the compaction temperature.

- According to Compaction/Construction Densification Index (CDI), WMA mixtures were more compactable than HMA mixtures. On the other hand, according to Traffic Densification Index (TDI), the densification under traffic loading was similar for WMA and HMA mixtures. WMA additive dosage increments minorly affect these parameters, though it could be suggested to optimize the amounts. Marshall samples indicated its sensitivity to temperature and additive changes. As expected, workability and compactability (WEI and CEI) increased with increase in compaction temperature and dosage of additives according to energy parameters. These findings from the parameters calculated from Marshall densification curve met the known field behavior of WMA and HMA mixtures, whereas it was not possible to drive the same conclusions for SPGC.

- Compactibility ratio revealed that determination of the lowest acceptable compaction temperature is critical for successful field applications. The stop temperature at the field for HMA mixtures should be determined carefully.

- WMA additives could be used as compaction aid at traditional temperatures to overcome the problems in the field (i.e. climatic problems, long hauling distance, etc.)

By considering pollution in the world and global warming, environment-friendly construction methods gain importance. WMA additives that reduce carbon footprint with temperature drop have been used in paving engineering for the last two decades. According to this study, WMA additives had a positive effect on the compactability of mixtures while providing a decrease in temperatures.

5.3. Recommendations for Future Work

Although important findings have been obtained in this study, this study can be expanded. Firstly, the findings of this study should be verified in the field. Besides, the performance of mixtures under dynamic loading at high temperatures, the cracking and moisture susceptibilities need to be studied broadly. This study was limited with a single gradation and a binder. Therefore, gradation and binder might be varied.

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APPENDICES

A. Matlab Analysis Steps

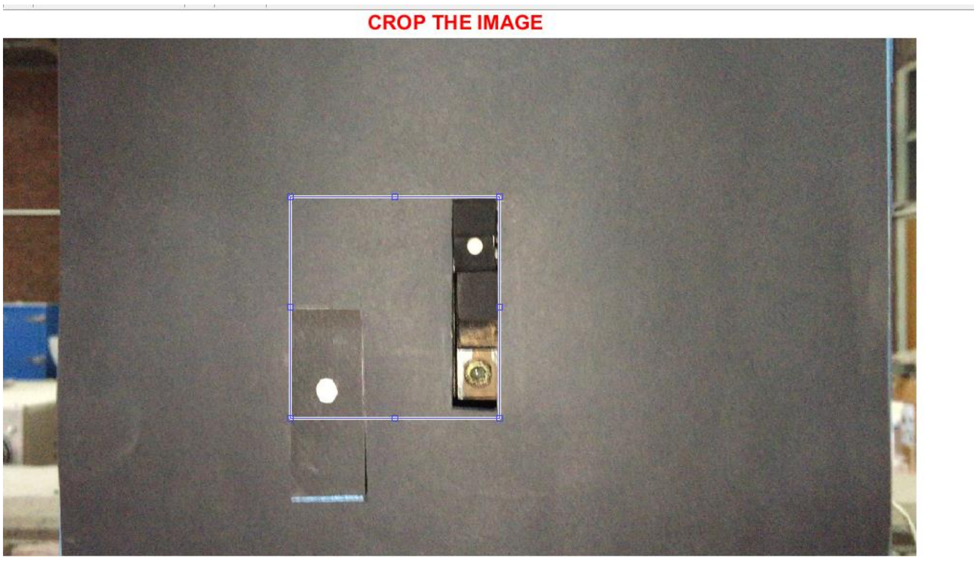


Figure A.1. Determination of the area to be analyzed

Figure A.2. Determination of the frames that corresponds to the blows

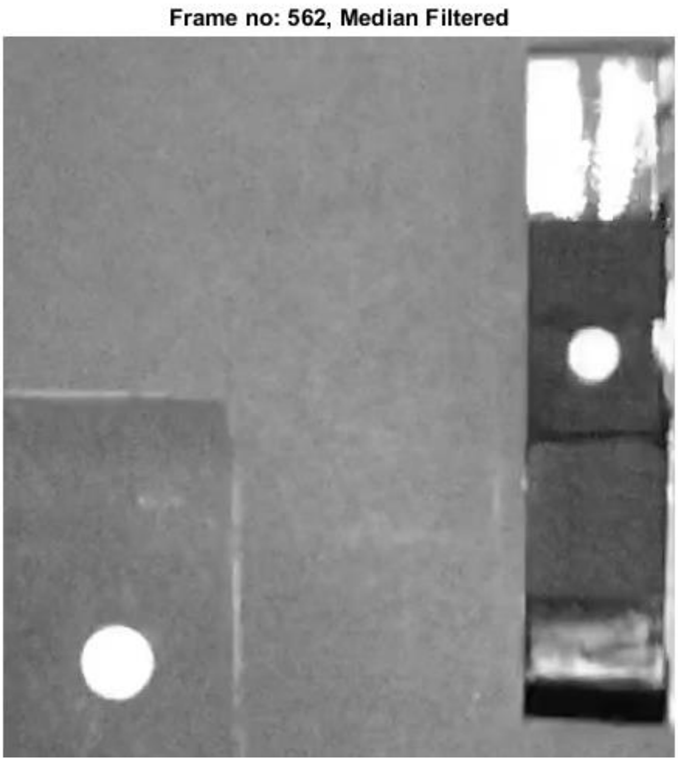


Figure A.3. Observing the extracted video

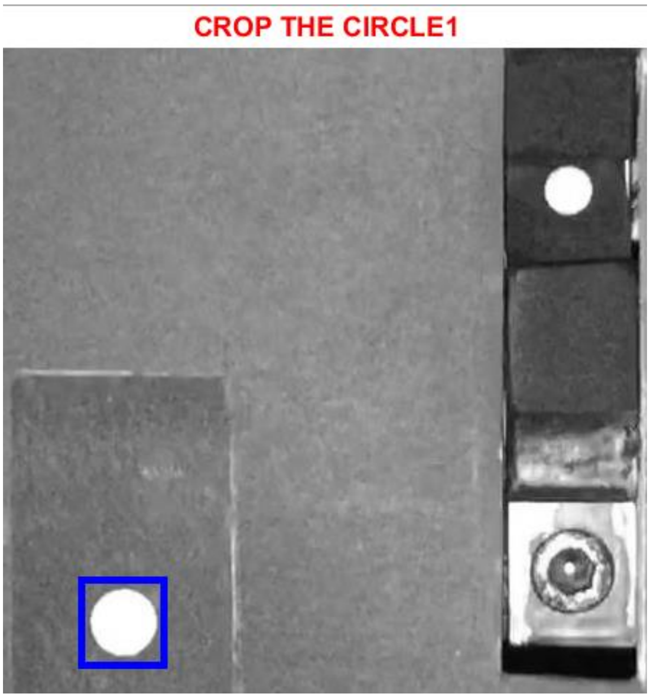


Figure A.4. Selecting first stable circle (bottom left)

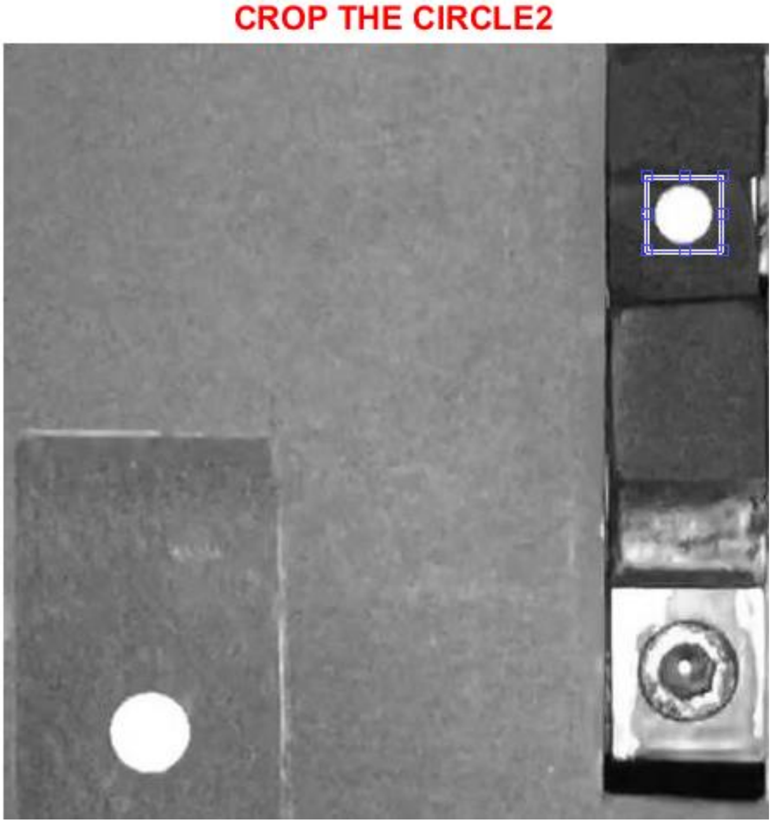


Figure A.5. Selecting second moving circle (up right, on hammer shaft)

