DRY PROCESS CRUMB RUBBER MODIFICATION IN WARM MIX ASPHALT

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submitted by **FARSHAD KAMRAN** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** ____________________

Prof. Dr. İsmail Özgür Yaman
Head of Department, **Civil Engineering** ____________________

Asst. Prof. Dr. Hande Işık Öztürk
Supervisor, **Civil Engineering Dept., METU** ____________________

Examining Committee Members

Prof. Dr. Murat Güler
Civil Engineering Dept., METU ____________________

Assist. Prof. Dr. Hande Işık Öztürk
Civil Engineering Dept., METU ____________________

Prof. Dr. İsmail Özgür Yaman
Civil Engineering Dept., METU ____________________

Assoc. Prof. Dr. Hediye Tüydeş Yaman
Civil Engineering Dept., METU ____________________

Assist. Prof. Dr. Hikmet Bayırtepe
Civil Engineering Dept., Gazi University ____________________

Date: July 31, 2018

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Farshad Kamran

Signature :

ABSTRACT

DRY PROCESS CRUMB RUBBER MODIFICATION IN WARM MIX ASPHALT

Kamran, Farshad
M.Sc., Department of Civil Engineering
Supervisor: Asst. Prof. Dr. Hande Isik Ozturk

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Since the last decade, environmentally friendly asphalt production techniques have significantly advanced for savings in natural resources, energy and economy. From these techniques, Warm Mix Asphalt (WMA) provides a reduction in mixing and compaction temperatures and also overcomes various challenges of Hot Mix Asphalt (HMA). Additionally, Crumb rubber (CR) modification of asphalt mixtures helps the disposal of waste tires and also improves the asphalt mixtures properties. Among CR modification methods, dry process (Dry) method has various advantages. Thus, the focus of the study is to overcome the major disadvantages of Dry CR (i.e. high production temperatures) with WMA additive. In this study, the association of WMA and dry process are studied for the first time through a broad laboratory study. Therefore, seven different asphalt mixtures including HMA, dry process CR modified HMA (DryHMA) and five sets of dry process CR modified WMA (DryWMA) are prepared to analyze the compactibility, volumetrics, and low-temperature performance properties of these mixtures. DryWMA mixes are prepared by changing various design parameters (i.e. WMA additive dosage, conditioning time, compaction and mixing temperatures). The results of this study stated that the decrease in the mixing temperatures could not be compensated by extending the conditioning time. However, the compaction temperature could be considerably lowered without compromising the low-temperature performance and strength of the mixes. In addition, use of the WMA additive with the dry CR modified mixtures provides better compactibility and workability. Moreover, the decreases in the cooling rate of DryWMA provides longer compaction frame.

Keywords: Warm Mix Asphalt, Dry Process Crumb Rubber, Compactibility, Volumetric Properties, Low temperature performance

ÖZ

KURU KARISIM LASTIK MODIFIKASYONUNUN ILIK KARISIM ASFALTLARDA KULLANİMİ

Kamran, Farshad
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Dr. Öğr. Üyesi Hande Işık Öztürk

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Son on yıldan beri, çevre dostu asfalt üretim teknikleri, doğal kaynaklar, enerji ve ekonomideki tasarruflar için önemli ölçüde ilerlemiştir. Bu teknikler arasından, Ilık Karışım Asfalt (IKA) karıştırma ve sıkıştırma sıcaklıklarını azaltır ve Bitümlü Sıcak Karışım Asfaltın (BSK) getirdiği çeşitli zorluklarını ortadan kaldırır. Bir diğeri, lastik modifiyeli asfalt karışımlar hurda lastiklerin bertaraf edilmesine yardım eder ve asfalt karışımların özelliklerini geliştirir. CR modifikasyon yöntemleri arasında kuru karışım yönteminin çeşitli avantajları vardır. Bu nedenle, çalışmanın odak noktası, IKA katkısı ile kuru karışım en büyük dezavantajlarının (ör. yüksek üretim sıcaklıklarının) üstesinden gelmektir. Bu çalışmada, IKA ve Kuru karışım arasındaki ilişki, ilk defa geniş bir laboratuvar çalışması ile incelenmiştir. Bu nedenle, BSK, kuru karışım BSK (KuruBSK) ve beş kuru proses kuru karışım IKA (KuruIKA) içeren yedi farklı asfalt karışımı, bu karışımların sıkıştırılabilirlik, hacimsel, düşük sıcaklık performansı özelliklerini analiz etmek için hazırlanmıştır. KuruIKA karışımları, çeşitli tasarım parametrelerini (ör. IKA katkı dozajı, koşullandırma süresi, sıkıştırma ve karıştırma sıcaklıkları) değiştirerek hazırlanmıştır. Bu çalışmanın sonuçları, koşullandırma süresinin uzamasıyla karıştırma sıcaklıklarındaki azalmanın telafi edilemeyeceğini belirtmiştir. Bununla birlikte, düşük sıcaklık performansı ve karışımların mukavemetinden ödün vermeden sıkıştırma sıcaklığı önemli ölçüde düşebilir. Ek olarak, kuru karışımlar ile IKA katkı maddesinin kullanımı daha iyi bir sıkıştırılabilirlik ve işlenebilirlik sağlar. Ayrıca, KuruIKA soğuma hızındaki düşüş, daha uzun çalışma süresi sağlar.

Anahtar Kelimeler: Ilık Karışım Asfalt, Kuru Karışım Öğütülmüş Lastik, Sıkıştırılabilirlik, Hacimsel Özellikler, Düşük Sıcaklık Performansı

To My Parents, Lovely Sisters and Spirits of My Grandfathers

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AASHTO: American Association of State Highway and Transportation Officials

AC: Asphalt Concrete

ANOVA: Analysis of Variance

AR: Asphalt Rubber

ASTM: American Society for Testing Materials

CR: Crumb Rubber

CSP: Copper Slag Powder

DryHMA: Dry Process Crumb Rubber Modified Hot Mix Asphalt

DryWMA: Dry Process Crumb Rubber Modified Warm Mix Asphalt

DSR: Dynamic Shear Rheometer

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

IDT: Indirect Tensile Test

LAS: Liquid Antistripping

LDVT: Linear Variable Differential Transformer

LSP: Limestone Powder

METU: Middle East Technical University

NAPA: National Asphalt Pavement Association

NCAT: National Center of Asphalt Technology

PA: Porous Asphalt

PCC: Portland Cement Concrete

PG: Performance Grade

RAP: Reclaimed Asphalt Pavement

RAS: Recycled Asphalt Shingles

RMA: Rubber Manufacturers Association

RTFO: Rolling Thin-Film Oven

SCB: Semi-circular Bending Test

SMA: Stone Matrix Asphalt

V_a: Air Voids

VFA: Voids Filled with Asphalt

VMA: Voids in Mineral Aggregates

VTM: Voids in the Total Mix

WMA: Warm Mix Asphalt

CHAPTER 1

INTRODUCTION

1.1 Research objectives

In the asphalt pavement industry, environmental and economic concerns trigger the development of new technologies and methods. In addition, the recent researches are focusing on the association of the existing and new methods. Crumb rubber (CR) used in asphalt pavement production has been recognized as one of the oldest environmentally friendly methods. On the other hand, Warm Mix Asphalt (WMA) technologies are relatively new, though their use is globally increased due to their various benefits. Both CR and WMA have different application methods. In the recent years, many researchers have studied their association. However, these studies were limited with wet process CR modification. This study for the first time investigated the use of dry process CR application with WMA. In the dry process CR application, the CR particles are used as the fine aggregate replacement. Thus, it is possible to dispose more CR within the mixture. However, its biggest challenge is the high production temperatures when compared to traditional mixes. In this study, the advantages of WMA technologies are incorporated with dry process to turn the negative sides to positive (i.e. to lower the mixing temperatures). Therefore, various design parameters (i.e. conditioning time, mixing and compaction temperatures) were studied. Conditioning time is a significant parameter that affects the bonding between CR and binder. Therefore, conditioning the mixture prior to compaction in the oven for four different periods (0, 45, 90 and 120 minutes) and its effects on the CR-binder interactions were evaluated. In addition, the mixing temperature, which also influences the bond strength between CR and binder, was studied.

Also, as the last selected parameter, compaction temperature, which is related to the compactibility and workability of mixtures, was analyzed.

In this study, the Marshall Mix design procedure was used due to its superiority in temperature sensitivity. Accordingly, physical and performance properties of Dry process CR modified HMA (DryHMA) and Dry process CR modified WMA (DryWMA) were evaluated through traditional Marshall Procedure. Moreover, according to the literature, the performance properties of CR modified asphalt mixtures indicated that these mixtures are more susceptible to low-temperature cracking. Various researches studied the effects of CR modification and reported the essential research requirements on low-temperature properties. In this study, indirect tensile strength test was used to study the low-temperature performance of DryHMA and DryWMA mixtures.

Finally, to simulate the field conditions, the cooling rates of DryWMA with DryHMA mixtures were estimated using a free access tool, Multicool, since it is essential for an actual field project to be able to estimate the cooling period for better management. If not, it could cause various problems during the lay down of mixture in the field.

1.2 Scope

The major steps of this study were given as follows:

1- Preparation of Marshall Mix Designs for Hot Mix Asphalt (HMA), Dry process CR modified HMA (DryHMA) and Dry process CR modified WMA (DryWMA).
2- Development of the experimental matrix. In other words, selection of the mix parameters (i.e. conditioning time, compaction and mixing temperatures), physical and performance tests.
3- Analyzing the effect of mix parameters on the physical properties (i.e. on volumetrics) and on the performance according to stability and flow.
4- Reducing the sample size according to the outcomes of Step 3.

5- Performing indirect tensile strength (IDT) test to study the low-temperature performance properties of mixtures.
6- Determination of the cooling curves of DryHMA and DryWMA to compare the construction time frames using the Multicool program.

1.3 Outline of research

Chapter 2 includes a broad literature review of both CR and WMA, separately. As well, it presents the latest literature on the association of wet process CR and WMA. In addition, the test methods used in this study are summarized in this chapter.

Following the literature review part, chapter 3 is prepared to identify the materials that are used in this research. Mixture properties, experimental plan, sample preparation methods and testing procedures are provided in details.

Chapter 4 contains the results and discussion of the tests. Initially, the volumetric properties of the samples are given and discussed. Then, the initial performance evaluation of these mixes is done based on the stability and flow results. In the following, low temperature cracking resistance is analyzed through Indirect Tensile Strength tests. Accordingly, the relation between the mixture parameters and performance attributes are discussed in detail. Finally, the cooling rate of the mixtures is studied and compared in this chapter.

In chapter 5, conclusions are driven according to the results provided in chapter 4. In addition, recommendations for future works are provided in the light of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the pavement industry, new technologies and production methods have been progressively introduced not only because of the importance of cost and time saving but also because of the environmental concerns. In this chapter, two of these methods, Warm Mix Asphalt (WMA) and crumb rubber modified mixtures, and also their associations are discussed in detail by summarizing the latest available literature.

2.2 Warm Mix Asphalt

2.2.1 History and Benefits of Warm Mix Asphalt

WMA is the name of a relatively new technology, which allows producers to prepare, transport, mix and place the asphalt mixture in lower temperatures than conventional temperatures (Moreno, Rubio, & Martinez-Echevarria, 2011). This reduction in temperature can be about 20-40˚C lower than that of Hot Mix Asphalt (HMA). This temperature reduction means less energy consumption by burning less fuel, which could reduce approximately the energy use by 30-35%.

WMA technologies reduce the viscosity at lower temperatures, which increase the compactibility. It results in more uniform density and decreases the roller passes to targeted density (Hossain, et al., 2009; D'Angelo, et al., 2008). Besides, it cools slower than the convenient HMA and offers workers more time to work in lower temperatures and increase the hauling distances. Therefore, the paving can be done in cold regions and as well in cooler months. Furthermore, this method can be used in combination with reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS) and other reused materials that makes it subject of interest (West, et al., 2014). Using additives and foaming technologies are the major methods of WMA. Various field and laboratory studies have already proven that if WMA mixtures are designed properly, these mixtures are able to perform equivalent or better than HMA mixtures (West, et al., 2014).

First WMA studies were initiated in Europe during 1995-96, which yielded to the first field trial in 1997-99. Since then, WMA took attention in USA and National Asphalt Pavement Association (NAPA) organized a study tour to Europe in 2002. Denmark, Germany and Norway were their destination in which various technologies of WMA such as (i) Aspha-min (ii) WAM Foam and (iii) Sasobit were investigated (Qin, Farrar, Turner, & Planche, 2015; Prowell, Hurley, & Frank, 2011). In the light of this tour, first field trails in USA were followed with Aspha-min in Florida and Indiana, and then Ontario and Quebec in Canada.

In 2005-06 numerous field trials were done and the State of Missouri started to use WMA in paving based on successful trials. National Center of Asphalt Technology (NCAT) published research results on Aspha-min, Sasobit and Evotherm around the same time (Prowell B. , 2007). In 2007, AASHTO-Federal Highway Administration (FHWA) started a tour to Belgium, France, Germany and Norway. Over 20 WMA technologies were available in the U.S. market by 2010. According to a survey prepared by FHWA, WMA usage in 2009 and 2010 was estimated to be 17 million tons and 47 million tons, respectively. At the end of 2011, all 50 states of the USA had WMA trail sections. Engineering, environmental and economic benefits of WMA technologies were the reasons that their usage has been significantly increased (Larsen, Moen, Robertus, & Koenders, 2004; Cervarich, 2003; De Groot, et al., 2001; Prowell B. , 2007).

2.2.2 Warm Mix Asphalt Additives

WMA technologies majorly categorized as (i) Chemical Additives or Surfactants, (ii) Foaming Processes and (iii) Non-foaming Additives. Under each technology, there are various materials and methods developed in recent years. Therefore, for each technology, one or two of the common methods were selected and discussed in this section.

2.2.2.1 Chemical Additives or Surfactants

Evotherm (Figure 2.1), one of the oldest chemical additives in the industry, is manufactured by MeadWestvaco Asphalt Innovations. It is developed in the U.S. under the names of Evotherm Emulsion Technology (ET) (2004), Evotherm Dispersed Asphalt Technology (DAT) (2007), and Evotherm 3G. These additives are mixed with hot aggregates to reduce the mix temperatures approximately till 85˚ to 115˚C. Typically, the additive is added approximately 5% by weight of binder.

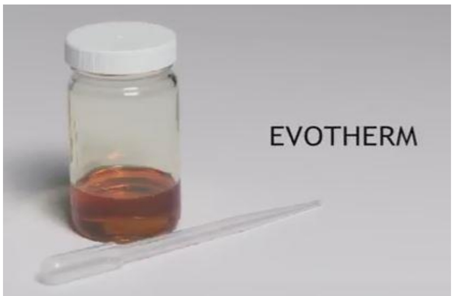


Figure 2.1 WMA Chemical additive (EVOTHERM) (Evotherm, 2016).

Evotherm have benefits such as liquid antistripping (LAS) replacement, more RAP and RAS usage, fiber removal, reduction in binder usage during design step; longer hauling, lower emissions, less thermal segregations in the production of pavement; also longer life and compaction improvement as the performance phase (Ingevity; Prowell, Hurley, & Frank, 2011).

2.2.2.2 Foaming Process

Advera WMA (Figure 2.2) is one of the most common foaming based additives which is supplied by PQ Corporation. It is a synthetic zeolite in powder form with very fine gradation (passing No. 200 sieve.) The major ingredients are zeolite (78-82%) and water (18-22%), which the water releases when the temperature of the mix is over the boiling point of it and this results in foaming. Thus, it provides workability improvement by increasing the binder volume. Advera is insoluble in the water with a melting point over 1000˚C and classified as an odorless material. Typically, 0.20 to 0.25% by weight of total mixture is recommended to be used in the asphalt mixtures. However, if binder content is over 7% by weight of the mix, it is recommended to add at higher dosage levels. The mixtures prepared with Advera have approximately 28˚C lower mixing and compaction temperatures than the traditional HMA. Since 2006, over 1 million tons of WMA mixtures with Advera have been used in US and Canada. Besides, this additive is also widespread through Europe and Asia (Hasan, Goh, & You, 2013; PQCorporation, 2015; Prowell, Hurley, & Frank, 2011).

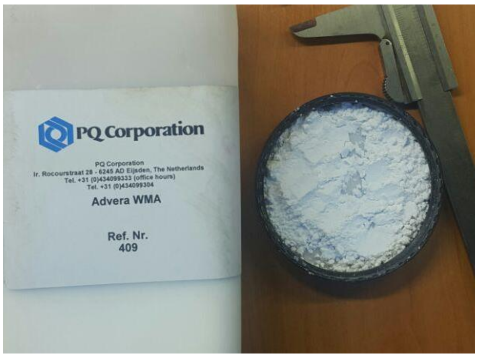


Figure 2.2 WMA foaming additive (ADVERA)

Aspha-min (Prowell, Hurley, & Frank, 2011) is another foaming based additive developed by Aspha-min GmbH in Hanau, Germany in 2006. It is also a zeolite manufactured synthetically containing 20% water by weight. Thus, the foaming starts after the boiling point of water. Aspha-min provides a longer working period compared to Advera (up to 6 to 7 hours) and it can be used before mixture cooled down to 100˚C. It is recommended to be used typically 0.3% by weight of the total mix. Its gradation is coarser than Advera, with particle size around 0.3mm. It should be noted that it can be also used as a compaction aid in HMA (TheHubbardGroup).

Figure 2.3 WMA foaming additive (Aspha-min)

2.2.2.3 **Non-foaming Additives (Prowell, Hurley, & Frank, 2011)**

Sasobit is one of the oldest non-foaming additives, which is supplied by Sasol Wax North America Corporation (Figure 2.4). It is a synthetic paraffin wax. In the production of Sasobit, Fischer-Tropsch method is used based on hot coal or natural gas treating with steam by catalyst assistance. Sasobit is composed of long-chain aliphatic hydrocarbon waxes that have the congealing point of 100˚C. Sasobit has high viscosity than asphalt binder below the melting point and low viscosity above the melting point. It is typically introduced to the mixture at a dosage of 1.5% by weight of the binder. However, this dosage varies in the range of 0.8-4% by weight of binder depending on the application. This organic additive is added to the binder prior to mixing. Therefore, it can be added in various methods to the mixture such as directly into binder, through the RAP collar, at the same time with the binder and etc. (Qin, Farrar, Turner, & Planche, 2015; Prowell, Hurley, & Frank, 2011). It has advantages listed as following: increase in workability, stability and service life with the early opening to traffic, as well as a decrease in the production temperature. As it is obvious in Figure 2.5, Sasobit has significant effects in bitumen viscosity and this modification is different in below and above the boiling point. By adding Sasobit to bitumen over 115˚C, it reduces the viscosity since it is soluble. On the contrary, cooling down the binder with Sasobit (under the boiling point) causes crystallizing after 90˚C that makes binder stiffer. This viscosity reduction provoked the emissions and decreased the binder-aging process (Jamshidi, Hamzah, & Aman, 2012; SasolPerformanceChemicals, ProductInformation_en; Moreno, Rubio, & Martinez-Echevarria, 2011).

Binder modified by Sasobit has the higher softening point and lower penetration values than conventional bitumen, which results in a change of low-temperature performance. However, a recent research on WMA mixtures has indicated that the mixtures prepared with Sasobit do not have an adverse change in low-temperature performance (SasolPerformanceChemicals, Low Temperature Behaviour, 2016). In addition, it has been studied that the additive dosage has significant effects on the compactibility and stability of WMA (Ozturk & Pamuk, 2017).

Figure 2.4 WMA Non-foaming additive (Sasobit)

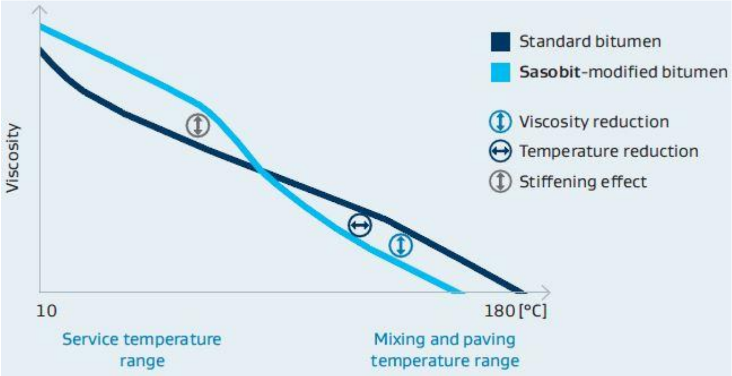


Figure 2.5 Sasobit viscosity modification (SasolPerformanceChemicals, ProductInformation_en)

2.3 Crumb Rubber Modification

2.3.1 History and Benefits of Crumb Rubber Modification

Scrap tires are one of the most problematic waste materials in terms of the disposal. It threatens the human life since the degradation in nature takes approximately 50 to 80 years. Therefore, it is reused in several sectors such as ground rubber, tire-derived fuel, and etc. For scrap tires, leading recycling industry is tire-derived fuel use and followed by ground rubber sector, which has a share of 25.8%, as reported in 2015.

In the ground rubber sector, the shares of “molded/extruded”, “sports surfaces”, “Playground Mulch”, “asphalt”, and others are 35%, 25%, 22%, 15% and 3%, respectively, according to Rubber Manufacturers Association (RMA). In 2015, around 1.2 million tons of ground rubbers were used in the asphalt mixtures (RMA, 2016). California State in the US has already prepared official instructions for increasing in crumb rubber usage in asphalt pavements (Caltrans, 2003)

First rubber modification of binder was made in the 1840s, and then after 1950s, various suppliers started to provide rubber for asphalt pavements. Considering several researches have been completed in years, three major crumb rubber modification methods are introduced as discussed in the following section (Santucci, 2009).

2.3.2 Crumb Rubber modification methods

Three major methods used in asphalt modification are wet process, dry process and terminal blend. There are several advantages and disadvantages of these methods as discussed in the following.

2.3.2.1 **Wet Process**

According to ASTM D8, MacDonald Method named as Asphalt Rubber (AR) or wet process crumb rubber modification is defined as a blend of asphalt binder with additives and crumb rubber, in which CRs’ amount should not exceed 15% by weight of the binder that is about 1-1.5% of total weight of mixture. It is the oldest method of CR modification, which started in the 1960s. In this method, the CR particles in the hot asphalt binder should be properly mixed and swelled by holding around 190-225˚C for at least 45 minutes to permit an interaction within the particles and binder. However, this blending procedure results in the increase of the binder viscosity. It should be noted that time and temperature for blending, type and amount of mechanical mixing, CR properties (i.e. size, type and specific area), and also binder type are the effective parameters in the CR-binder interaction. Typically, the CR gradation is selected in the range of 0.075 to 1.2mm. In this method, the aggregate gradation is commonly preferred to be open graded. Beside, seal coats, interlayers and crack seals are alternative uses of AR (Rahman, 2004; Santucci, 2009; Wright Asphalt Products Co., 2008).

Mixtures prepared with wet process method have better or equal performance properties when compared to polymer-modified mixtures. On the other hand, segregation of CR particles may be observed if the CR-binder blending is not properly done (Ozturk, Tascioglu, Kutay, & Littrup, 2012).

2.3.2.2 **Dry Process**

Dry process is based on the replacement of 1-3% of the fine aggregates with CR. In this method, aggregates, binder and CR are mixed at the same time. Therefore, CR in the mixture appears as rubber aggregates. In the 1960’s, first dry process modified mixture was applied in Sweden and patented under the name of “Rubite”. Later in 1978, this technology was transferred to the United States by the name of “PlusRide” (Heitzman, 1992; Rahman, 2004). Although there can be a limited amount of interactions between CR and asphalt binder throughout the time of mixing in the plant, storage, hauling and compaction of the mixture, asphalt binder is not considered to be modified in the dry application (Wright Asphalt Products Co., 2008). As the advantages of the dry process CR modification, improve in skid resistance and de-icing properties, inexpensive application and more CR disposal could be listed. On the other hand, anti-oxidants are not completely mixed with binder due to short binder-CR interaction period. Therefore, if dry process CR modified mixtures are not designed properly, it may lead to the several performance problems in the pavement.

To compact the dry process crumb rubber mixes, high mixing and compaction temperatures are required in order to prevent the segregation and poor performance. It is recommended to increase the conventional mixing and compaction temperatures by 10˚C to have the binder-CR interaction (Moreno, Rubio, & Martinez-Echevarria, 2011). Typically, these temperatures are about 149-177˚C. Aggregates should be heated and mixed with CR before adding bitumen to provide homogeneous distribution CR within the aggregate batch. Furthermore, the laying and stopping temperatures should be at least 121˚C and 60˚C, respectively. Stopping temperature is specified to prevent the possibility of rubbers swelling (Amirkhanian, 2001; Rahman, 2004).

2.3.2.3 **Terminal blend**

Terminal blend method is similar to the wet process, but, polymers are also used to prevent CR particles to suspend in the modified binder. In this method, CR particles are mixed with binder and polymers at the refinery or terminal. CR is typically added to the binder at 190-204˚C at a rate of 0.6% by total weight of mixture in this method (Wright Asphalt Products Co., 2008).

In this method, dense graded aggregate gradations can be used in addition to open and gap graded ones. As the advantages of this method, it could be mentioned that it could provide superior performance as compare to many polymer modified asphalt pavements (Santucci, 2009). There is no segregation of CR particles and hauling distances for the mixture are longer. On the other hand, its production is costly, and also CR amount used in this method is less, as compare to other CR modification methods.

2.4 Marshall Mix Design

Marshall Mix design was developed by Mississippi Highway Department in 1939. In the following years, U.S. Army advanced this method during World War II to overcome the load and tire pressures created by huge military aircraft. The procedure aims to determine the optimum binder content at the targeted density while meeting the minimum stability and flow value (White, 1985).

Six main steps for Marshall Mix design are defined as follow:

a) Selection of aggregates and determination of aggregate gradation: Physical properties of aggregates such as toughness and abrasion, durability and soundness, cleanliness and deleterious materials, particle shape and surface texture are determined according to the desired standards to certify its usage in asphalt pavement production. Then, aggregate gradation is identified within the limits of the desired specification, which is followed by aggregate blending calculations. Finally, the specific gravity and absorption of the aggregate blend are determined for further calculations.

b) Evaluation of asphalt binder: Binder properties such as penetration, softening point, flash and fire point, ductility and etc. are determined to identify the appropriateness for the design location according to climate. As well as these properties, viscosity test is performed to determine the mixing and compaction temperatures.

c) Procedure for Sample preparation: According to the estimated binder content for the aggregate blend specified in the initial step, sample sets with three replicates are typically prepared as three sets over and three sets below the optimum binder with the increments of ±0.5%. The physical (i.e. air voids, (V_a), density, voids in mineral aggregates (VMA) and voids filled with asphalt (VFA)) and the performance (i.e. stability and flow) properties of these samples are analyzed to determine the optimum binder content.

Marshall compactors (Figure 2.6) can be manual or automatic with features specified in the standard. Samples sizes are approximately 102mm in diameter and 64mm in height. Tamper foot is flat and circular with a diameter of 98.4mm, 76cm^2 area. A hammer weighing 4536gr applies the compaction pressure by falling freely from a height of 457.2mm. According to the design traffic load, compaction effort varies as 35, 50, 75 blows per side.

Figure 2.6 Automatic Marshall Compactor

d) Determination of Marshall Stability and flow: Marshall Stability is a simple measurement for performance attributes of the specimens. It measures the maximum load, which can be carried by the test sample at the loading rate of 50.8mm/minute. Meanwhile, a gauge records the plastic flow of the sample.

e) Determination of Volumetric properties: Bulk specific gravity (G_{mb}) of the compacted mixtures and theoretical maximum specific gravity (G_{mm}) of loose mixtures are determined in order to calculate V_a, VMA and VFA.

f) Selection of optimum asphalt binder: Last step in Marshall mix design procedure is the determination of the optimum binder. This content is estimated by analyzing the results of stability, flow, density, air voids, VMA and VFA with respect to binder content. The optimum asphalt binder content corresponding to the specified air void content is determined and the six parameters listed above are compared with respect to standard limits. As a final step, a final mix with the estimated optimum binder content should be prepared for the verification of the design. If these results do not meet the standard limits, it needs to be redesign (Roberts F. L., Kandhal, Brown, Lee, & Kennedy, 1996).