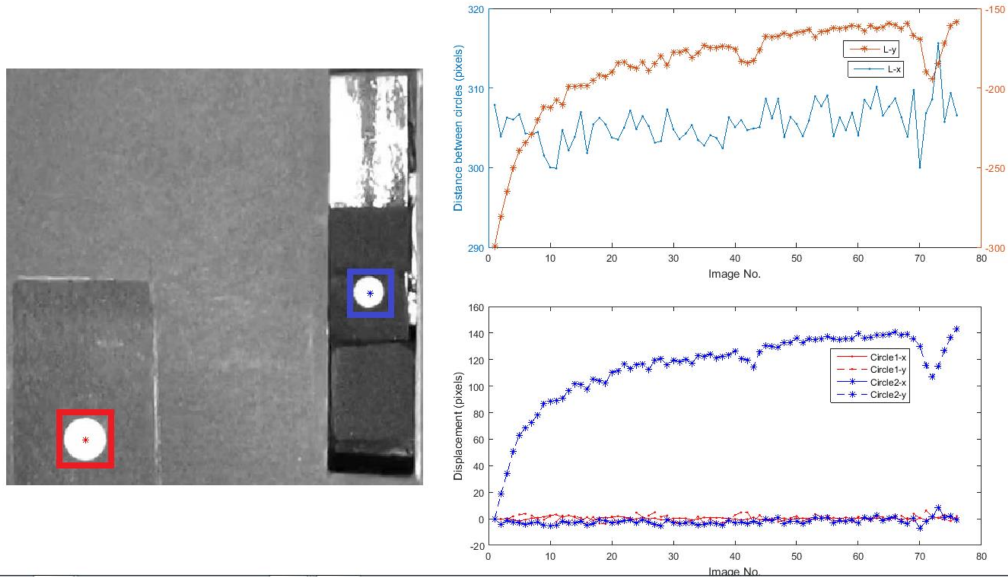


Figure A.6. Observing movement of the second circle in the pixel manner

B. Sample Compaction Heights

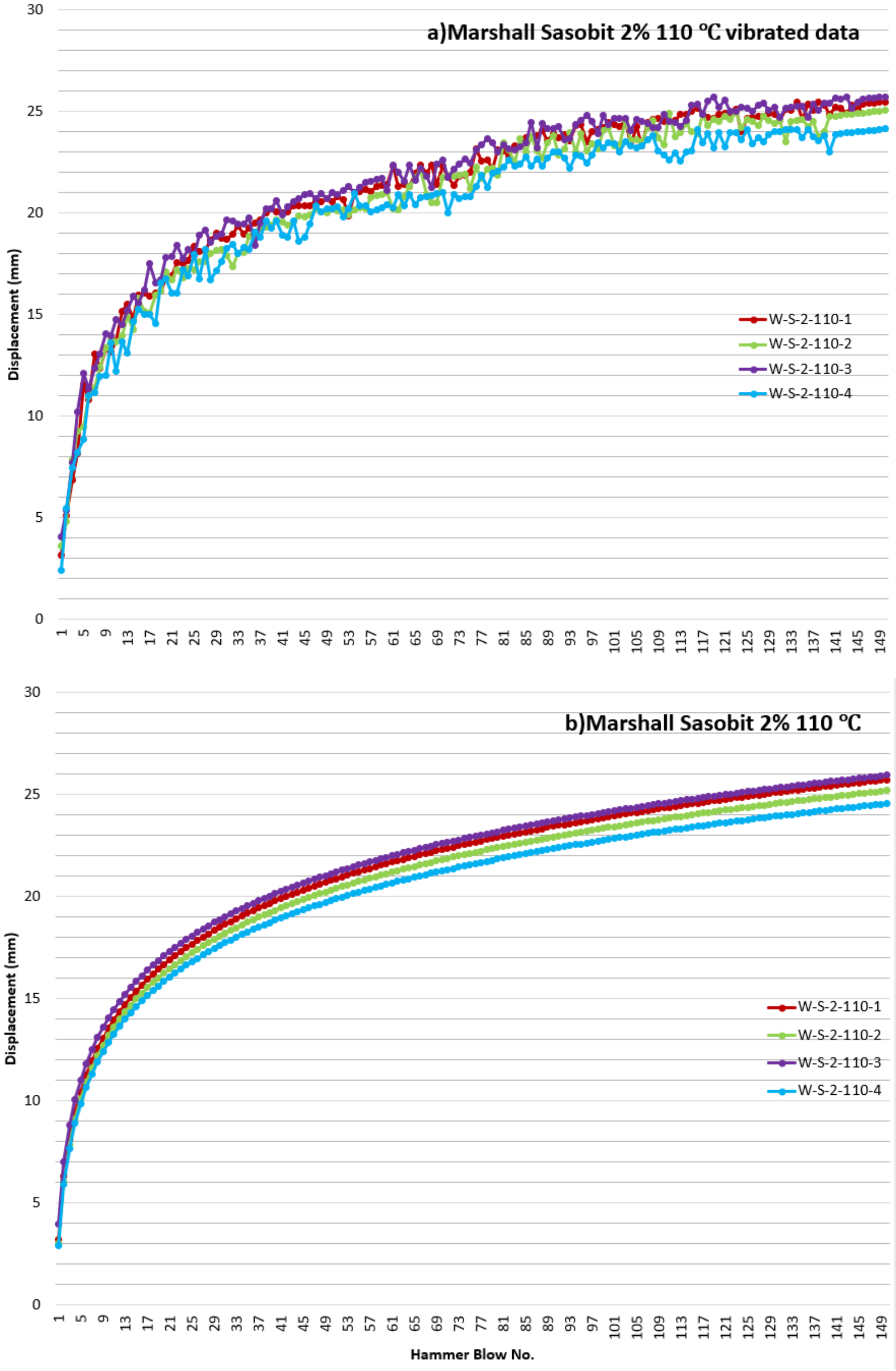


Figure B.1. Example of vibrating and smoothed displacement curves

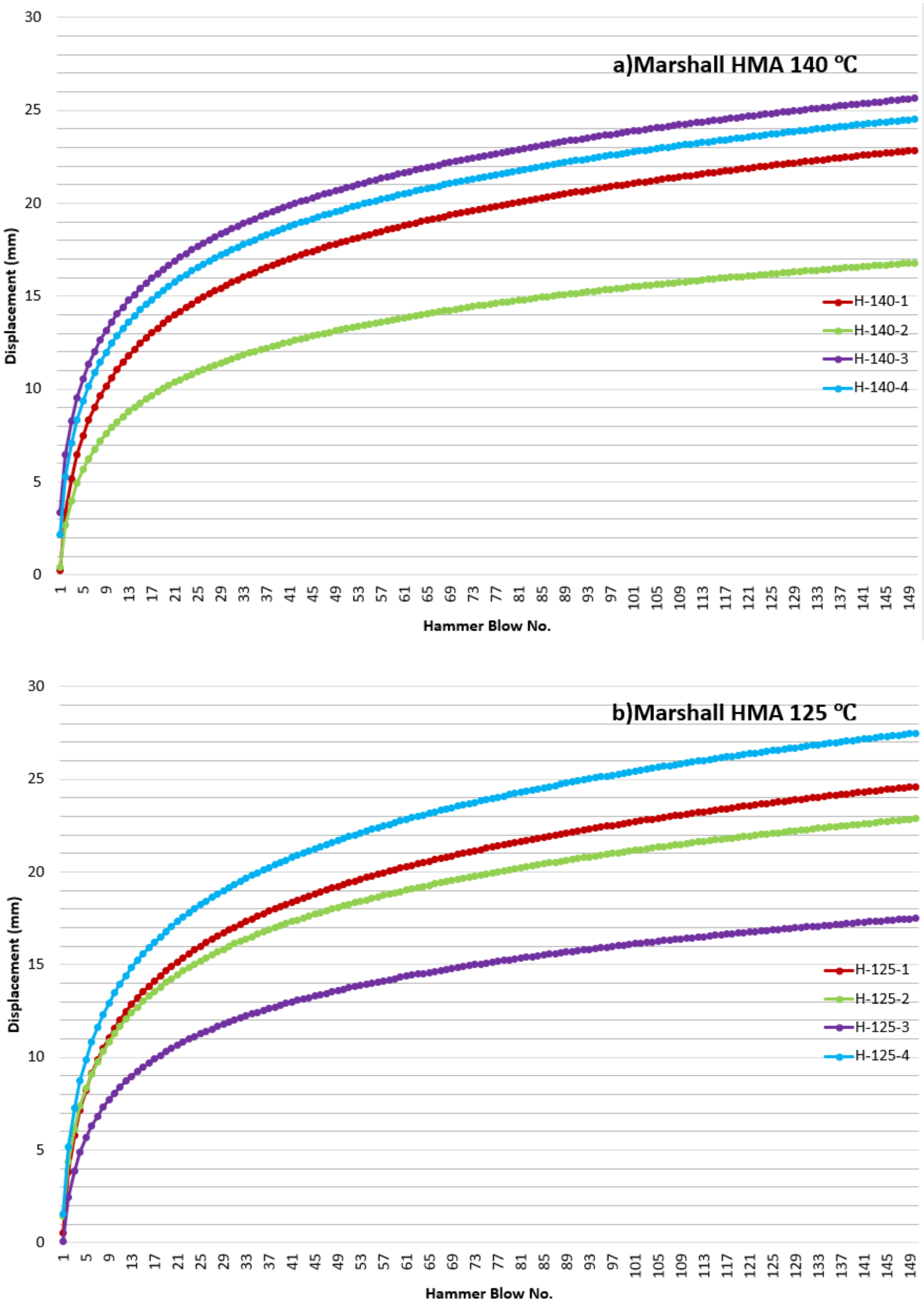
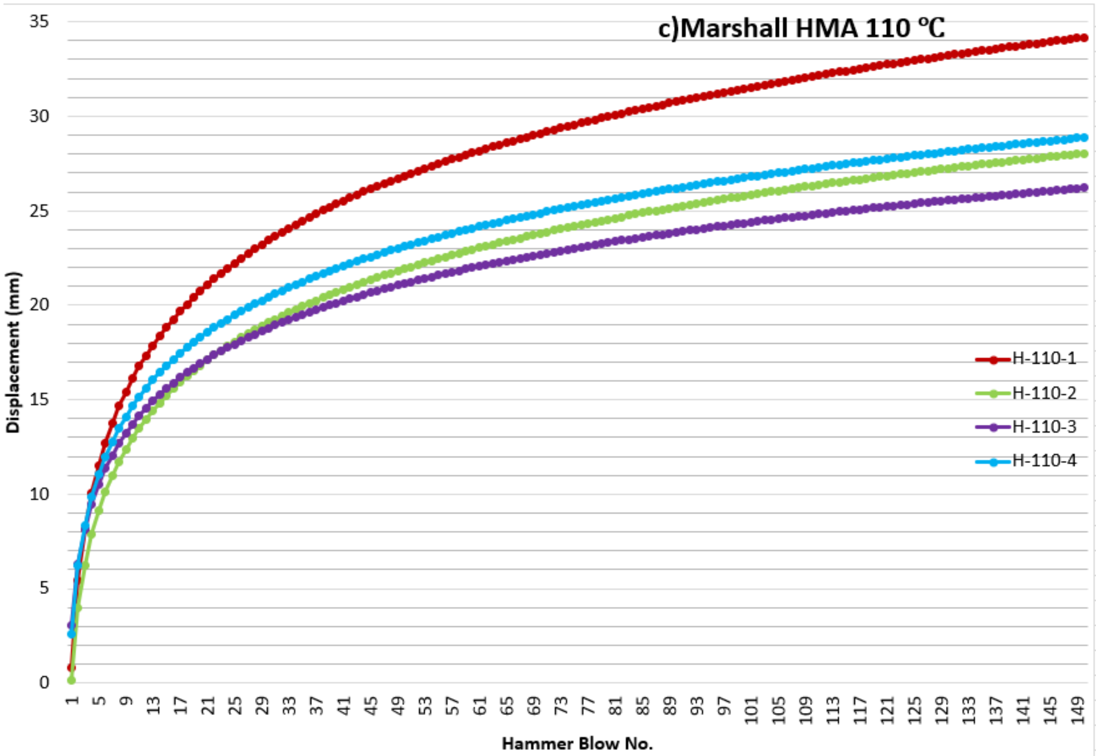