Figure 2.7 Marshall Stability Testing Apparatus

2.5 Performance Tests

Mix designs need to be further evaluated to estimate their field performance. Therefore, several performance tests are developed to simulate the field distresses through the life of the pavement. Marshall stability and flow test is one of the basic performance tests, to measure the strength of the mixtures. However, further analyses are needed to investigate the low and high temperature performance of mixtures. Therefore, various tests are advanced to estimate fatigue cracking, rutting, moisture susceptibility; as well to measure tensile strength and stiffness (Brown, Kandhal, & Zhang, 2001).

High temperatures performance of CR modified mixtures were studied by many researchers and results of these studies indicated that CR modification of asphalt mixtures commonly yielded to have better performances in terms of rutting (Rodríguez-Alloza, Gallego, Pérez, Bonati, & Giuliani, 2014; Sebaaly, Gopal, & Epps, 2003; Subhy, Presti, & Airey, 2017; Wang, Dang, You, & Cao, 2012). On the other hand, some researchers pointed out that low-temperature performance of the dry process crumb rubber is critical. Therefore, upon these various performance parameters, only indirect tensile strength is discussed in this chapter. Indirect tensile strength test is used to investigate the low-temperature cracking potential of the asphalt mixtures; since low-temperature cracks typically result in top-down cracks regardless of the presence of traffic loads (Brown, Kandhal, & Zhang, 2001).

2.5.1 Indirect Tensile Strength Test (IDT)

Indirect tensile strength test is typically used to estimate the cracking potential of asphalt mixtures due to its ease in testing, in which higher tensile strength tends to better crack resistance (Bindu, 2012).

ASTM D6931: Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures is followed to test the 100mm diameter Marshall samples. The samples are placed between the loading strips having a thickness of 12.70±0.3mm and loaded towards its diametric plane with a constant rate of 50mm/minute, as shown in Figure 2.8 and Figure 2.9. In addition, for the samples with 150mm diameter, the wider loading strips (19.05±0.3mm) can be also used to test according to same procedure (Fedrigo, Nunez, Castaneda, Kleniert, & Ceratti, 2018; Cerni, Bocci, Cardone, & Corradini, 2017; Islam, Hossain, & Tarefder, 2015a; Peng, Wan, & Sun, 2017).

According to ASTM D6931, for specimens with the nominal maximum particle size of 19mm or less, the minimum height is given as 38mm for specimens with 100mm diameter. However, the sample heights are significantly varied in the literature. Since air voids, sample size and testing temperature are not clearly specified in ASTM 6931, a comprehensive literature review is completed as part of this study and experimental parameters are tabulated in Appendix A (IDT test literature review), including the test conditions. The standard only refers 4 hours conditioning before testing at the 25˚C temperature and requires the testing to be completed in less than 2 minutes. In accordance to ASTM D6931, IDT strength is calculated using the peak load applied to sample divided by geometrical factors:

$$S_t = \frac{2000P}{\pi t D} \tag{2-1}$$

Where S_t is equal to IDT strength (kPa), P is the maximum load (N), t is the specimen height (mm) and D is the specimen diameter (mm).

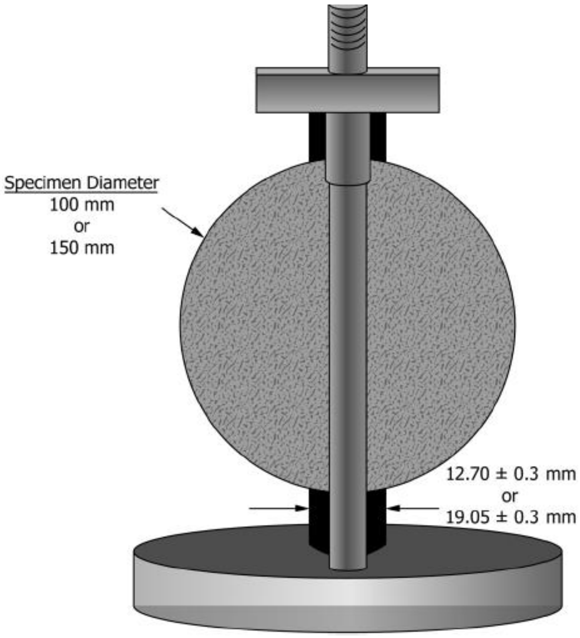


Figure 2.8 IDT strength loading fixture (ASTM D6931, 2012)

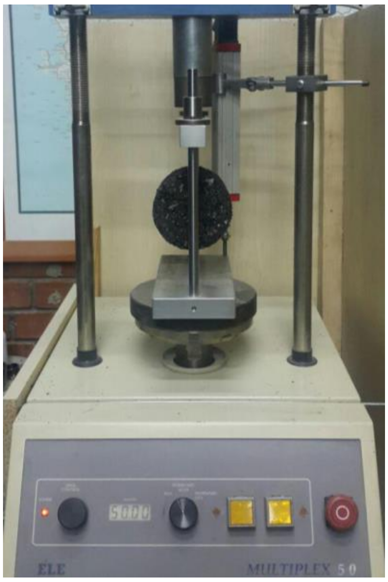


Figure 2.9 Indirect Tensile Test Apparatus

2.6 Determination of Cooling Curves using MultiCool

Compaction temperature plays an important role in order to achieve the targeted air void contents in the asphalt mixtures. For instance, starting the construction below the compaction temperature causes higher air voids. In this case, the mixtures become more prone to fatigue, permanent deformation and moisture damages. Therefore, appropriate planning and accurate scheduling for the construction phase of the project is necessary. This emerges the need to predict the cooling rates of the asphalt mixtures; however experimental predictions are not reliable due to low accuracy since it is a complex phenomenon.

Cooling rate of the asphalt mixture is based on the heat transfer, which has majorly three phases, named as conduction, convection and radiation. Conduction refers to heat transfer between the nearby layers that has lower temperature than asphalt concrete layer. Base layers with lower temperatures during the mixture laying transfer the heat through conduction method. The process, in which heat transfers between a solid layer and a fluid, is named as convection. This heat loss mostly happens when upper layer transfer heat with air, so air temperature has a huge influence in compaction. Finally, radiation heat transfer occurs between two layers through solar energy (Vargas-Nordcbeck & Timm, 2011).

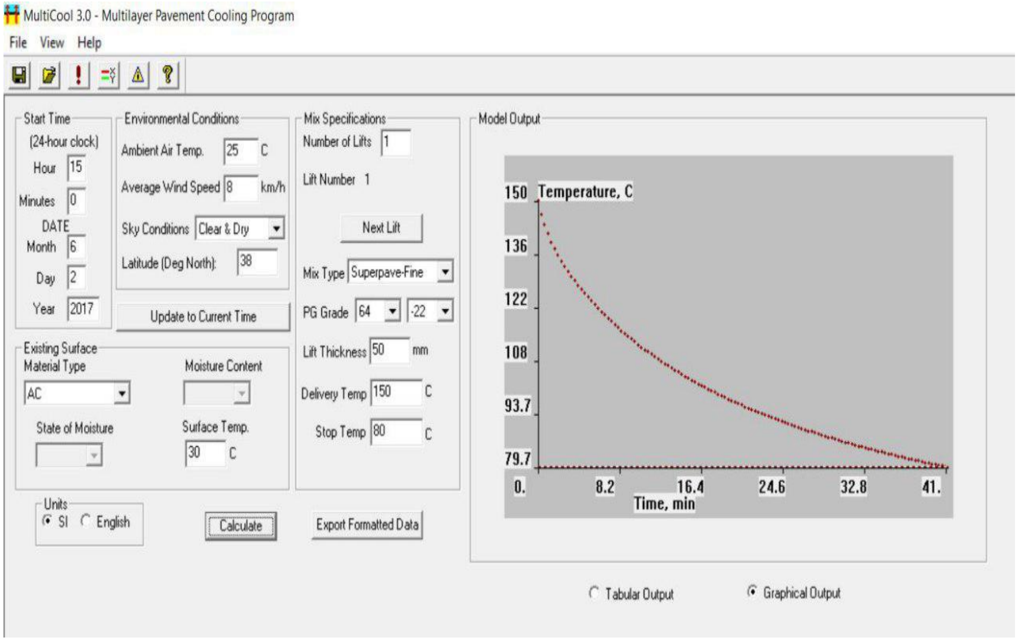
Convection heat transfer as indicated before refers to process of cooling between mixture and air. Different variables can increase the transfer through this process such as wind, air temperature and etc., For instance, higher wind speed causes rapid energy transfer. However, convective heat transfer can be estimated by an equation (2-2) as indicated below (Chadboum, et al., 1998; Diaz Sanchez, 2013):

$$q = H(T_f - T_s) \tag{2-2}$$

where T_f and T_s are mean fluid and surface temperatures, respectively.

Heat transfer between two objects by electromagnetic waves or photon particles named as radiation. To simplify this process, it can be explained that the energy transfer happens assuming no reflection between two black objects where one of them is completely enclosed to other one. In reality, there is not any object that perfectly emits or absorbs the radiation, so there is a factor for each object to indicate the ratio of radiation transfer. Stefan-Boltzmann law states that fourth power of the absolute temperature of an object is directly comparable to the transferred energy and it indicates that the maximum rate of radiation heat was emitted or absorbed (Chadboum, et al., 1998; Diaz Sanchez, 2013).

PaveCool developed at University of Minnesota, incorporated by Minnesota Department of Transportation (FHWA-00-055, 2000). Later, it was named as MultiCool (Figure 2.10) and advanced by researchers in Auburn University used to predict the cooling rate for wide range of asphalt mixtures such as Superpave mixture; stone matrix asphalts (SMA), WMA, RAP and CR modified asphalts. The program is capable of taking into account various construction parameters such as starting time of operation, environmental conditions, existing surface and mixture specifications. These predictions are typically within ±10˚C range for WMA and HMA mixtures (Vargas-Nordcbeck & Timm, 2011). However, there is not still enough accuracy for the modeling of RAP, RAS and CR modified mixtures. Under-predictions happen at the higher temperatures, whereas it changes to over-prediction at the lower temperatures (Sanchez & Timm, 2014).


MultiCool 3.0 - Multilayer Pavement Cooling Program

Start Time (24-hour clock)
Hour 15
Minutes 0
DATE
Month 6
Day 2
Year 2017

Environmental Conditions
Ambient Air Temp. 25 C
Average Wind Speed 8 km/h
Sky Conditions Clear & Dry
Latitude (Deg North): 38

Mix Specifications
Number of Lifts 1
Lift Number 1
Mix Type Superpave-Fine
PG Grade 64 -22
Lift Thickness 50 mm
Delivery Temp 150 C
Stop Temp 80 C

Existing Surface
Material Type AC
Moisture Content
State of Moisture
Surface Temp. 30 C

Units ● SI ○ English

○ Tabular Output ● Graphical Output

Figure 2.10 MultiCool Pavement Cooling Program

As a brief summary of Multicool, start time, environmental conditions, existing surface and mix specifications are four major parameters in the program. The effects of these parameters on the cooling rate are discussed as follows:

2.6.1 Starting Time of Operation

Time and date of the project could be set in this section to accurately simulate the conditions at the time of the construction.

2.6.2 Environmental Conditions

The environmental parameters are ambient air temperature, average wind speed, sky conditions and latitude. All parameters can be updated according to the GPS coordinates of the projects, based on the online forecast data. However, it is also possible to manually input these parameters.

Ambient air temperature specifies the average temperature of the construction site during the compaction phase. For relatively high ambient air temperature, there is more available time for compaction since it will take longer for the asphalt mixture to cool down till stop temperature (Scherocman, 2000). Thus, the ambient temperature is an essential parameter for the prediction of cooling of asphalt mixtures.

Wind speed is another essential parameter in the program that inversely affects the available compaction time. Higher wind speed decreases the compaction time as the cooling rate increases.

Beside temperature and wind speed, sky condition has adverse effects on the construction frame. The program is capable of predicting in different sky conditions such as clear and dry, partly cloudy and overcast etc.

2.6.3 Existing Surface Course

Four commonly used base materials, asphalt concrete (AC), Portland cement concrete (PCC), granular base and subgrade soil, are the options available in the program. Heat transfer through conduction is directly affected from the selected base type.

Moisture content and state of moisture can also be identified, when granular base and subgrade soil are selected. Additionally, dry and wet choices are available for moisture content and it can be also stated as frozen or unfrozen. However, this option is neglected for selection of the AC and PCC base.

Surface temperature is also as important as the ambient air temperature. Compaction time can be extended if the base temperature is higher (Scherocman, 2000).

2.6.4 Mix Specifications

Dense graded, SMA, Superpave-fine and Superpave-coarse asphalt mixtures are four mixture options in the program. In addition, number of lifts can also be indicated according to project plan and each lift separately requires its own data such as mix type, PG grade, lift thickness, delivery temperature and stop temperature.

Among these variables, lift thickness significantly affects the cooling rate, since it takes more time to cool for thicker layers as compared to thinner layers. In addition, wind speed and thickness parameters are directly linked to each other. For instance, a higher wind speed can cool a thinner layer more quickly than a thicker layer (Scherocman, 2000).

For the cooling rate calculation, delivery and stop temperatures are the other significant parameters. Mixing temperature commonly is accepted as delivery temperature. In addition, stop temperature is typically accepted as 80˚C, at which paver should finish the compacting to get the expected density (Behl, Kumar, Sharma, & Jain, 2013; ASTM D6932, 2013; Song & Ahmed, 2017; Transportation Department the City of Calgary, 2012; Dickson & Corlew, 1970; Texas. Department of Transportation, 2014).

2.7 Previous Studies

As it has been mentioned in Chapter 1, the focus of this study is the dry process crumb rubber modification of Warm Mix Asphalts, since it is the first attempt to associate these two methods. Different parameters such as temperature and conditioning time are taken into account according to the current literature. In this section, recent studies are summarized as follows.

2.7.1 Warm Mix Asphalt

Warm Mix Asphalt has been taking attention of many researchers, agencies and contractors. As discussed in section 2.2.2, there are various WMA technologies. Therefore, only a limited number of them are discussed in this section.

Arega and Bhasin (2012) studied the effects of chemical WMA additives on the stiffness, permanent deformation, fracture and thermal cracking resistance of asphalt mixtures, as well its effects on the binder such as viscosity. Sasobit, Cecabase RT 923, Evotherm DAT, Evotherm 3G and Rediset WMX were the additives selected in this study and were compared to control (unmodified) samples. It was concluded that viscosity of the binder aged or unaged prepared with WMA additives was similar or significantly less comparing to control samples. Thus, asphalt mixtures prepared with WMA additives could be stored in the silo for more time or hauled for longer distances. Sasobit added binders had a better response to early age stiffness and rutting resistance. Despite that, there was stiffness loss for other WMA additives due to additive and reduced aging. Additionally, it was concluded that using WMA additives with recycled asphalt increased the asphalt binder susceptibility to low-temperature cracking.

Ahmed et al. (2012) added chemical modifiers and asphaltenes to the asphalt binder in order to improve the workability, resistance to chemical aging and moisture damage. It was concluded that chemical and physical hardening of binders were significantly affected; ductile strain tolerance changed noticeably and cracking susceptibility increased by adding amide and polyethylene.

Xiao et al. (2012) studied the rheological properties for non-foaming WMA additives (Cecabase, Evotherm, Rediset and Sasobit) at high performance temperatures. According to results, it was stated that non-foaming additives reduced the viscosity. Viscosity reduction caused to lower mixing and compaction temperatures. In addition, rutting resistance improved at higher temperatures.

Ozturk (2013) utilized foam based WMA technique and concluded that foaming significantly reduces the mixture viscosity to facilitate better coating of the aggregates, increases the workability of the loose mixtures and provides better compaction at lower temperatures.

Gandhi (2008) studied WMA using the additives (Sasobit and Aspha-min) since there was a huge debate to decrease the emissions by lower mixing and compacting temperatures to avoid the global warming. Both aged and unaged binders with additives were used to analyze with respect to unmodified binders. Also, it was stated that even aged binders extracted from WMA had significantly lower viscosity. Thus, it resulted in lower mixing and compacting temperatures, in addition to the better rutting resistance.

Sheth (2010), Zhang et al. (2015), Behl et al. (2013), Abdullah et al. (2013), Canestrari et al. (2013), Yin (2009) and Behl et al. (2014) also indicated that using WMA additives decreased the viscosity and the mixing and the compaction temperatures. Thus, the green gas emissions were reduced. In addition, the asphalt performance is improved as compared to traditional HMA. In addition, better workability and compactibility were observed in WMA. Similarly, in many studies, the performance of different additives at various contents was investigated in binders and mixtures.

2.7.2 Crumb Rubber Modification

As summarized in Section 2.3.1, crumb rubber usage is commonly used in pavement industry since 1950's. Thus, the literature is significantly broad. Therefore, this section initially summarizes some of the recent studies on dry process modification. Then, it focuses on the available literature on wet process modified warm mix asphalts.

2.7.2.1 **Dry Process**

Moreno et al. (2011) studied the optimization of digestion time of dry process crumb rubber modified asphalt mixture. As an outcome, it was concluded that conditioning the mixtures did not effect on optimum binder selection. However, it improved the mechanical performance of asphalt pavement.

Dias et al. (2014) selected two gap-graded dry process CR mixtures to compare with a traditional gap-graded reference mix, as well with a wet process mixture. Observations indicated that bitumen had become harder, since CR particles absorbed the light fractions in the binder. Additionally, fatigue and rutting tests indicated that CR modification increased the mechanical performance of the mixture. Besides, fatigue and rutting results did not have a huge difference compared to wet process samples.

Cao (2007) investigated the properties of the dry process modification based on the crumb rubber content. The mixtures were modified with 1, 2 and 3% CR by weight of total mixture. Then, their resistance to permanent deformation performing rutting test at 60˚C and to cracking performing indirect tensile strength test at -10˚C were evaluated. It was recommended to use SBS modification for the gap-graded dry process CR modified samples. In addition, permanent deformation and indirect tensile tests indicated that CR modification could improve these properties and the samples with 3% rubber content had the best performance compared to other samples, which was concluded by Analysis of Variance test (ANOVA) on rutting and indirect tensile tests.

According to the literature, the key parameters are selected as conditioning time, mixing and compaction temperatures

2.7.2.2 **Wet Process Modification**

As WMA has been taking attention of many researchers, its incorporation with other modifications also got interest by many researchers. In recent years, studies focused on wet process CR modification of WMA mixtures.

Gallego et al. (2016) studied effects of wet process CR modification in WMA used Sasobit and Licomont BS 100 additives. The CR contents were selected as 15% and 20% by weight of the binder. Dynamic Shear Rheometer (DSR) tests were performed at specific temperatures and frequency ranges. Additionally, creep test was used to evaluate the performance properties of asphalt mixture. It was concluded that the addition of WMA additives and CR in the binder increased the elasticity and improved the rheological behaviors. Also creep test indicated that permanent deformation resistance improved in WMA mixtures.

Low temperature crack resistance of CR modified asphalt mixture was studied by varying the CR dosage, CR size and testing temperature by Wang et al. (2016). A dense and gap gradation was prepared by using five different rubber dosages (15, 18, 20, 22 and 25% weight of base binder). Accordingly, semi-circular bending tests (SCB) were conducted at 0, -10 and -20˚C. It was stated that low-temperature crack resistance properties of mixture containing small size CR particle were improved.

Oliveira et al. (2013) also investigated the rubber in the binder with and without WMA additives. Four different samples were prepared: HMA, WMA, Asphalt rubber HMA and Asphalt rubber WMA. Researchers studied the effects of using WMA additives in decreasing of mixing and compaction temperatures. Additionally, different contents of additives were used and increased during the addition of rubber. Thus, influence of these changes, on the performance of asphalt mixtures was studied. It was concluded that adding WMA additives decreased the both temperatures by 30˚C without compromising the performance.

Kim et al. (2014), Padhan et al. (2017), Wang et al. (2012), Kim & Lee (2015), Yu et al. (2016)and Ziari et al. (2016) were the other researches working on CR modification and evaluating the effects of AR incorporated by WMA additives. Ziari et al. (2016) studied moisture susceptibility, rutting resistance and structural response of AR mixtures by using tensile strength ratio, dynamic creep test, wheel tracking and indirect resilient modulus. It resulted that using CR in the mixtures incorporated by additives improved the asphalt performance. In addition, Kim & Lee (2015) indicated that using additives with CR increased the hauling time. However, viscosity of binder with additives changed over time for the samples with higher content of rubber. Overall, the viscosity decreased for the whole mixtures.

2.7.3 Conditioning time

Due to the segregation problems in the dry process CR modified asphalts, conditioning of the mixtures for a period of time is essential for digestion of particles in order to increase the cohesion between the particles. Conditioning time (digestion time) became the focus of many studies in order to study the effects on the binder-CR interactions. Since temperature and the duration of conditioning are the variables that influence the interaction, these parameters were tried to be optimized in various studies.

Jeong et al. (2010) studied the effects of binder-CR interaction for different contents of rubber. Thus, four different contents of rubber were selected to evaluate these relations. Accordingly, 5, 30, 60, 90, 120, 240 and 480 minutes of conditioning periods at 177, 200 and 223˚C were studied in this research. It was concluded that interaction time and the temperature had significant effects on the binder properties. Moreover, CR percentage affected the binder properties.

Ghavibazoo and Abdelrahman (2013) also investigated the CR-binder interactions. Properties of bitumen before and after modification with CR were analyzed. Besides, it was concluded that conditioning in lower and higher temperatures had different effects on the bitumen. In addition, 10, 120 and 240 minutes of conditioning periods were selected and it was indicated that increasing the time of conditioning improve the CR dissolution in bitumen.

2.7.4 Indirect Tensile Strength Test (IDT)

As indicated before, IDT is one of the most common performance tests. However, ASTM D6931 standard do not clearly specify testing parameters such as air voids, testing temperature, sample size and etc. Many researchers performed this test on Marshall samples (Fedrigo, Nunez, Castaneda, Kleniert, & Ceratti, 2018; Fu , et al., 2017; Šimun & Halle, 2014; Zhao, Yan, Yang, & Peng, 2018; Cerni, Bocci, Cardone, & Corradini, 2017; Corradini, Cerni, D'Alessandro, & Ubertini, 2017; Islam, Hossain, & Tarefder, 2015a; Modarres & Alinia Bengar, 2017; Peng, Wan, & Sun, 2017). In the literature, although the majority of samples had 63.5mm heights, there were samples with heights of 40, 50 and 65mm. Similarly, testing temperature ranged in a large scale. Typical test temperature was observed to be room temperature (25˚C) and other common temperatures were 20 and -10˚C. In addition, although air voids had significant importance in performance tests, there was no agreement in the percentage of air voids. On the other hand, loading rate was typically selected as 50mm/minutes.

Stiffness of the asphalt mixes is an essential parameter in order to evaluate the distresses as indicated in Šimun & Halle (2014). High stiffness modulus during winter and low-temperature conditions with cyclic loading can result in cracking. Indirect tensile test was used to evaluate the stiffness modulus of pavements in this research. 100mm diameter and 60-65mm height of samples were used with variable air void values and tested at different temperatures. Sample prepared with the lowest bitumen content, with highest filler amount, and also had the lowest air voids, was the stiffest specimen. In other words, increasing filler content and decreasing bitumen content in the asphalt mixtures resulted in higher stiffness modulus.

Modarres & Alinia Bengar (2017) used Marshall design as well, in order to evaluate the indirect tensile strength. In this study, the test temperature was selected as 20˚C and samples were conditioned for 5 hours at this temperature. Besides, Copper Slag Powder (CSP) and Limestone Powder (LSP) were used as filler for HMA samples with different contents. As the result, it was concluded that mechanical properties of samples were improved by adding CSP and filler properties had a significant effect on the indirect tensile strength of asphalt mixtures.

Zhao et al. (2018) used Sasobit and Deurex as WMA additives in asphalt mixtures in order to study the indirect tensile strength, Marshall stability, volumetrics and other properties of the specimens. Accordingly, as the part of this study, the samples with 101.6mm diameter and 63.5mm height were tested under a loading rate of 1mm/minute at -10˚C. Samples with various air voids were tested in the range of 3.5 and 4.8%. It was concluded that these additives resulted in better low-temperature cracking resistance.

Lusher (2017), Richardson & Lusher (2008), Islam et al. (2015b), Yin et al. (2017), Dan et al. (2018), Yin et al. (2018) and Liu et al. (2015) also studied indirect tensile strength of different mixtures and used samples with 150mm diameter. Although most common height selected for these samples was 50mm, samples with height of 32, 38, 40 and 130 were also used in these studies. Important difference of Superpave samples is about the loading rate compare to Marshall ones and loading rate was varied as 12.5mm/minute in some of these studies, whereas the loading rate was kept as 50mm/minute in others. Besides, air voids were varied in a wide range and the test temperatures were also changed from -10 to 25 °C.

2.7.5 Cooling Curves

The determination of cooling rates of the mixtures is essential for managing and scheduling of the projects. Therefore, many laboratory and field studies were conducted in the recent years.

Chang et al. (2009) studied the dense graded and porous asphalt (PA) mixtures to evaluate the mechanical properties and to estimate the available time frame for construction during night time until completing compaction. Therefore, laboratory test conducted from lay down till compaction. To control the cooling temperature rate in different layers, thermocouples were placed to each layer. Initially, it was observed that there was a difference of temperature in 0, 2.5 and 5cm depths. However, it became stable during the compaction. By increasing the thickness of the layer, it was observed that available compaction time significantly increased till 10cm. Overall, it was concluded that a method could be developed to find the pavement-cooling rate.

Song & Ahmed (2017) studied the cooling rate of WMA as compared to HMA. It was indicated that WMA would have slower cooling rate than HMA. Thus, it was resulted an extension in the available hauling time and better compaction to achieve the specified density. Night construction, late season paving and long hauling were three major advantages of WMA mixtures, which were concluded by running Multicool program (Timm, Voller, Lee, & Harvey, 2001).

Study conducted by Goh & You (2009) indicated that WMA could be used in cold regions due to slower cooling rates, in addition to the temperature reduction, lower emission, binder aging, energy saving and early opening to traffic. This low rate could be a result of comparably less difference between production and ambient air temperatures. In a field project, Ahmed (2015) investigated two paving projects (WMA with Sasobit and HMA) and also indicated better performance for WMA. Additionally it was concluded that longer period of compaction time allowed to use the WMA for long hauling, night time work and late season paving.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter includes properties of materials, experimental design and preparation procedures followed in this study. All the tests and experiments completed in METU transportation laboratory, following the ASTM and AASHTO standards and Turkish General Directorate of Highways specifications.

3.2 Materials

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

3.2.1 Aggregates

3.2.1.1 Aggregate gradation selection

Seven different trial aggregate gradations were examined in the range of various implemented dry process CR modified asphalt mixtures in the literature, since there is no standard referring the gradation limits (Moreno, Rubio, & Martinez-Echevarria, 2011; Dias, Picado-Santos, & Capitao, 2014; Cao, 2007; Rahman, 2004; Rahman, Airey, & Collop, 2005; Rahman, Airey, & Collop, 2010; Yu, Wu, Zhou, & Easa, 2014; Al Qadi, AlHasanat, & Haddad, 2016). Based on the trial aggregate skeletons, samples were prepared to determine the optimum binder content at the desired air void content. The details of the mix design were given in Section 3.3. The final aggregate batch and CR gradations were presented in Table 3-1. The aggregate batch consisted of 66.4% of coarse aggregates, 27.8%

fine aggregates and 5.8% filler. The CR, the aggregate batch and the CR-aggregate blend gradations were plotted in Figure 3.1.