Figure B.2.a/b. *Marshall HMA samples displacements per blow cont.*



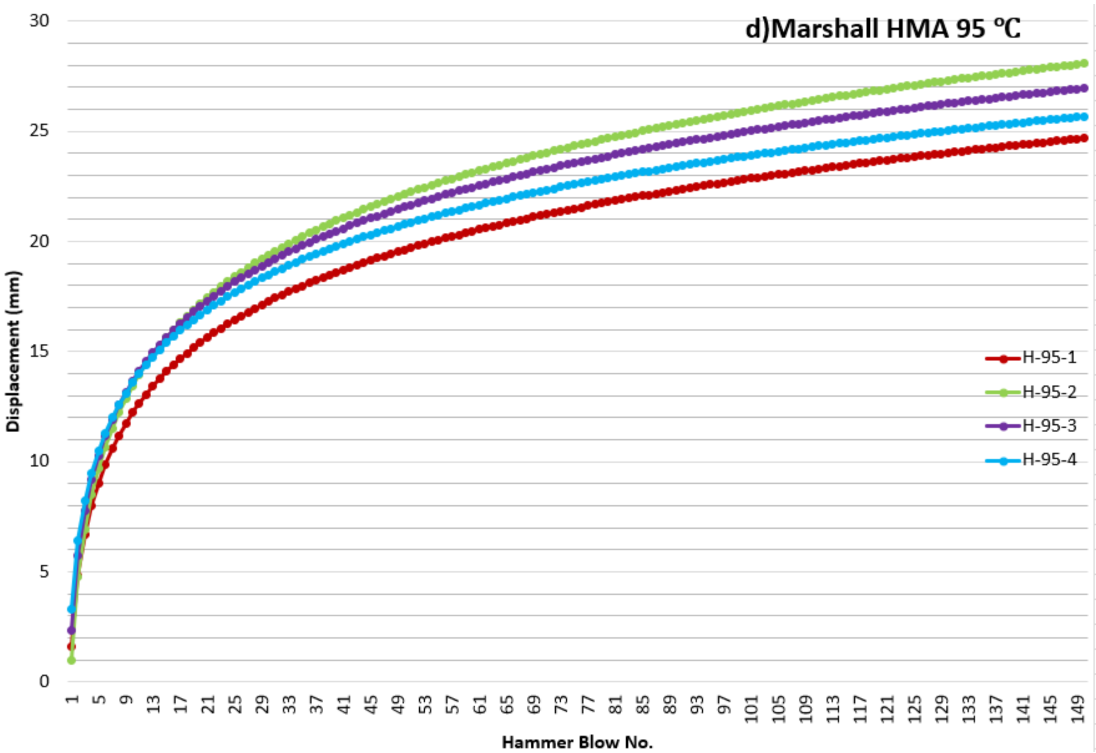
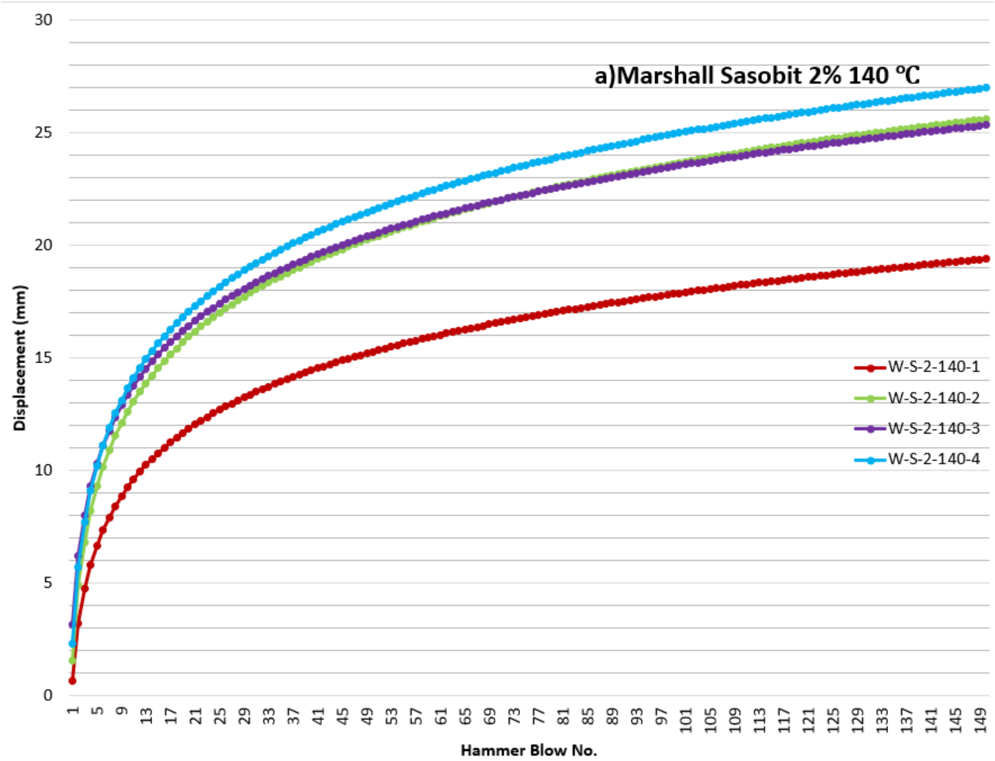


Figure B.2. Marshall HMA samples displacements per blow



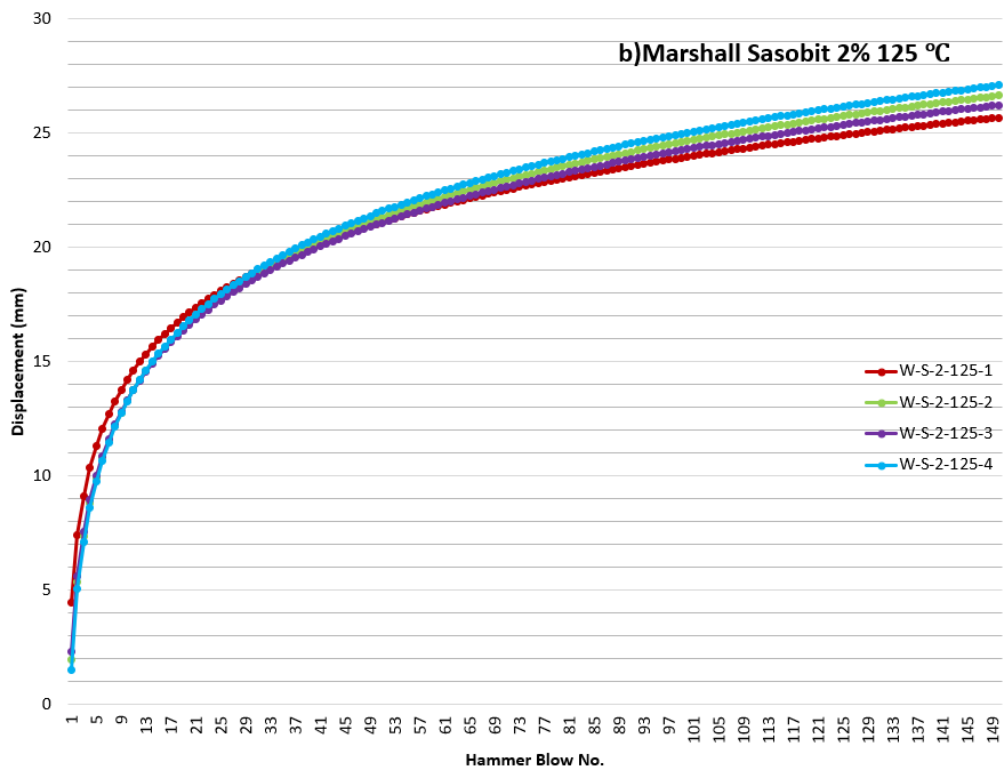
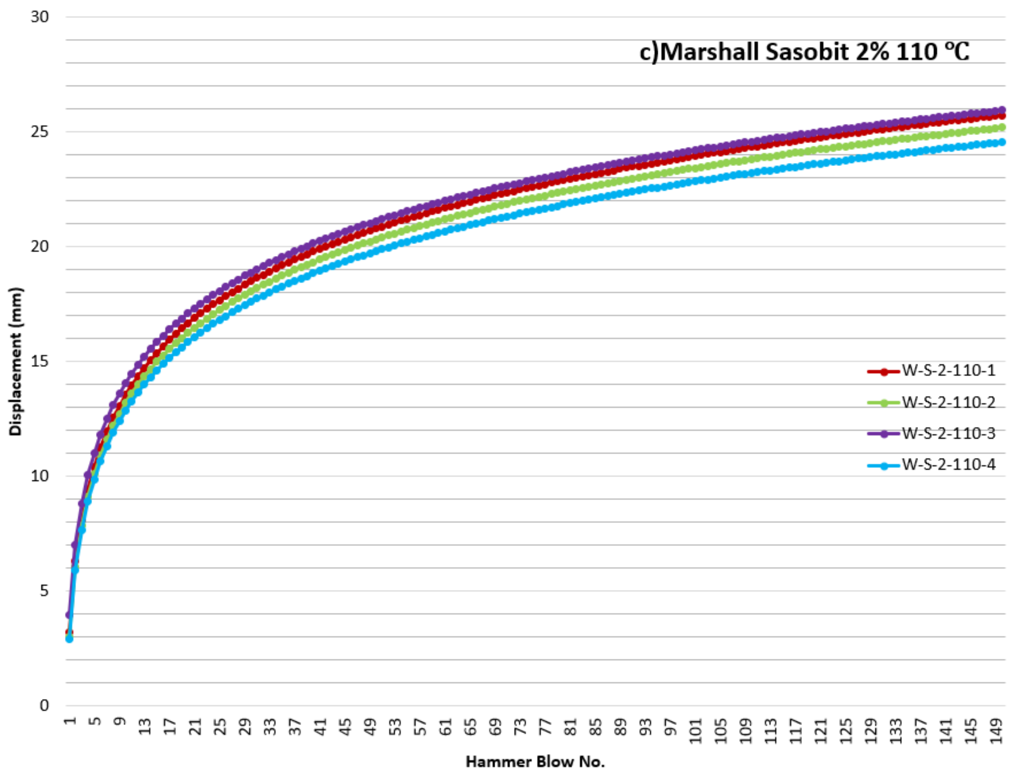