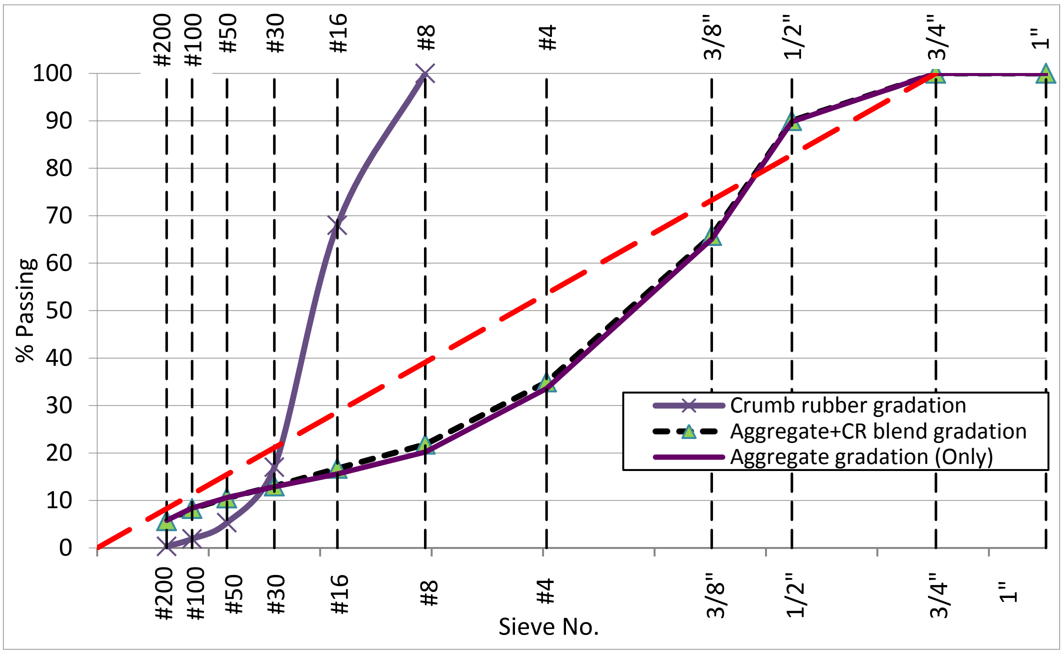


Figure 3.1 Aggregate and CR gradations

Table 3-1 Aggregate and CR gradations

Sieves		Aggregates	CR
3/4″	% Passing	100	-
1/2″		89.8	-
3/8″		65.1	-
#4		33.6	-
#8		20.2	100
#16		15.6	68
#30		12.9	17
#50		10.6	5.3
#100		8.4	1.9
#200		5.8	0.3

3.2.1.2 Aggregate properties

Prior to the design process, properties of materials should be determined. In this study, dolomite supplied from a local quarry was used and its physical properties were determined such as the specific gravity and water absorption. These properties were tabulated in Table 3-2 for fine and coarse aggregates, based on the referred standard. Accordingly, bulk specific gravity of the aggregate batch and CR-aggregate blend (G_{sb}) were calculated to be 2.782 and 2.704, respectively.

Table 3-2 Properties tests for aggregates

Property (Unit)		**Standard**	**Result**
Water Absorption (%)	Coarse	ASTM C128	0.604
Water Absorption (%)	Fine	ASTM C128	0.563
Specific gravity for Coarse aggregate	Bulk	ASTM C127	2.785
	SSD	ASTM C127	2.802
	Apparent	ASTM C127	2.833
Specific gravity for Fine aggregate	Bulk	ASTM C127	2.775
	SSD	ASTM C127	2.791
	Apparent	ASTM C127	2.819
Percent Loss Using Los Angeles Test	-	ASTM C131	18%

3.2.2 Asphalt binder

One type of asphalt binder, Pen 50/70, was used to prefabricate the asphalt mixtures. The physical properties of the asphalt binders were determined based on viscosity (Figure 3.2), softening point, ductility, penetration, flash and fire point and specific gravity tests (Table 3-3).

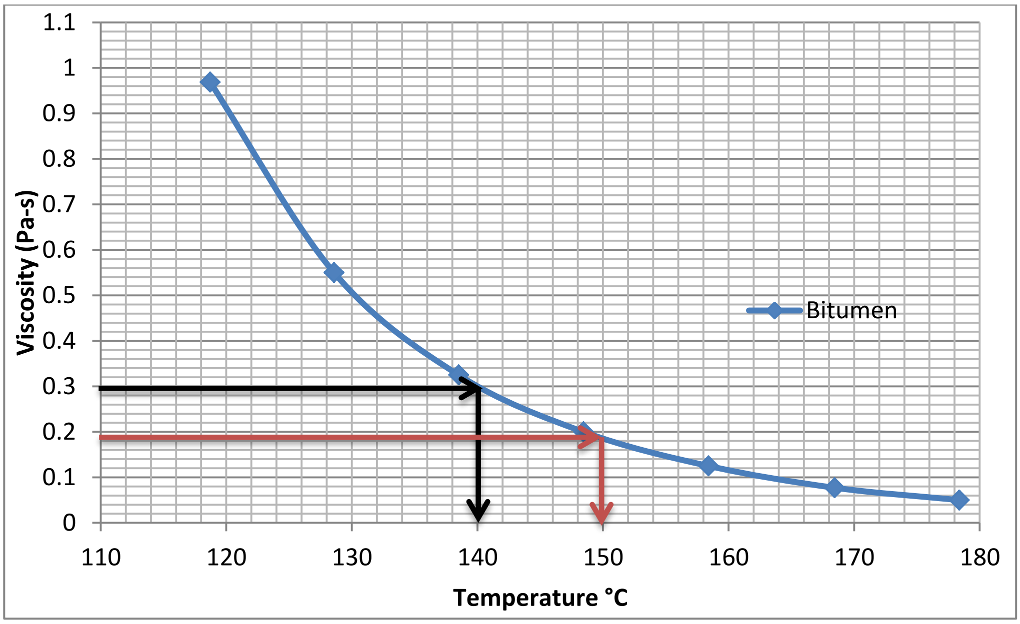


Figure 3.2 Viscosity - Temperature Curve for Ashpalt Bitumen

The mixing and compaction temperatures for HMA mixtures were determined according to viscosity-temperature curve, with respect to Asphalt Institute method. Thus, the temperatures corresponding to viscosity ranges of 0.17± 0.02 Pa-s and 0.28 ± 0.03 Pa-s were determined as the mixing and compaction temperatures, respectively. Accordingly, mixing and compaction temperatures were identified as 150 °C and 140 °C, respectively.

Table 3-3 Asphalt binder properties

Property (Unit)	Standard	Result
Binder grade	-	Pen 50/70
Softening point (˚C)	ASTM D36	53.5
Ductility (cm)	ASTM D113	>100
Penetration (25˚C, 0.1mm)	ASTM D5	64
Flash point (˚C)	ASTM D92	320
Fire point (˚C)	ASTM D92	364
Specific gravity G_b (gr/cm^3)	ASTM C70	1.024

3.2.3 WMA additives

Additive selected in this study was a non-foaming WMA additive (Sasobit) based on the availability in Turkey. To study the effect of additive content on the mixture properties, 1.5 and 3% Sasobit by weight of binder were used. 1.5% of Sasobit is the typically suggested additive dosage by the suppliers. However, this dosage can vary in the range of 0.8-4% by weight of the binder according to the aggregate gradation (Prowell, Hurley, & Frank, 2011). Additionally, Ozturk and Pamuk (2017) studied the different percentage of the WMA additive including Sasobit and it was indicated that the mixtures prepared with 3% Sasobit had better compactibility than 1.5% Sasobit containing mixtures. It should be referred that Shaw (2007) indicated that Sasobit dosage varies the performance grade (PG) of binder. Therefore, in the early stages of the study, the two different dosages (1.5% and 3%) were initially used and their influence on mixture properties was analyzed. Then, only one dosage (3%) was used in the further steps of the study. The reasons were further discussed in detail within the Chapter 4.

3.2.4 Crumb Rubber

Crumb rubber gradation selection is significant for the success of the binder-CR interaction. Therefore, a fine CR gradation is selected similar to the ones selected in the literature. As given in Figure 3.3, the one on the left side is the CR sample used in this study, whereas the one on the right side with larger gradation typically is used in concrete production. Crumb Rubber used in this study provided by a local supplier with the gradation given in Table 3-1 and Figure 3.1. CR content kept constant for all DryHMA and DryWMA as 2% by weight of the total mixture. On contrary to the aggregates, for sample preparation, CR has been used in the samples without any further sieving. Additionally, HMA samples were also prepared without CR to compare the effects of CR usage in this study. Typically, the color of the CR used in this study was black.

Figure 3.3 Different CR physical properties

3.3 Design properties

Marshall mixture design was selected as the design method in this study since one of the major focuses is the production temperature. Although it is known that Superpave mix design better simulates the compaction in the field, gyratory compactor is not sensitive to temperature changes (Roberts F. , Kandhal, Brown, Lee, & Kennedy, 1991; Huner & Brown, 2001; Delgadillo & Bahia, 2008; Hurley & Prowell, 2006; Bahia, et al., 2001). On the other hand, it is proven by many researchers that Marshall compaction is sensitive to compaction temperature changes (Hurley & Prowell, 2006; Prowell, Schreck, & Sasaki, 2011).

3.3.1 HMA

HMA samples were prepared in accordance to the gradations given in Figure 3.1. The final gradation of HMA was the same as the aggregate and CR blend, but CR was replaced with fine aggregates in this mixture. As indicated, Marshall design was used in the determination of the optimum bitumen content based on the NAPA method. Only three trial binder contents (4, 4.2 and 4.5% by weight of the total mix) were tried to determine the optimum binder content. Voids in Mineral Aggregates (VMA), Voids Filled with asphalt (VFA), air voids (VTM), density, stability and flow were given in Table 3-4. Optimum binder content was selected as 4% by weight of the total mix. It should be noted the trials were limited with three, since DryHMA and DryWMA mix designs were completed earlier and the range was estimated based on experience.

Table 3-4 Marshall design properties for HMA without CR

Asphalt Content (%)	VTM (%)	VMA (%)	VFA (%)	Density (gr/cm^3)	Flow (mm)	Corrected Stability (kgf)	G_{mb}
4.0	4.684	14.049	70.696	155.472	1.897	928.732	2.490
4.2	2.942	14.378	72.402	155.199	2.223	878.481	2.486
4.5	3.118	13.743	82.036	156.841	1.830	993.536	2.512

3.3.2 DryHMA and DryWMA

Samples with binder content of 5, 5.5, 6 and 6.5% by weight of total mixture were prepared as given in Table 3-5 and Marshall design graphs were drawn as plotted from Figure 3.4 to Figure 3.9 for DryHMA. According to the standards, air voids-binder content, VMA-binder content, VFA-binder content, density-binder content, flow-binder content, stability- binder content and G_{mb}-binder content graphs were used in order to find the optimum bitumen percentage. Initially, the optimum bitumen corresponding to 4.4% air voids was determined based on the NAPA method. In the following, VMA, VFA, density, flow, stability and G_{mb} values were determined according to the optimum bitumen in previous step, as given in Table 3-6. Finally the Marshall design was completed and used in the further steps of the study and the optimum binder content was kept same for DryWMA.

Table 3-5 Marshall Mixture Design Properties of DryHMA

Asphalt Content (%)	VTM (%)	VMA (%)	VFA (%)	Density (gr/cm^3)	Flow (mm)	Corrected Stability (kgf)	G_{mb}
5.0	5.063	18.148	65.835	149.624	3.737	742.775	2.397
5.5	4.467	18.494	71.137	149.779	5.480	760.385	2.399
6.0	3.587	18.830	76.314	149.960	4.926	657.806	2.402
6.5	3.315	19.511	79.540	149.499	6.423	648.821	2.395

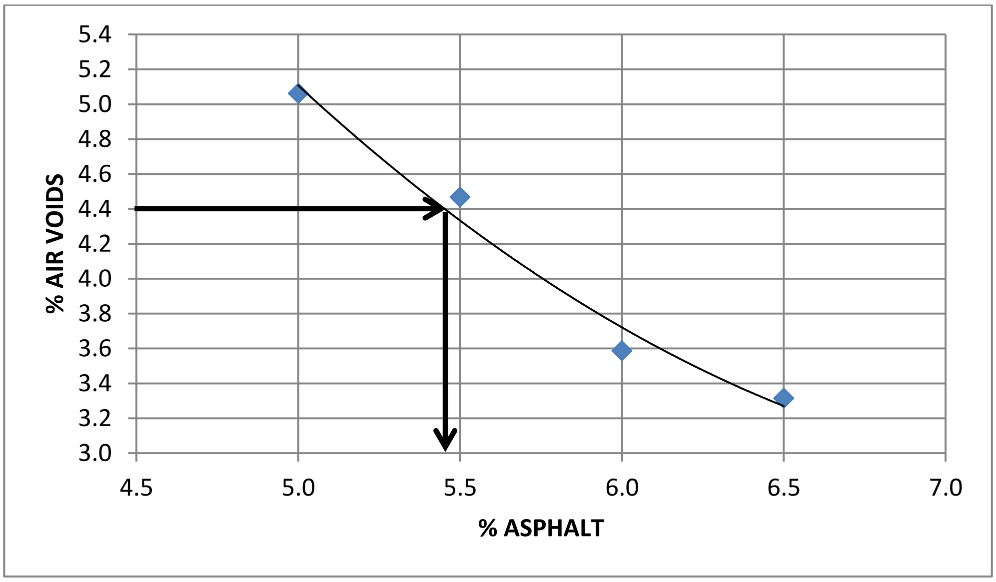


Figure 3.4 Air Voids - Asphalt Content

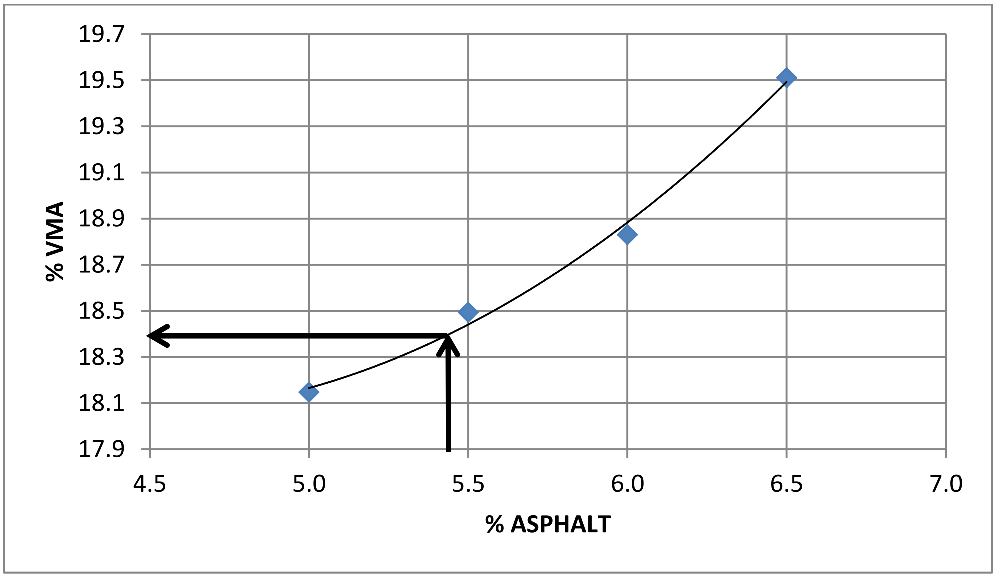


Figure 3.5 VMA - Asphalt Content

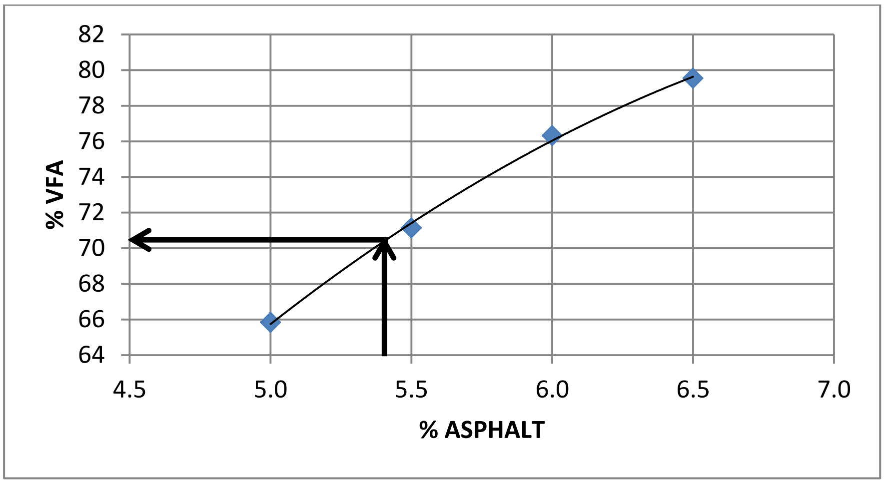


Figure 3.6 VFA - Asphalt Content

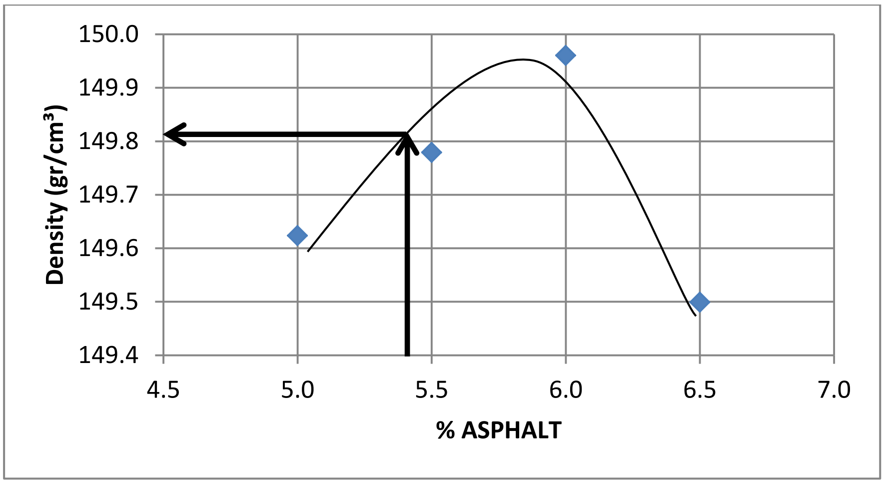


Figure 3.7 Density - Asphalt Content

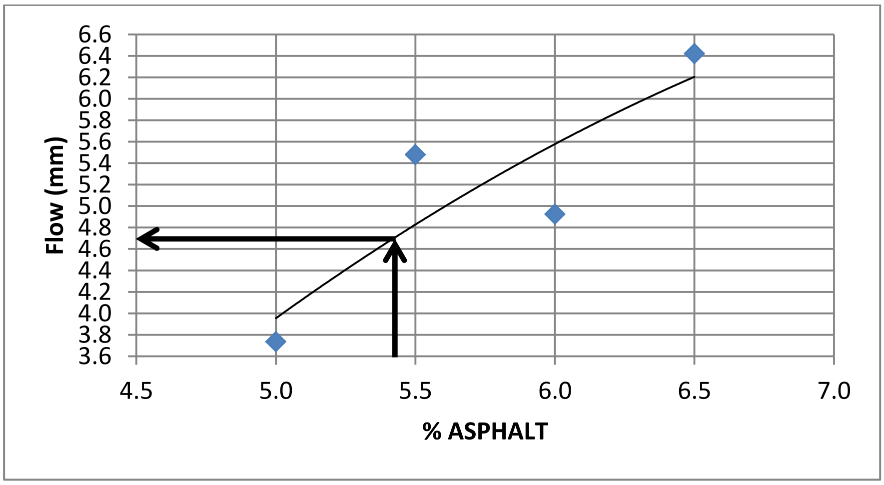


Figure 3.8 Flow - Asphalt Content

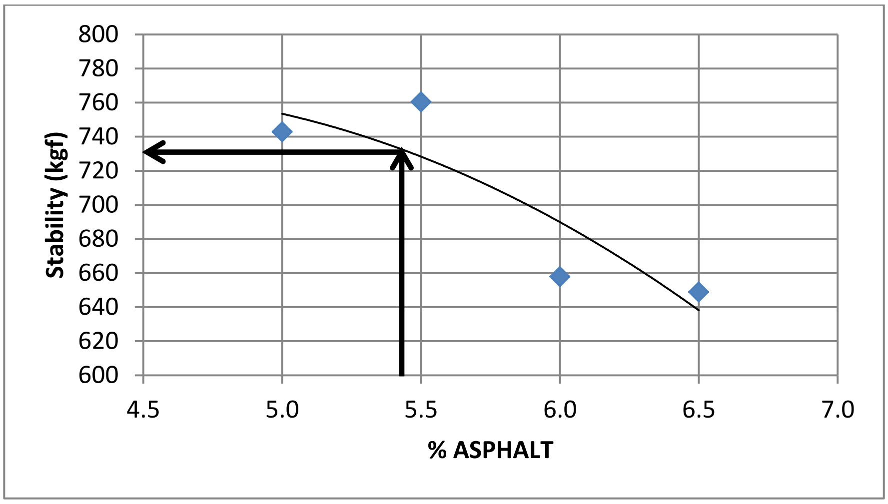


Figure 3.9 Stability - Asphalt Content

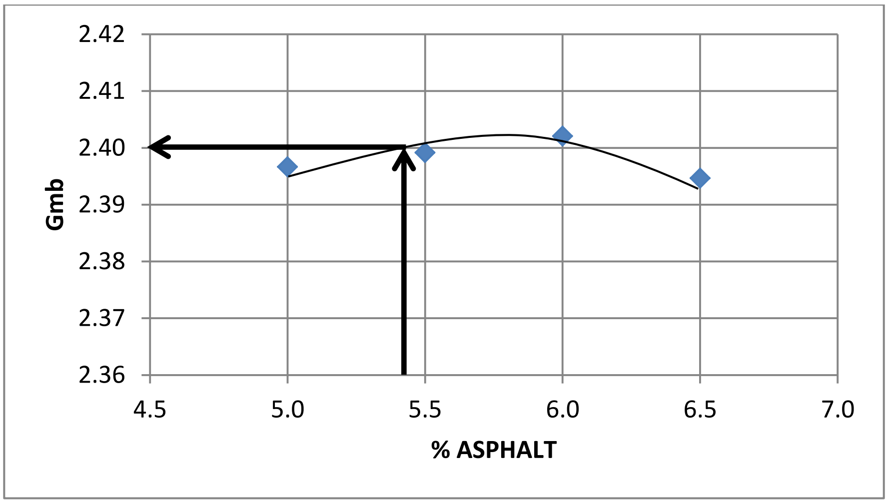


Figure 3.10 Gmb - Asphalt Content

Table 3-6 Optimum Design Properties

%Air Voids	%A.C.	%VMA	%VFA	Density (gr/cm^3)	Flow (mm)	Stability (kgf)	Gmb
4.40%	5.45%	18.40%	70.8%	149.81	4.70	730	2.40

3.4 Experimental design

Seven different mixtures were prepared consist of one HMA, one DryHMA and five DryWMA. The details of the mixtures were discussed in this section.

3.4.1 HMA samples

First mix was the traditional HMA mixture without CR and Sasobit. Mixing and compaction temperature for this mixture was determined according to the viscosity curves discussed in the previous section. Also considering the optimum air voids (4.5% for the all mixes), 4% binder content was selected for this mixture set in order to have a better comparison with the other samples.

3.4.2 DryHMA samples

Second mix was the dry process CR modified HMA (DryHMA), which has 2% CR without Sasobit additive. 5.5% binder content was used in these samples to achieve 4.5% targeted air voids. Unlike the HMA samples, all other samples were conditioned for 0, 45, 90 and 120 minutes in the oven in order to study the effect of conditioning time on the samples. The mixing and compaction temperatures of DryHMA samples were specified as 160˚C and 150˚C, respectively. These temperatures were 10˚C more than the conventional mixing and compaction temperatures. To provide the interaction between binder and CR, it was suggested to increase the temperatures in several researches for dry process CR mixtures (Moreno, Rubio, & Martinez-Echevarria, 2011). Experimental matrix for this study was presented in Figure 3.11 in detail.

3.4.3 DryWMA samples

Dry process CR modified WMA mixtures were prepared by varying the design parameters. Five different mixtures were discussed in the following (Table 3-7):

DryWMA 1 was the sample set prepared by 2% CR by weight of the total mix and 1.5% Sasobit by weight of binder in the four different conditioning times. 5.5% binder content was selected as mentioned before. Initially, volumetrics, stability and the performance tests were used to evaluate and compare with other samples. The same mixing and compaction temperatures as DryHMA were used for DryWMA 1. This was necessary to study the effect of adding WMA additive to DryHMA.

DryWMA 2 consisted of 2% CR by weight of the total mix and 3% Sasobit by weight of binder. Four different conditioning times also applied for this mixture set. Binder content of 5.5% by weight of total mixture was also utilized. Besides, mixing and compaction temperatures kept same as DryWMA 1 and DryHMA in order to study the effects of additive content on mixture properties.

DryWMA 3 had the same CR and WMA content as the DryWMA 2 but this time, 15˚C lower mixing and compaction temperatures were selected. As well, four different conditioning times same as the other samples were taken into account to study the effects of digestion time with respect to temperature.

DryWMA 4 was mixed at 160˚C, but only compaction temperature is lowered by 15˚C. Other than that, the CR and WMA contents and conditioning periods were kept same as DryWMA 2 and DryWMA 3.

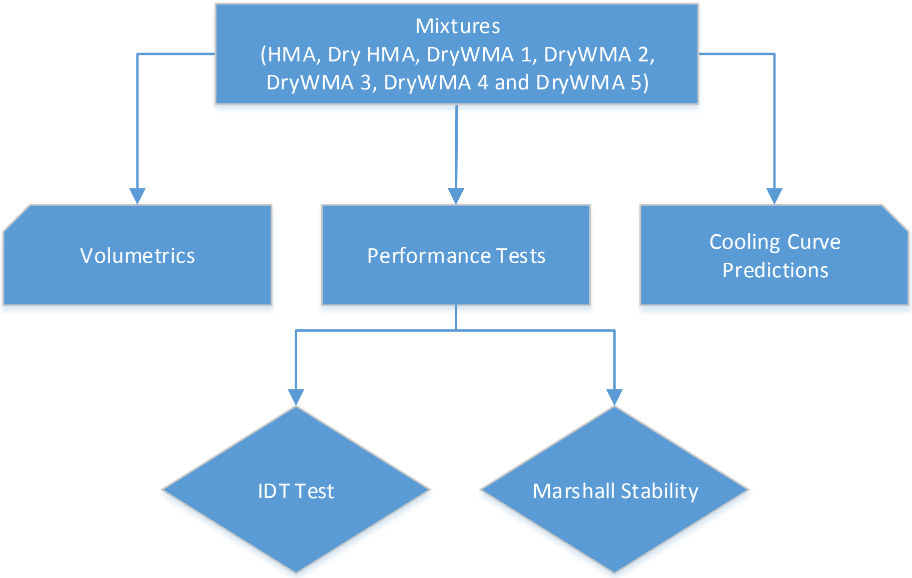


Figure 3.11 Experimental Matrix

DryWMA 5 was prepared same as DryWMA2, but the laboratory compaction effort was reduced. All samples, except DryWMA 5, compacted by 75 blows per side with Marshall hammer. However, 50 blows per each side were selected to compact the DryWMA 5 to study the impact of compactibility. Decreasing the number of compaction blows resulted in an increase in the air voids within the samples to the air void level of the other sample sets (i.e. DryHMA, DryWMA3 and DryWMA4). Thus, the performance properties became comparable to other mixture sets.

Table 3-7 was prepared to summarize the details of the different sets of asphalt samples, as discussed above.