Figure B.3.a/b. *Marshall Sasobit 2% samples displacements per blow cont.*



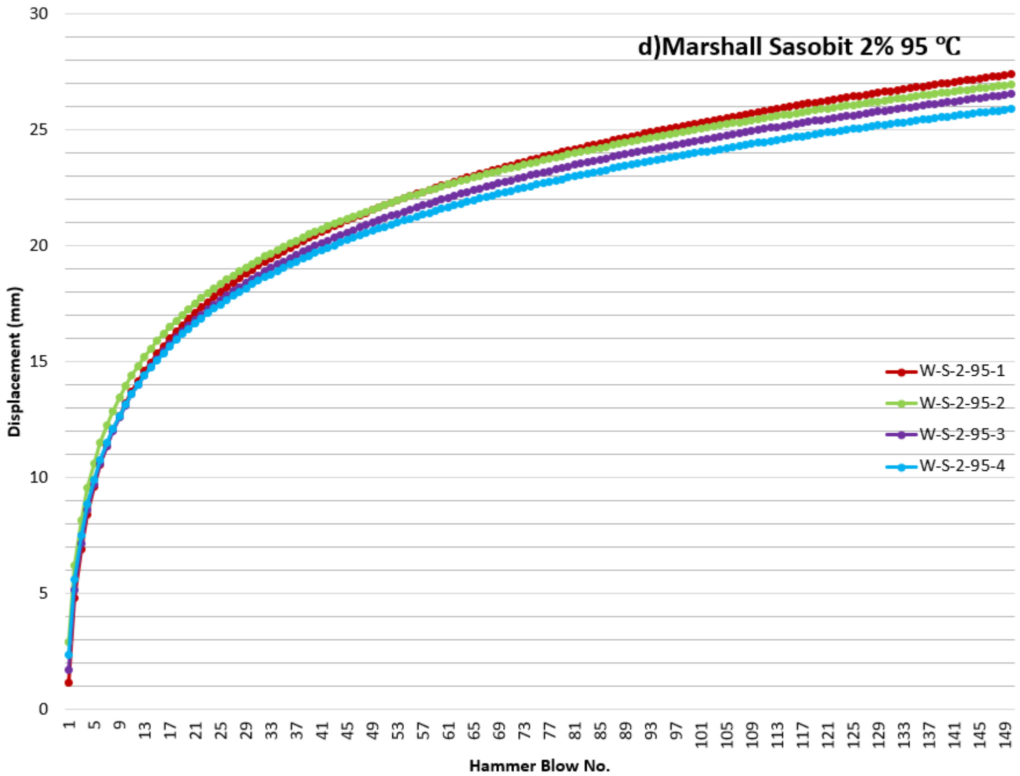


Figure B.3. Marshall Sasobit 2% samples displacements per blow

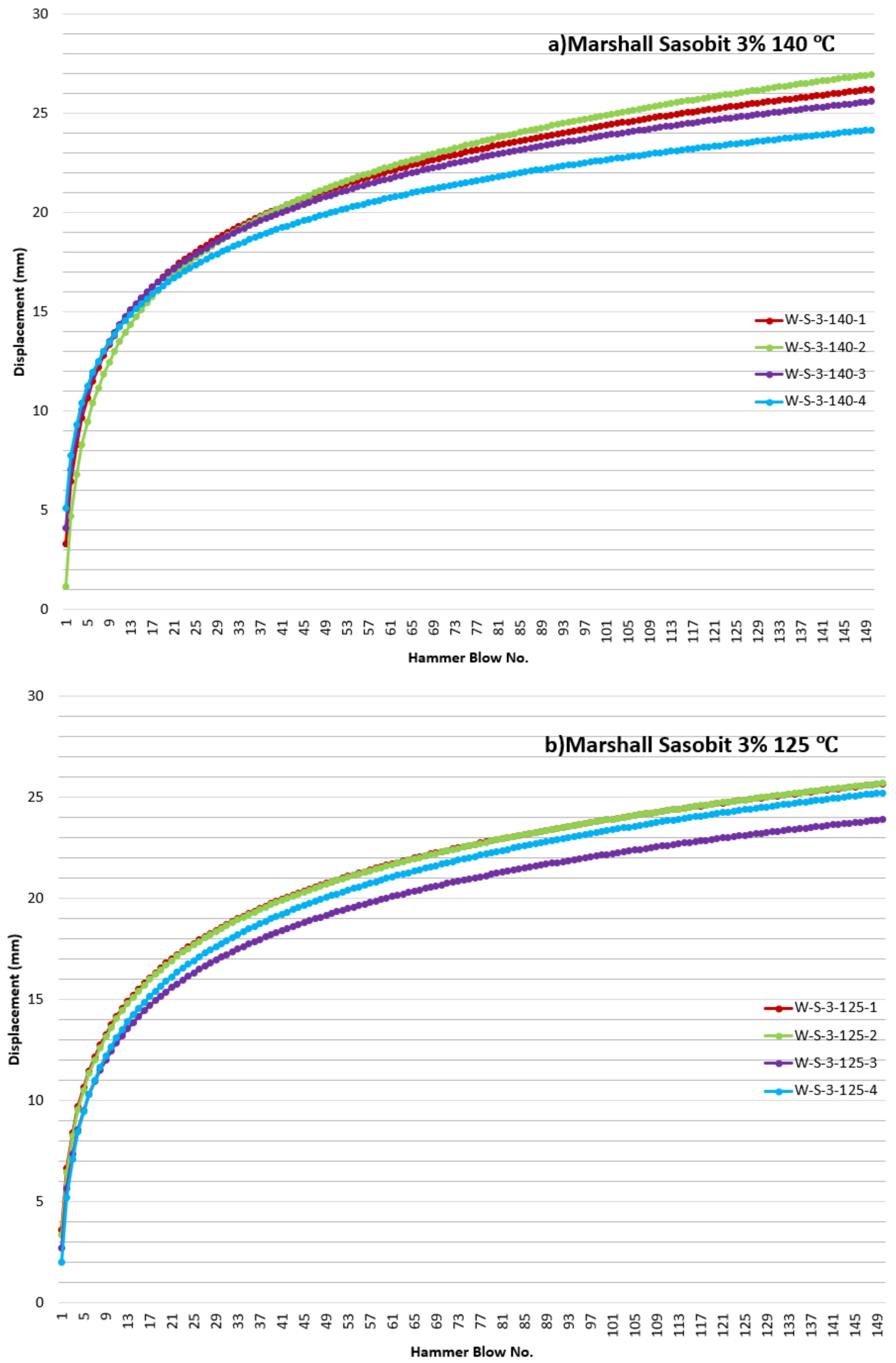


Figure B.4.a/b *Marshall Sasobit 3% samples displacements per blow cont.*

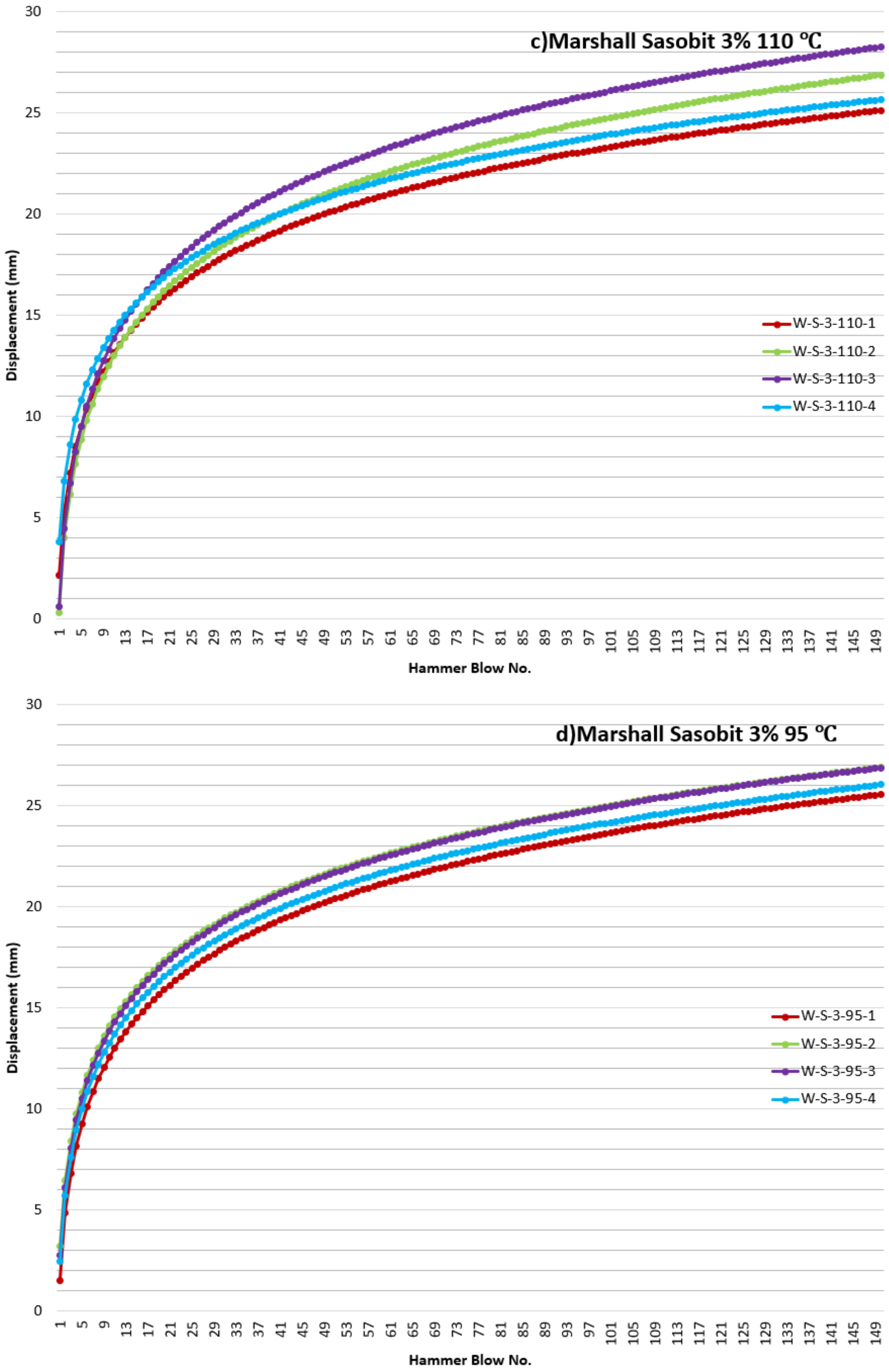
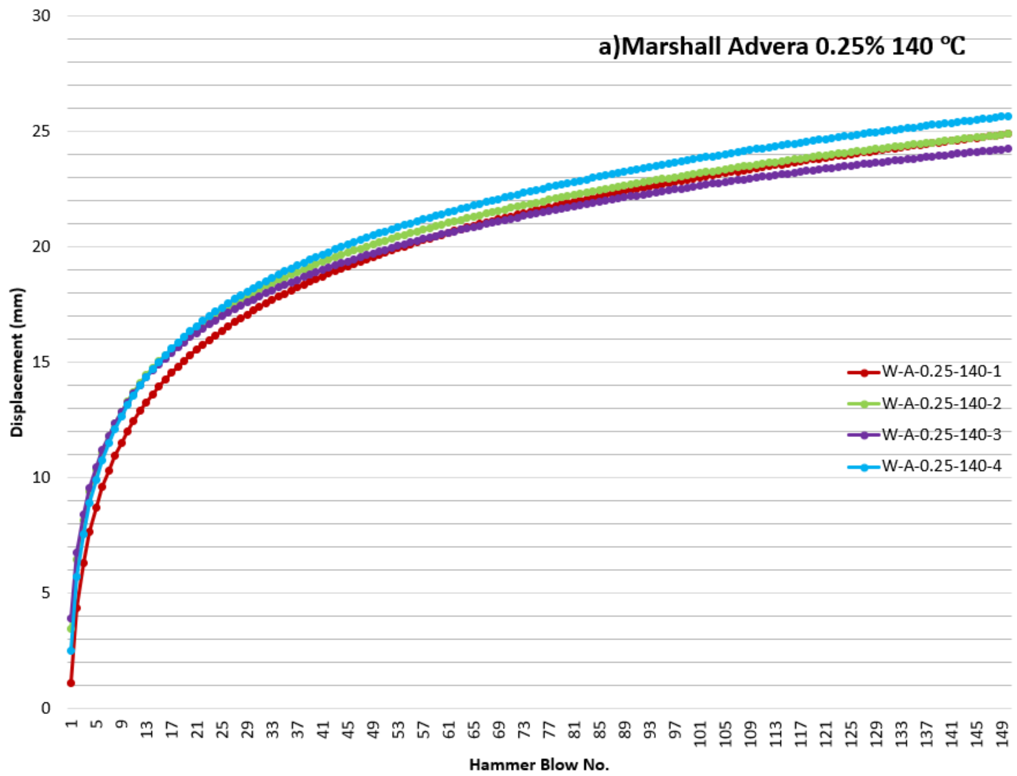