Table 3-7 Sample properties matrix

Mixture Type	Mixing Temperature (˚C)	Compaction Temperature (˚C)	WMA Additive (%)	No. of Blows	CR Content (%)
HMA	150	140	0	75	0
DryHMA	160	150	0	75	2
DryWMA 1	160	150	1.5	75	2
DryWMA 2	160	150	3	75	2
DryWMA 3	145	135	3	75	2
DryWMA 4	160	135	3	75	2
DryWMA 5	160	150	3	50	2

Volumetrics and stability results of all samples except DryWMA 5 have been evaluated for all test samples and at least 6 samples were prepared for each set.

3.5 Sample preparation

As discussed in detail in the previous section, there are majorly three different mixtures: HMA, DryHMA and DryWMA. Therefore, their preparation procedures are varied and explained in this section. To achieve repeatability in the sample preparation, these steps kept constant for each testing set as explained in the following.

3.5.1 HMA preparation

HMA samples are prepared in accordance to the following procedure:

- The binder was poured into the pre-heated aggregate blend, which was 5˚C more than the mixing temperature.
- This mixture was mixed in the heater equipped mechanical mixer at the mixing temperature for 3 minutes.

- The samples were brought to the 7˚C more than the compaction temperature by stirring with a spatula to maintain the homogeneous cooling.
- The cooled samples were poured to the molds, which were pre-heated in the oven at the compaction temperature for compaction (Figure 3.12).

3.5.2 DryHMA preparation

DryHMA samples were prepared according to the following procedure:

- The CR and pre-heated aggregates were rapidly mixed with a spatula for 30 seconds in a pre-heated bowl. Thus, the homogenous distribution of the CR particles was achieved in the blend.
- Binder was poured in the crater, which was created in the CR-aggregate blend that was brought to 5˚C more than the mixing temperature to compensate the temperature loss during the preparation.
- The batch was mixed in the mechanical mixer, equipped with a heater for 3 minutes.
- The rest of the compaction procedure for DryHMA is same as the HMA samples.

3.5.3 DryWMA preparation

DryWMA samples were prepared according to the following procedure:

- Sasobit was added to the pre-heated aggregates and then mixed with spatula for 15 seconds in the pre-heated bowl.
- Next, CR was added to the aggregate batch mixed with Sasobit. Then, CR-aggregate blend was mixed for extra 30 seconds.
- The same mixing and the compaction procedures were followed according to the mixing and compaction temperatures with the specified number of blows, as given in Table 3-7.

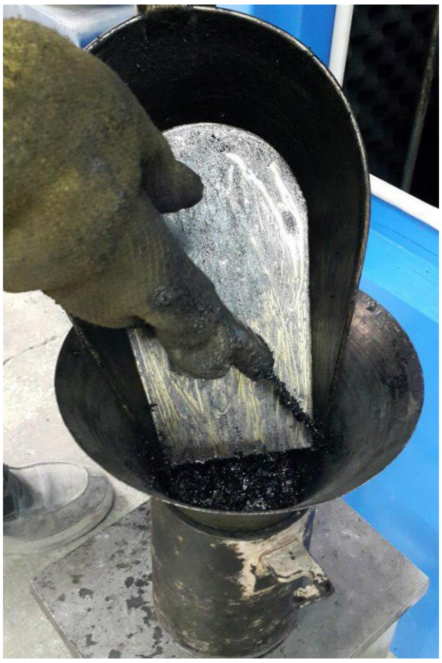


Figure 3.12 Pouring sample to molds before compaction

3.6 Experimental testing equipment

Two different devices were used in this research to evaluate the performance properties of the samples.

3.6.1 Marshall flow and stability

ELE Marshall Test-E device using a 25kN load cell was used in order to test the samples for flow and stability. Type NO. DBBKM-25kN ELE load cell was used to load the samples till sample failure at the maximum bearing load. Prior to loading the samples according to ASTM D6927 Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, the samples were conditioned in water bath at 60˚C for 30 to 40 minutes. It should be also noted that the load cell and the linear variable differential transformer (LDVT) are used to determine the stability and flow should be zeroed before starting the test.

Result of the test appeared in the screen with the unit of millimeter and kgf for flow and stability, respectively. Then, the stability was corrected with respect to sample height (Figure 3.13).

Figure 3.13 Height measurement by caliper

3.6.2 IDT testing machine

ELE Multiplex 50 coupled with a data acquisition system to record the deformation (mm) and load (kN) was used in this study. In the test setup, a 5 ton load cell was used in order to provide adequate energy to reach the maximum bearing load in the samples. Besides, in this study, a program was written in LabVIEW® language by Prof. Dr. Murat Guler for the data acquisition, On the other hand, the speed controller on the equipment allowed controlling the loading speed at 50mm/minute. According to the literature review done in this study, the samples were conditioned in a cooling chamber prior to the testing for 4 hours and overnight conditioning at the -10, 5 and 20˚C.

CHAPTER 4

RESULTS AND DISSCUSION

4.1 Introduction

As it was discussed in the previous chapters, various experiments need to be performed to reveal the physical and performance properties of the asphalt mixtures. Therefore, volumetrics, stability and flow, and indirect tensile strength properties of mixtures were measured to evaluate the effect of WMA incorporation with dry process CR modification. In addition, the cooling curves were determined to simulate the field conditions. In this chapter, the results of these tests were presented and discussed in order to determine the advantages and disadvantages of the proposed method.

4.2 Volumetrics

The results of this study clearly revealed that the incorporation of CR and WMA additive to the asphalt mixtures have significant impacts on the volumetric properties. Additionally, conditioning time, mixing and compaction temperatures are also other crucial factors affecting the volumetric properties. These influences on the volumetrics of the mixture sets are presented from Figure 4.1 to Figure 4.3 with respect to the conditioning time.

According to the Marshall mix design specifications; all samples are prepared based on the specified conditions given in Table 3-7. In Figure 4.1, the air void percentage variations are given with respect to the conditioning time. At 0 conditioning time, the air voids of all samples are varied in the range of 4.5 ±0.5%, which are within the design criteria limits. However, the variations in the air void percentages change with respect to conditioning time, which also reveal the importance of optimization for conditioning time, since it directly affects the performance of the asphalt mixtures. It should also be noted that similar variations were observed in a research study, focusing on the crumb rubber percentage and conditioning time optimization in HMA mixtures by Moreno et al. (2011).

According to Figure 4.1a, the air void content of DryHMA kept increasing as the conditioning time extended up to 90 minutes, but then a decrease was observed when conditioned for 120 minutes. However, for DryWMA 1, the only difference from DryHMA was the inclusion of WMA additive at a dosage of 1.5% by weight of the binder, there was a slight decrease in the air void percentages (approximately 0.5%). This indicated that this dosage did not improve the workability of the asphalt mixture and it was too stiff to compact. Therefore, the dosage was increased to 3% by weight of the binder in DryWMA 2, while keeping the mixing and compaction temperatures same as DryHMA and DryWMA 1. As clearly illustrated in Figure 4.1c, the air void percentage decreased as the conditioning time extended. This indicated that the binder-CR reaction continued and the workability of the mixtures increased at this additive level. Therefore, the additive percentage for the rest of the mixtures (DryWMA 3 and DryWMA 4) was also kept same as DryWMA 2. Also, the mixing and compaction temperatures were varied to observe if it was possible to also reduce these process temperatures. While preparing the DryWMA 3, both mixing and compaction temperatures were selected 15˚C lower than the other samples discussed. Although it was suggested by many researchers that, mixing and compaction temperatures for dry modified CR mixtures should be 10°C higher than conventional mixtures. At this point, it was aimed to observe that the temperature decrease can be compensated or not by the extension in conditioning time. According to Figure 4.1d, the air void percentage was in the same range (approximately 4.5% at 0 and 45 minutes of conditioning). However, a steep increase in the air void percentages was observed when the conditioning duration was extended to 90 minutes. This indicated that the CR-binder interaction did not continue due to the lower temperature and the workability decreased. Therefore, DryWMA 4 was prepared at the same mixing temperature as DryHMA, DryWMA 1 and DryWMA 2, but the compaction temperature was selected 15 °C lower than these samples, same as DryWMA 3. It was observed that the air void variation trend and even the air void values of DryWMA 4 was significantly similar to DryHMA with respect to the conditioning time. Lastly, HMA mixtures were conditioned only for 90 minutes in order to observe the influence of the conditioning process while compacting with Marshall Hammer. However, no effect was observed on HMA mixtures. The air void changes were observed from Figure 4.1a to Figure 4.1e for CR modified mixture sets.

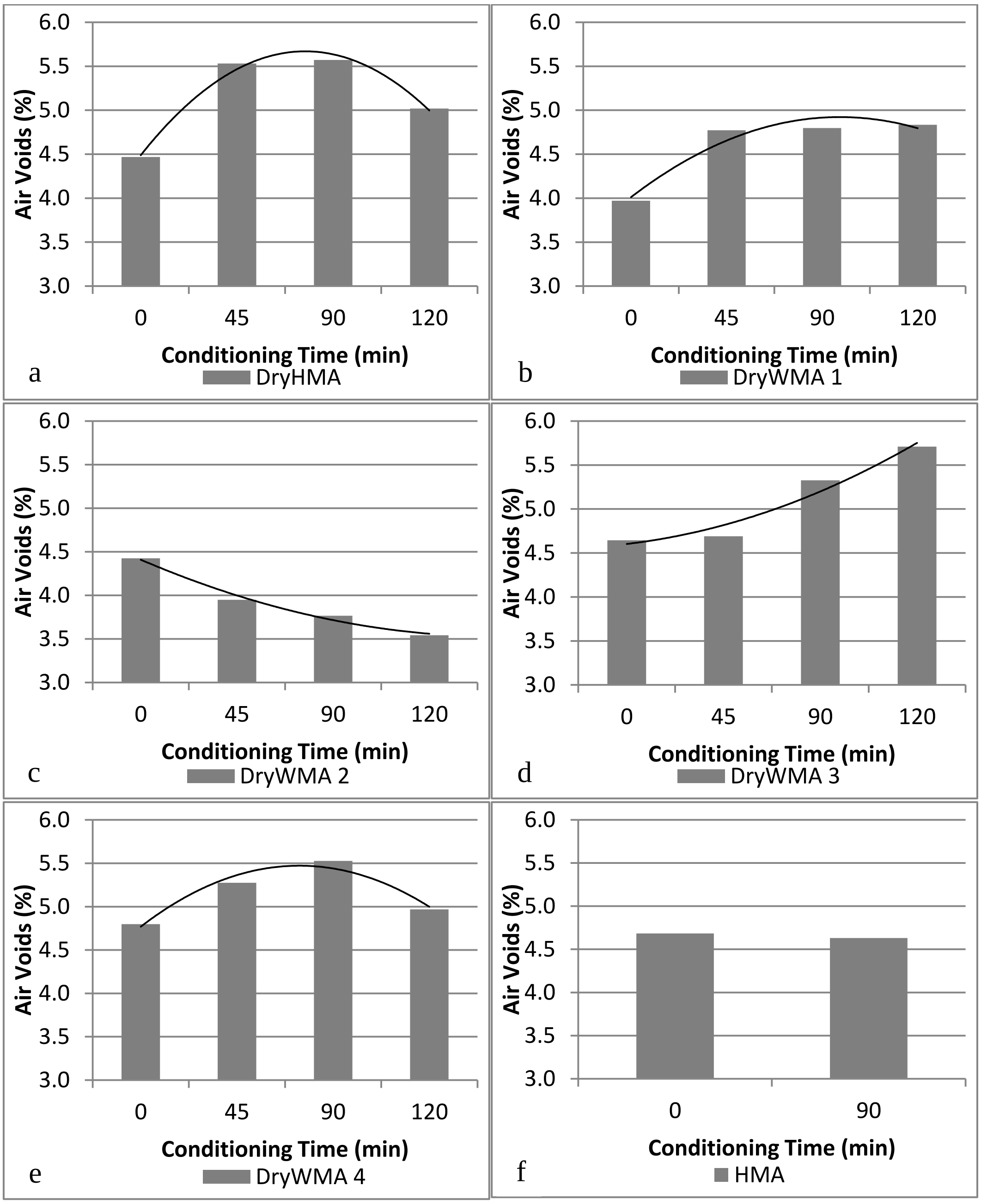


Figure 4.1 Air voids of mixtures with respect to conditioning time

There are no specifications of VFA and VMA values for dry process CR modified asphalts, so in this study all the VFA and VMA values were compared based on the DryHMA volumetric properties. Due to the aggregate gradation in this study, it is expected to have the high values for VFA and VMA, as given in Figure 4.2 and Figure 4.3.