Figure B.4. Marshall Sasobit 3% samples displacements per blow



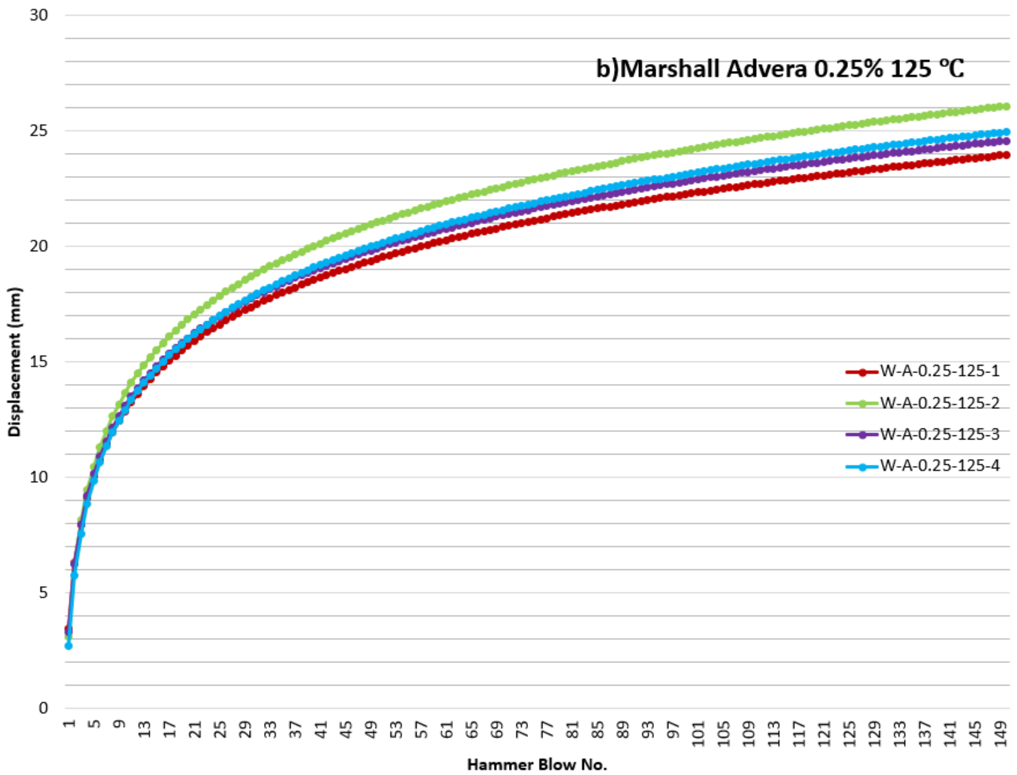


Figure B.5.a/b. *Marshall Advera 0.25% samples displacements per blow cont.*

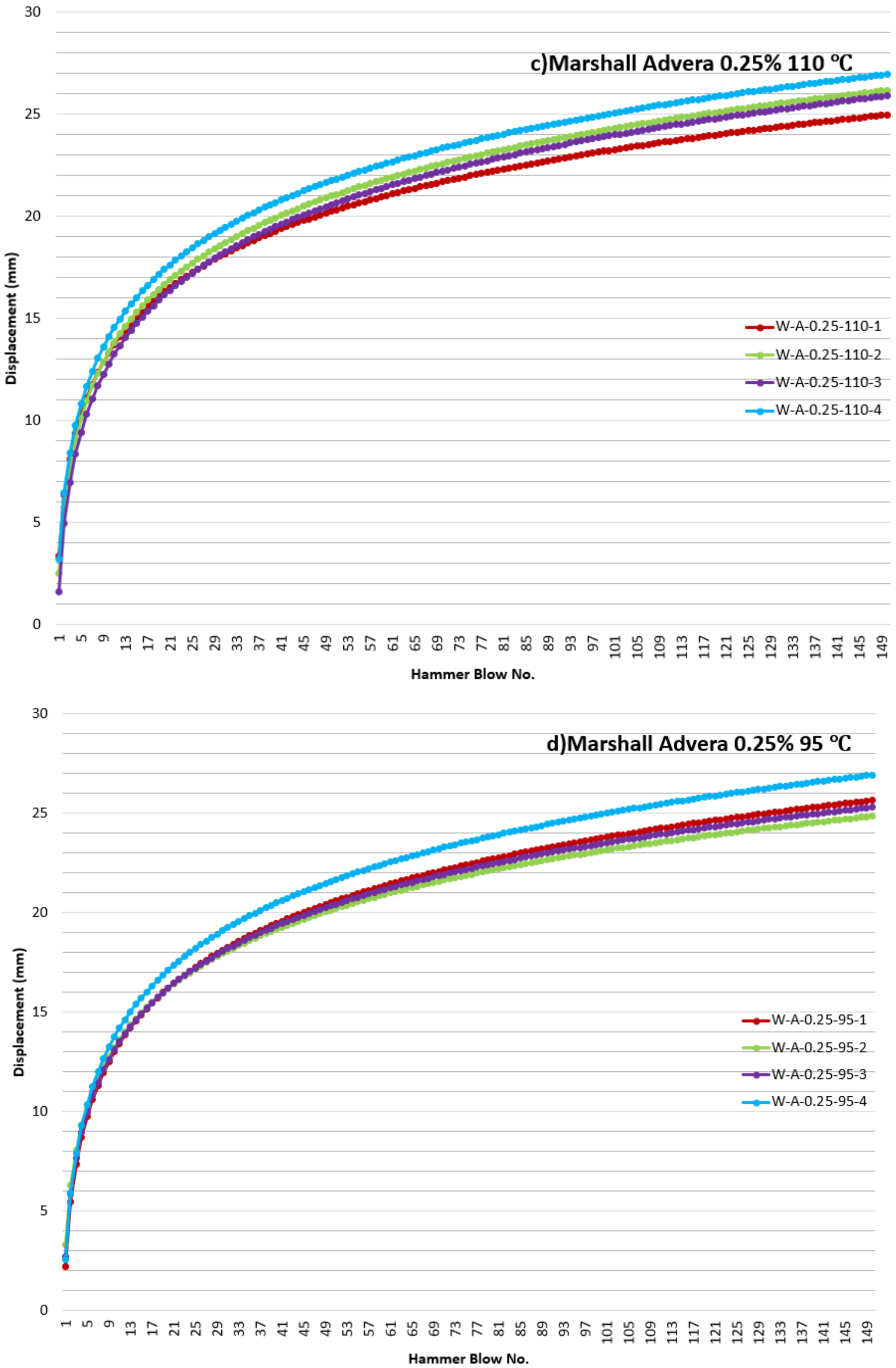
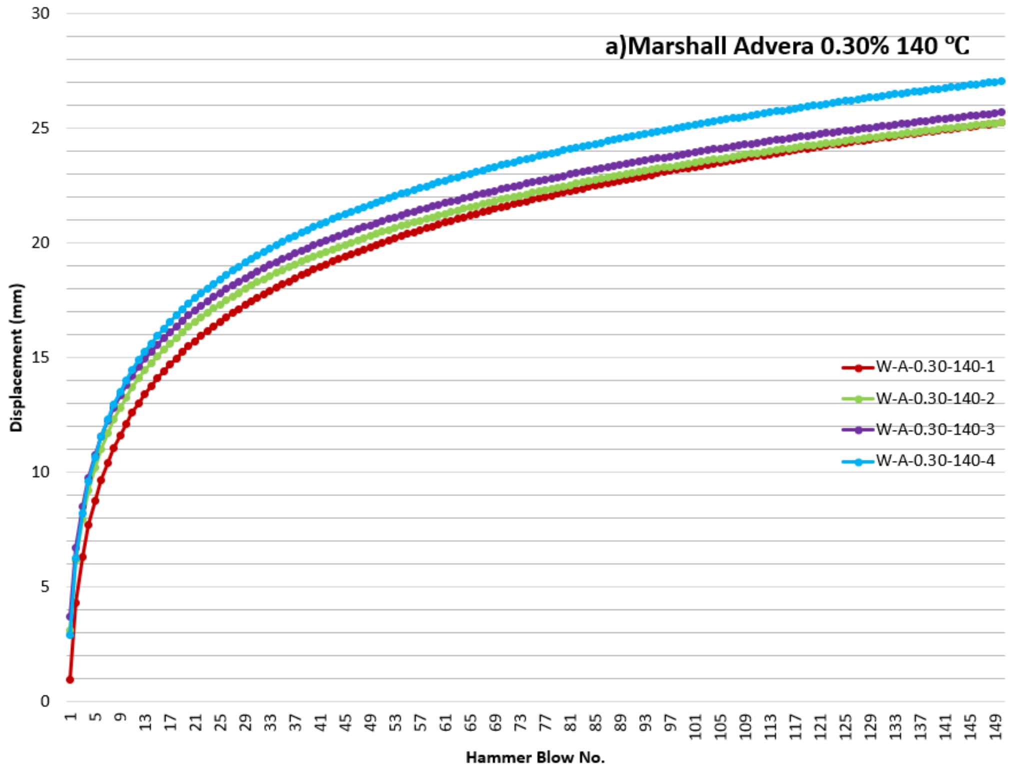


Figure B.5. Marshall Advera 0.25% samples displacements per blow



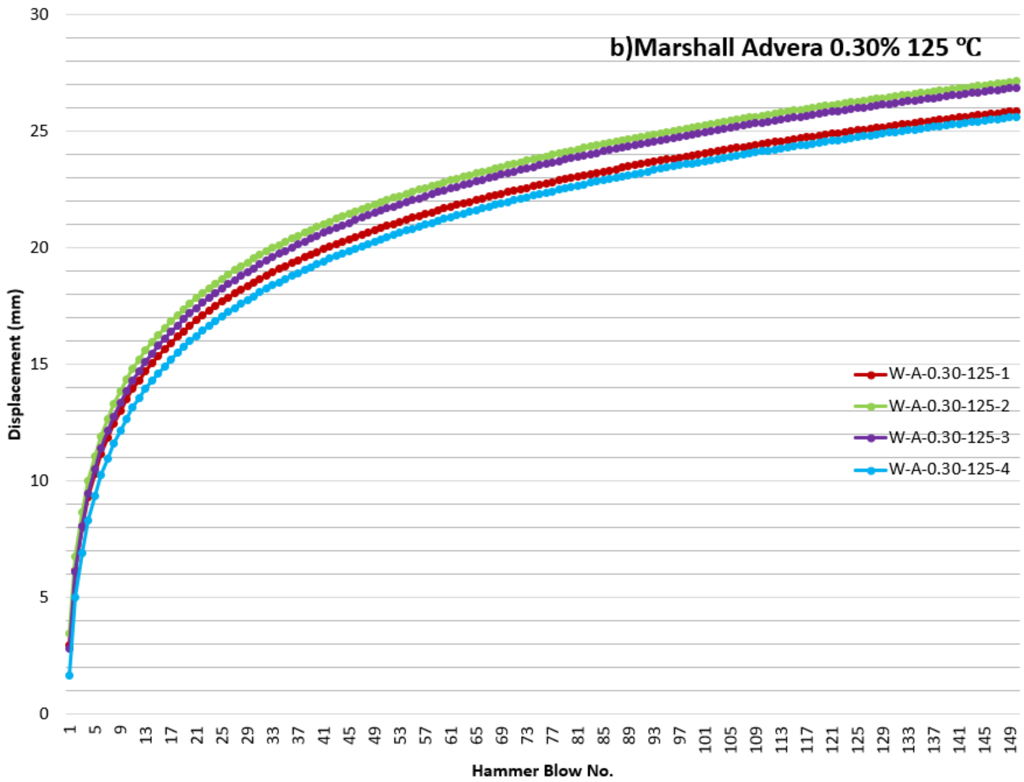
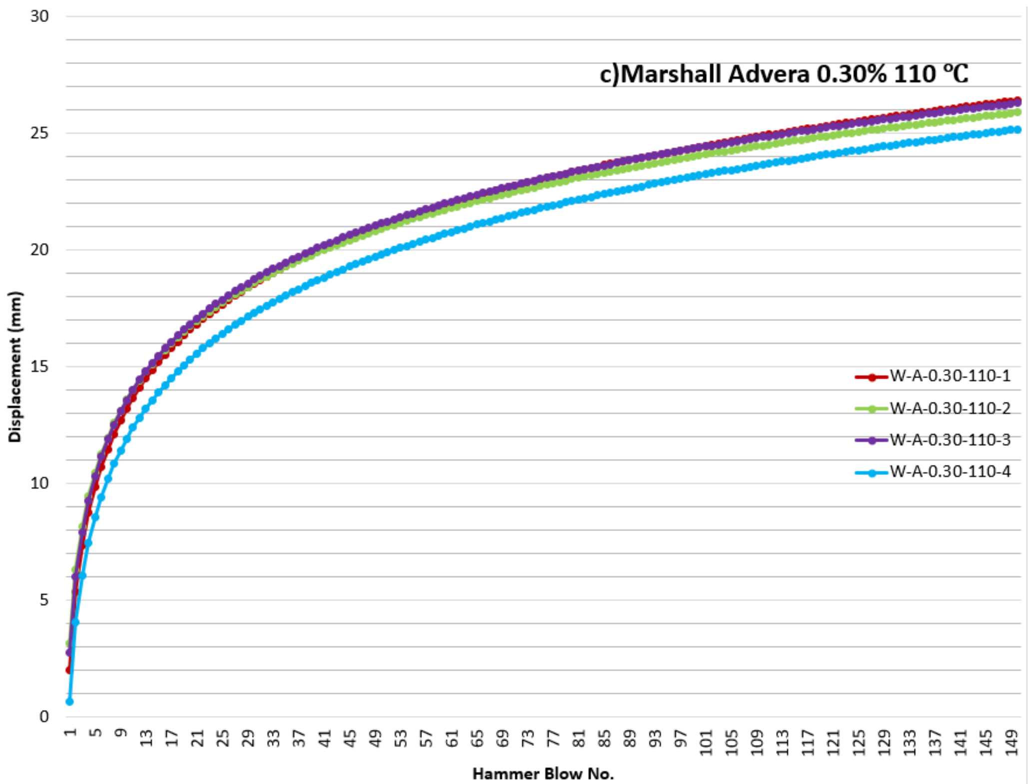


Figure B.6.a/b. *Marshall Advera 0.30% samples displacements per blow cont*



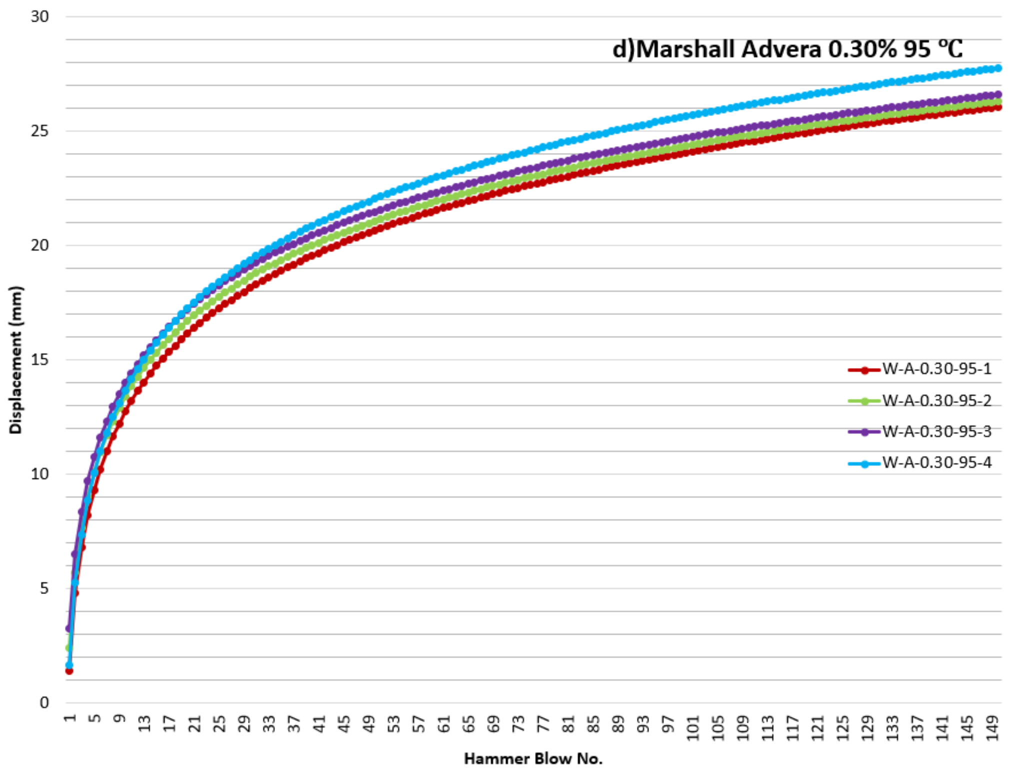


Figure B.6. Marshall Advera 0.30% samples displacements per blow

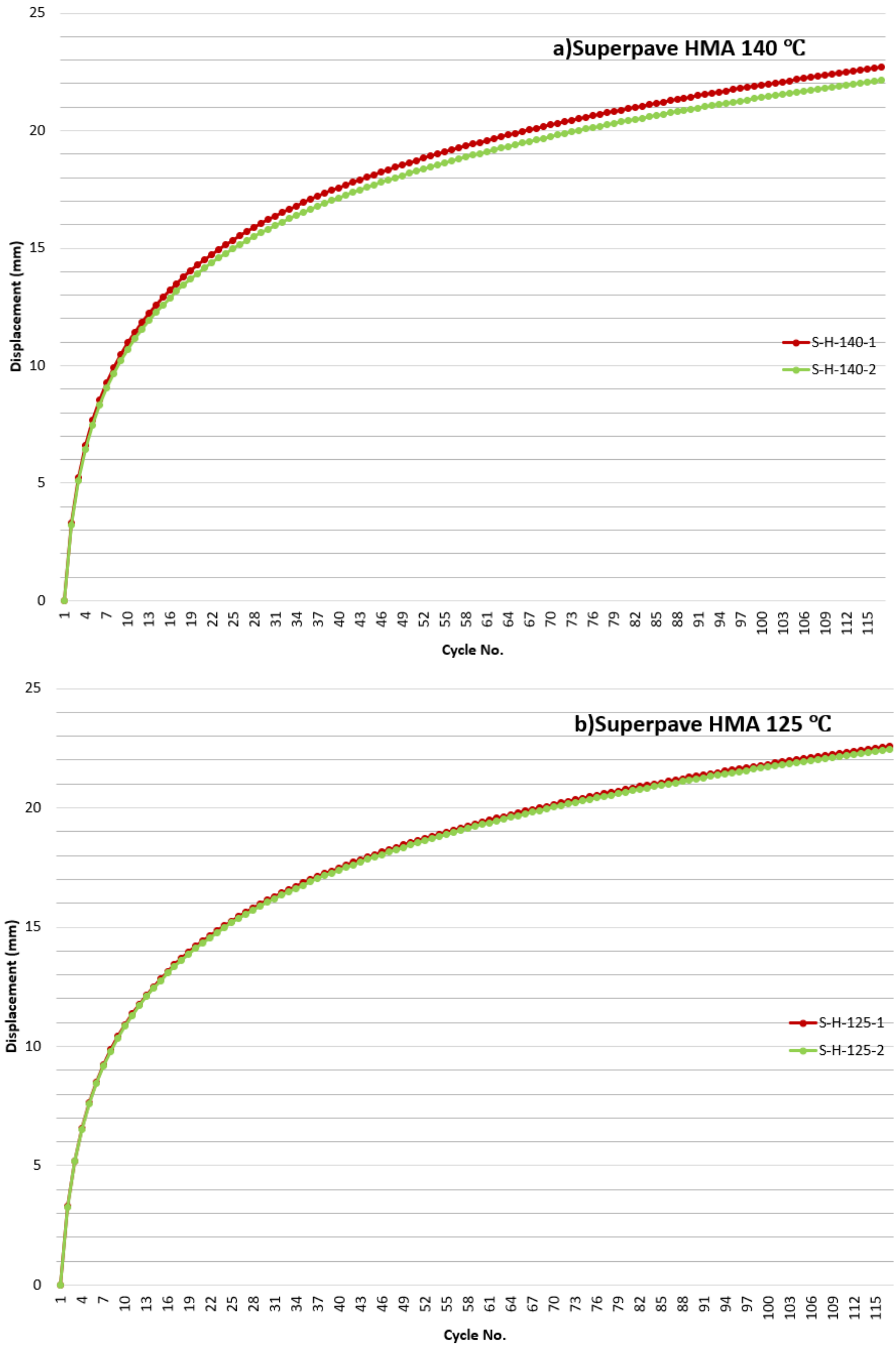


Figure B.7.a/b. *Superpave HMA samples displacements per blow cont.*

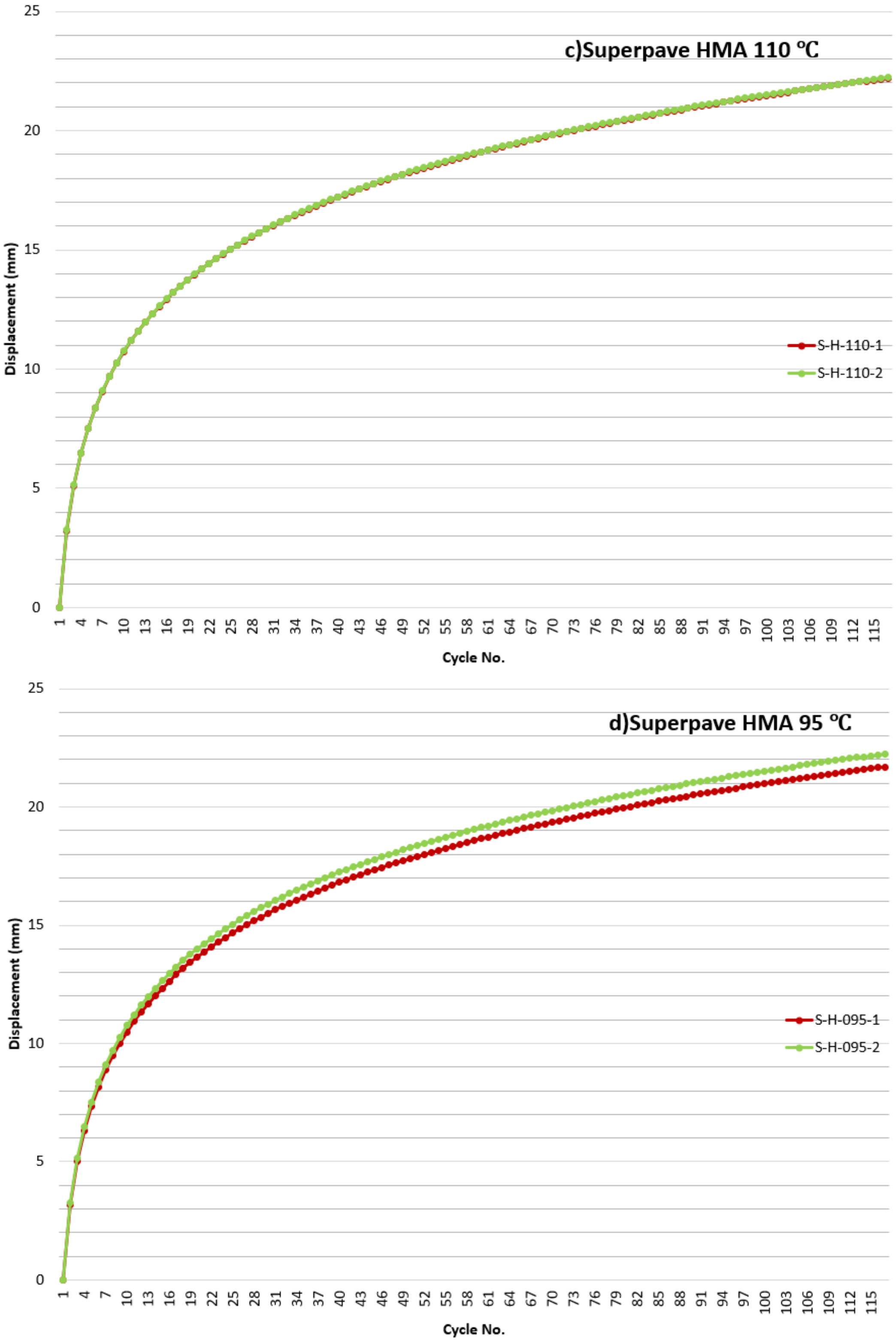
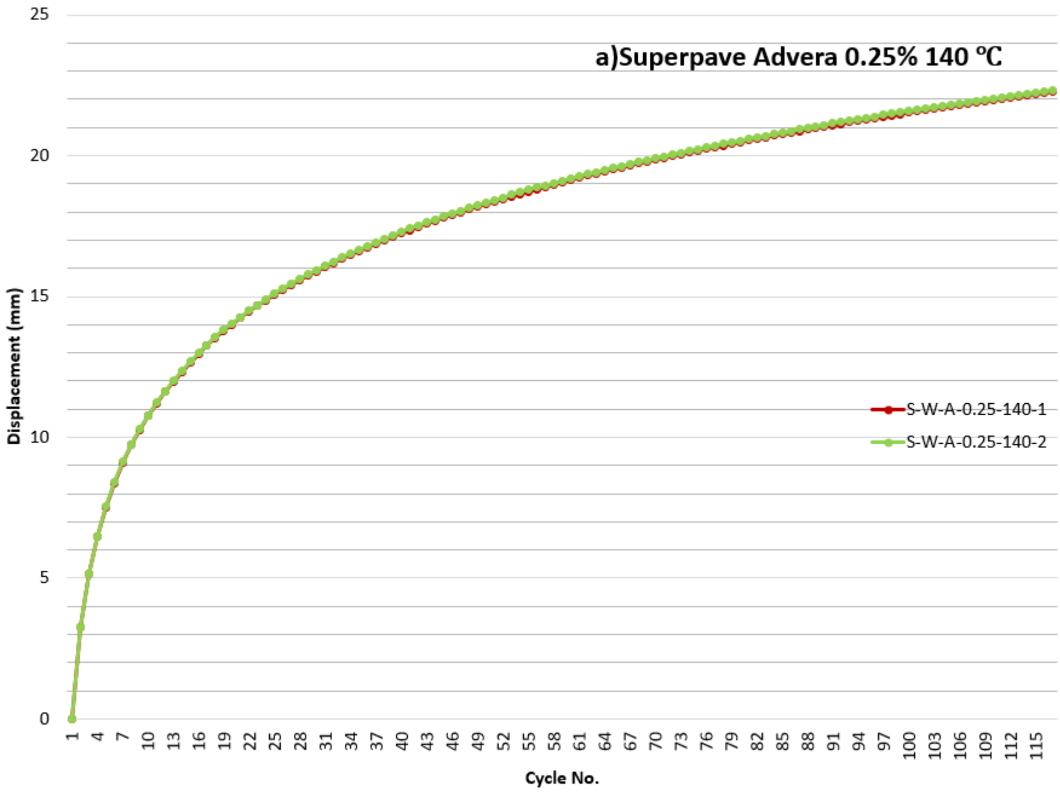


Figure B.7. Superpave HMA samples displacements per cycle



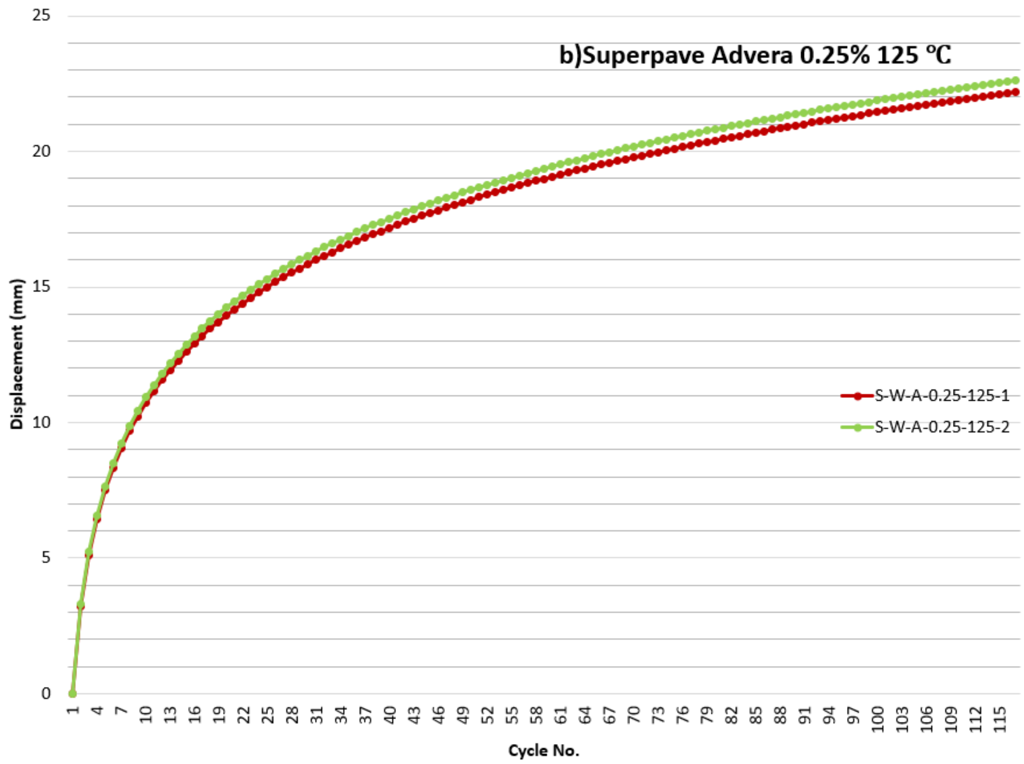


Figure B.8.a/b. *Superpave Advera 0.25% samples displacements per blow cont.*

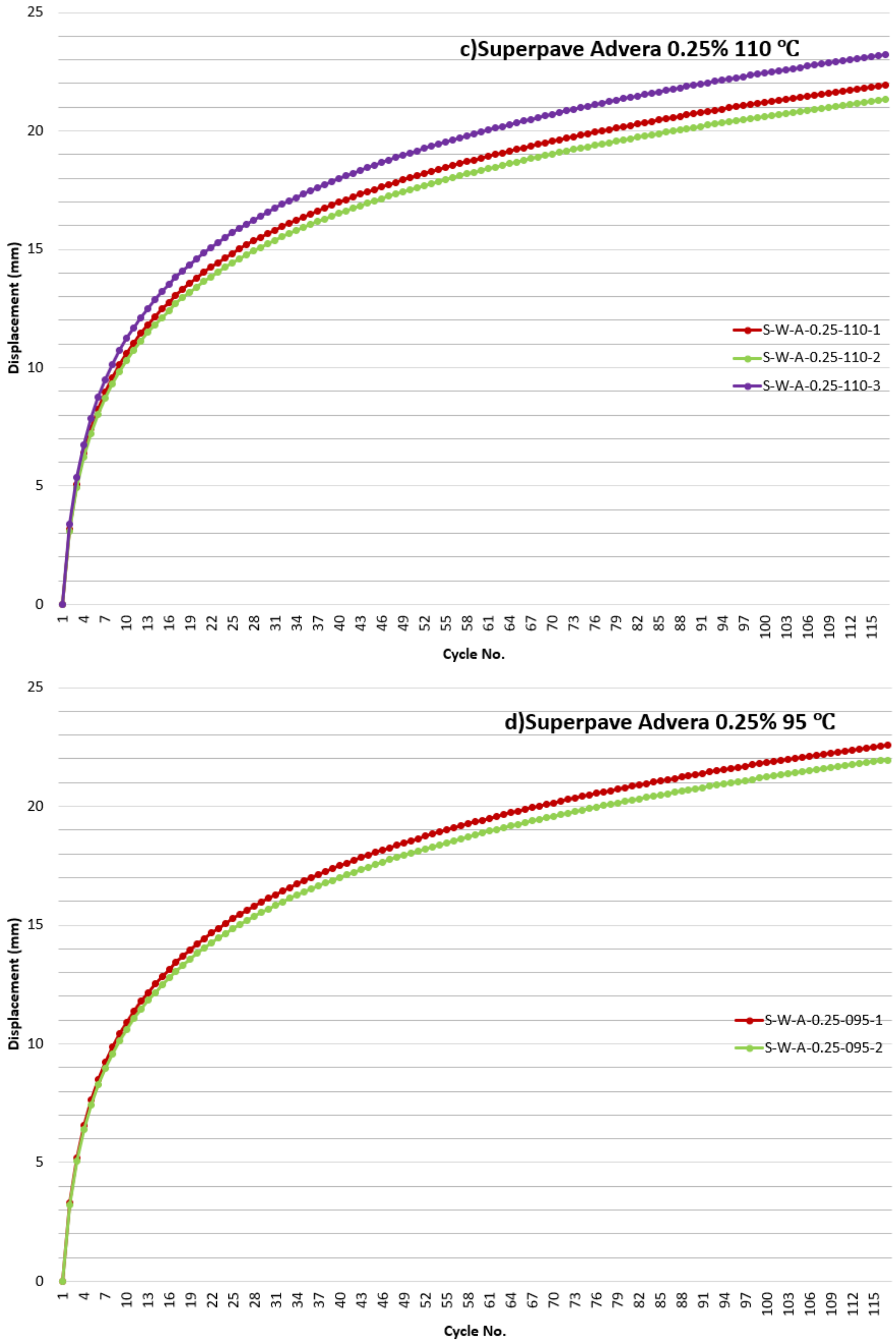
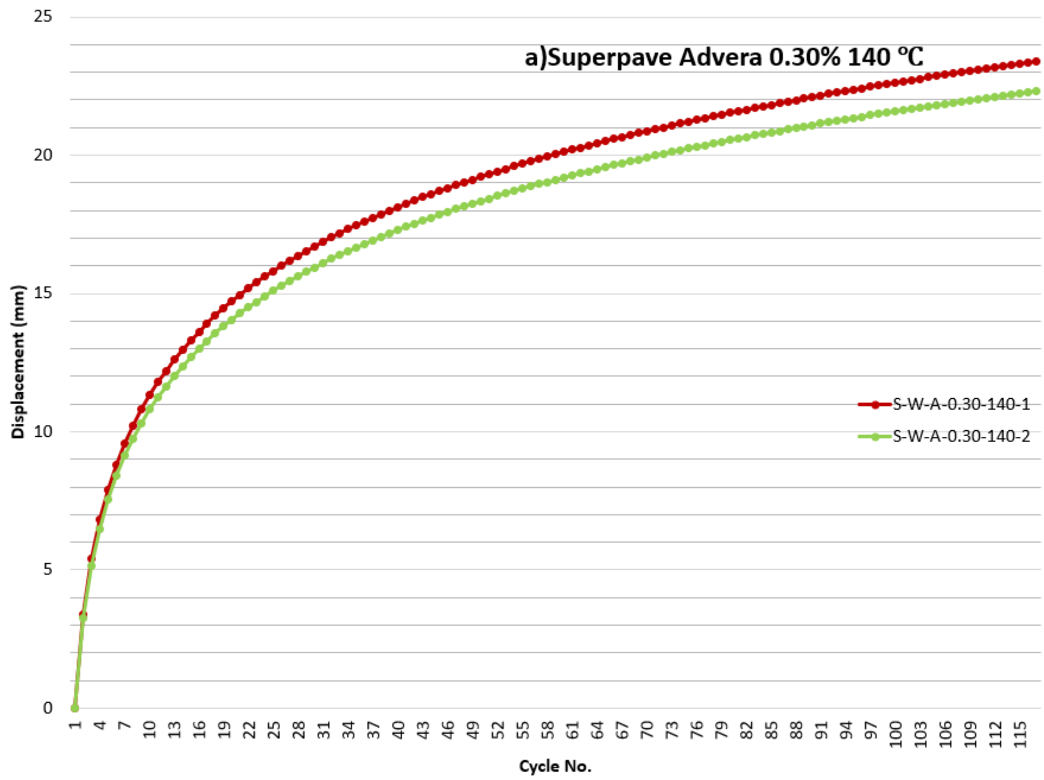


Figure B.8. Superpave Advera 0.25% samples displacements per cycle



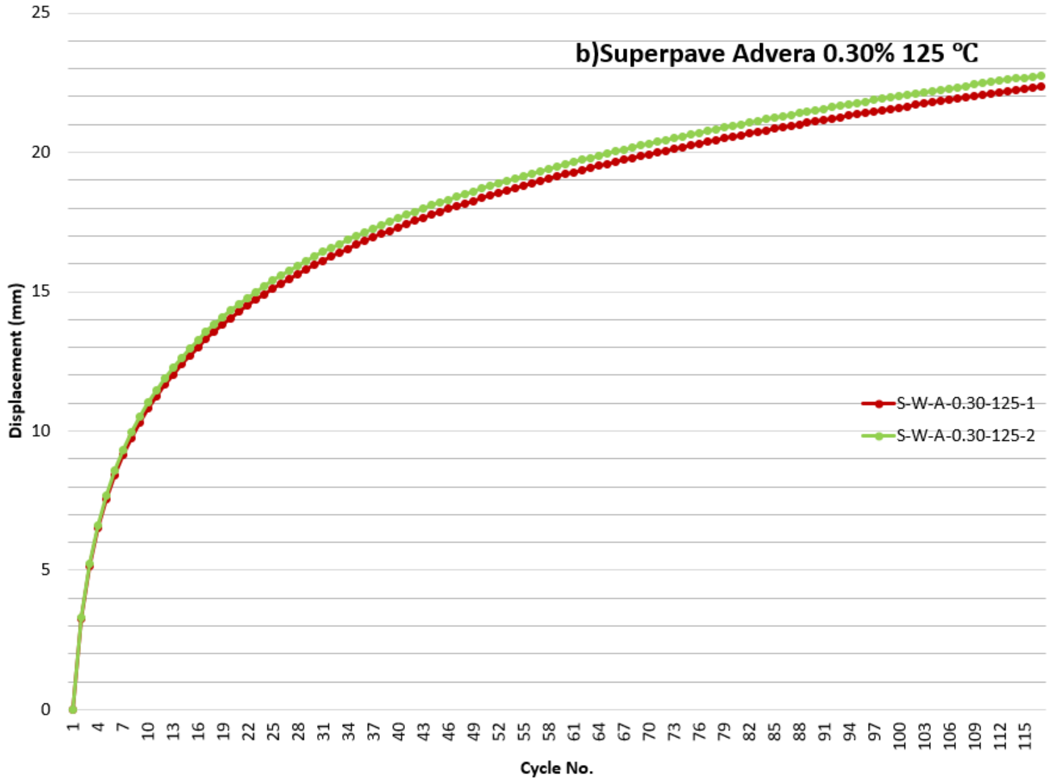


Figure B.9.a/b. *Superpave Advera 0.30% samples displacements per blow cont*

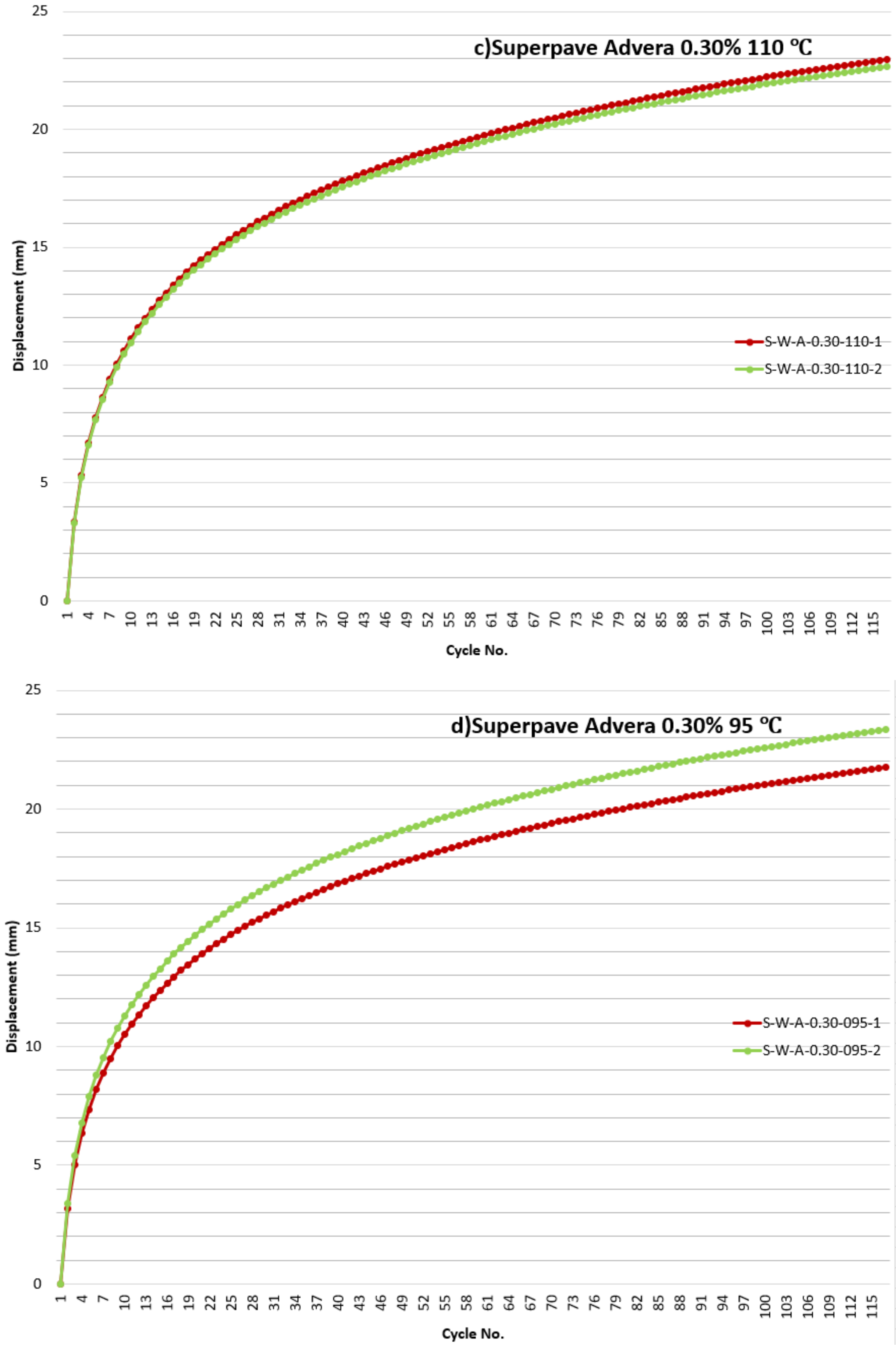


Figure B.9. Superpave Advera 0.30% samples displacements per cycle