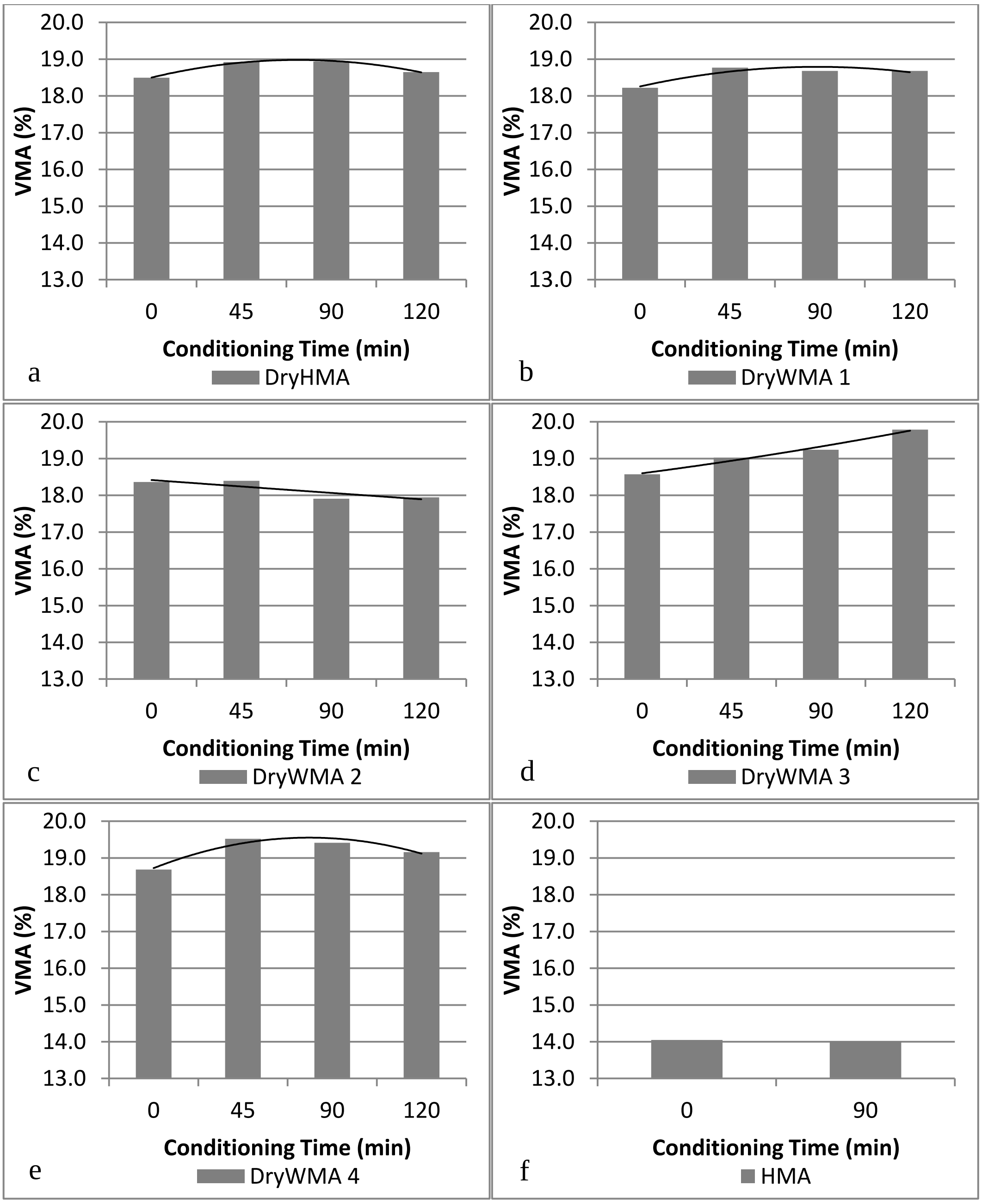


Figure 4.2 VMA of mixtures with respect to conditioning time

According to the Figure 4.2, VMA parameters were mostly constant in the samples. This meant voids in the samples getting around between the air and asphalt binder. However, the conditioning time has not too much effect in these parameters except the DryWMA 3 with lower mixing and compaction temperatures. Accordingly, all the samples also passed the minimum value of 17% for CR modified mixtures.

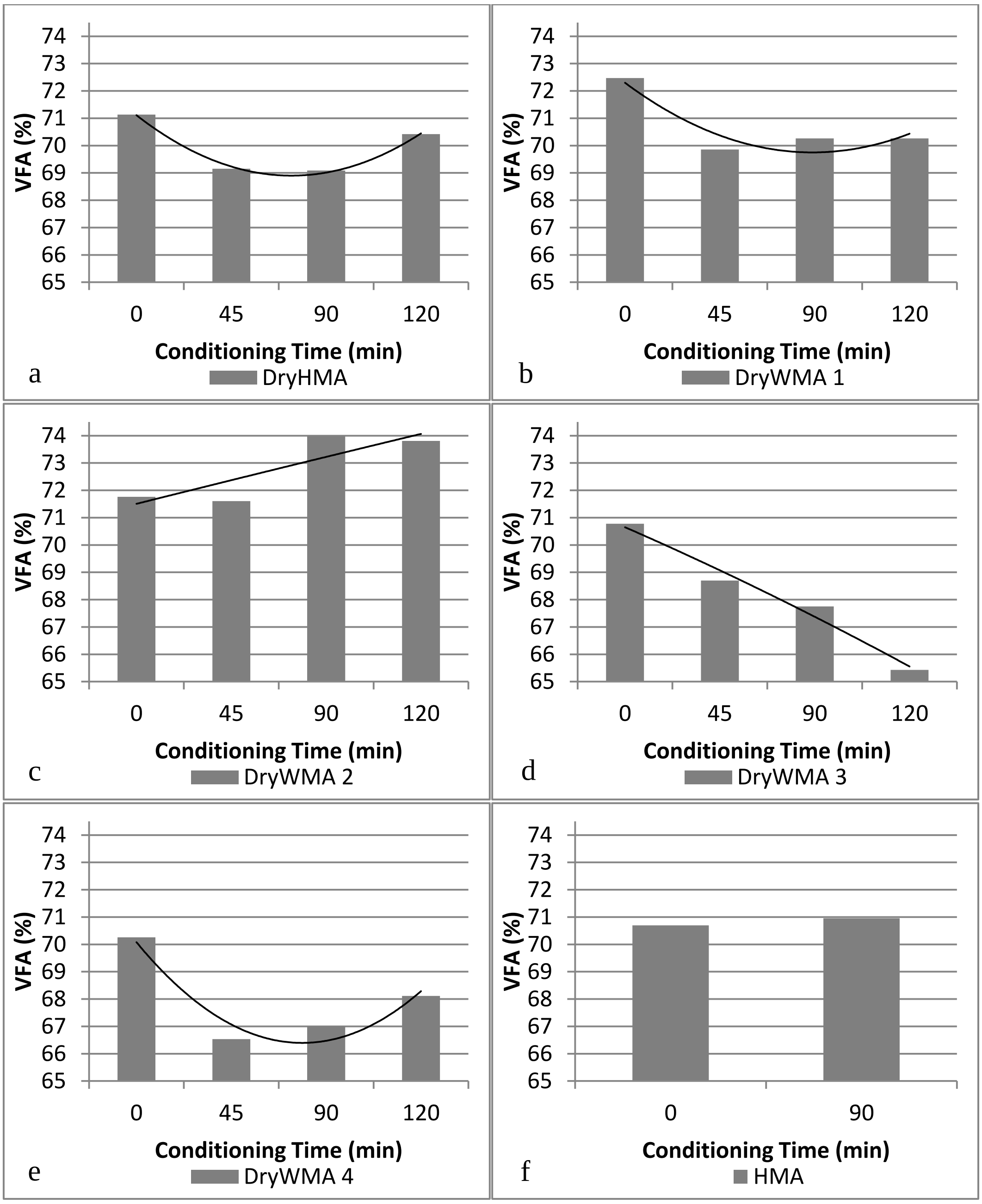


Figure 4.3 VFA of mixtures with respect to conditioning time

Figure 4.3 represented the VFA percentage of the samples with respect to the conditioning times. As it was denoted in the graphs, VFA values for all samples except 120 minute conditioning for DryWMA 3 were more than 66%, which was within the suggested limits in the literature.

As discussed in this section, the volumetric properties gave the basic physical properties of the mixtures and their variation, with respect to the conditioning time and processing temperatures. Although changing the processing temperatures and elongation in conditioning time resulted better or equal volumetrics properties, it might have negative impacts on the CR-binder interactions. This might cause in strength loss in the mixtures or even degradation of the samples during compaction. Therefore, their performance should also be studied to understand their actual behavior.

4.3 Marshall Stability and Flow

Marshall stability and flow parameters are two basic parameters that reflect the performance of the asphalt mixtures. Though these parameters are not adequate to understand the performance of mixtures, the stability should be high enough to handle the traffic loads. In this study, the stability and flow of mixtures were determined according to AASHTO T 245: Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus. In the Turkish General Directorates of Highway specifications or in the other standards, there are no specified values for CR modified mixtures and design criteria were varied and established according to the agency experiences. For HMA mixtures to be used in the wearing (surface) course the stability is specified as minimum 900 kgf and flow number is given in the range of 2-4 mm.

Since there were many variables (i.e., WMA additive dosage, conditioning time, mixing and compaction temperatures) in this study, the stability and flow in these samples were varied significantly as given in Figure 4.4 and Figure 4.5.

It should be reminded that in dry process CR mixtures, CR is used as fine aggregate replacement. Thus, the initial stabilities of all CR modified samples were lower than HMA. As given in Figure 4.4e, HMA samples with 0 minute conditioning had approximately a stability of 930 kgf. After 90 minutes of conditioning, the stability increase was about 20%, though the air voids were similar. Stability of all CR modified mixtures increased with respect to conditioning time except for DryWMA 3 and DryWMA 4. Slight decrease in the stability of these mixtures was observed during the conditioning from 90 to 120 minutes, although there was a decrease in air voids of the DryWMA 4. There could be various reasons for this stability loss: i) It may be due to aging of the mixtures, which may be investigated with chemical analysis, ii) it may be due to sample-to-sample variation.

As given in Figure 4.4a, the stability of DryHMA increased at an increasing rate with conditioning. Assuming the minimum 900 kgf stability limit as the design criteria, this was met after conditioning more than 45 minutes. Similarly, the DryWMA 1 and DryWMA 2 showed the same trend and desired stability was achieved after conditioning for 45 minutes. One more time, this indicated the importance of conditioning to achieve the binder-CR interactions. It should be also noted that this was regardless of air void percentage increase in these samples. However, the stability of DryWMA 3 never met the required limit. The highest measured was about 820 kgf at 90 minutes conditioning. This revealed that the decrease in the mixing temperatures could not be compensated by extending the conditioning time. When the stability of DryWMA 4 was observed as given in Figure 4.4e, the stability criteria was only met at 90 minutes conditioning. This was promising since the compaction temperatures can be lowered. In other words, compaction frame can be longer or it can be compacted at lower ambient temperatures without sacrificing the performance. However, further performance tests were needed to ensure the mixture performance.

According to Figure 4.4 and design criteria, these stability results indicated that 90 minutes conditioning could be selected as the optimum time for the digestion of the CR, Since some of the mixtures (DryWMA 3 and DryWMA 4) had the highest stability at 90 minutes and all the other mixture sets had higher stability than the criteria at this conditioning frame.

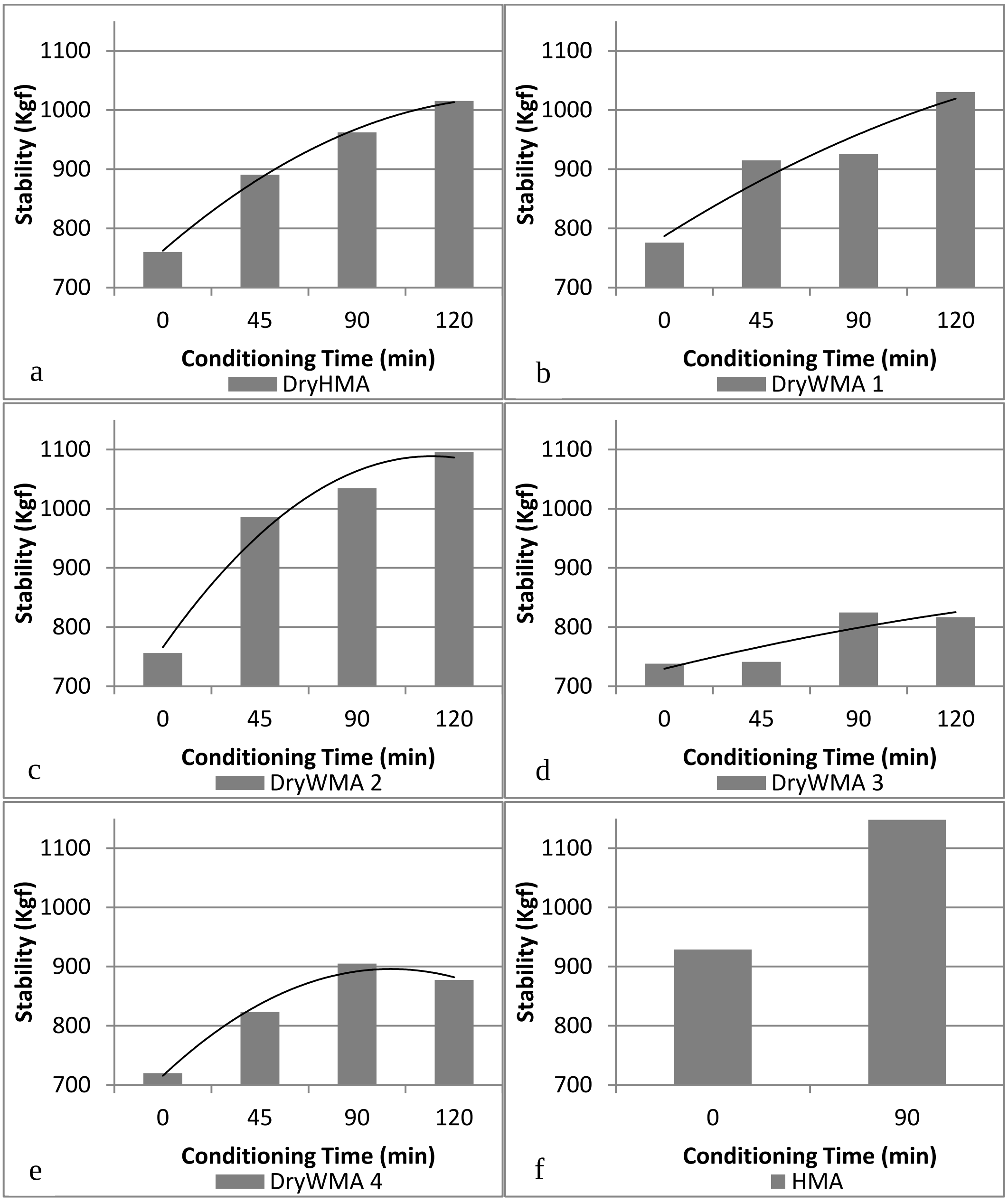


Figure 4.4 Stability of mixtures with respect to conditioning time

Flow is also essential parameter to estimate the deformation in the mixtures. As given in Figure 4.5, the flow numbers were significantly high for dry modified CR mixtures at 0 minutes of conditioning, since these samples were not stiff enough as they had poor binder-CR interaction. According to the fitted trend lines from Figure 4.5a to Figure 4.5d, the lowest flow values were measured for the samples conditioned for 90 minutes, which was also meeting the expectations according to stability results. Additionally, these values are within the specification limits.

However, the trend was significantly different in DryWMA 4 and the flow at 90 minutes was slightly higher than specification limits. This may be due to sample-to-sample variations, but will be clarified in the following section.

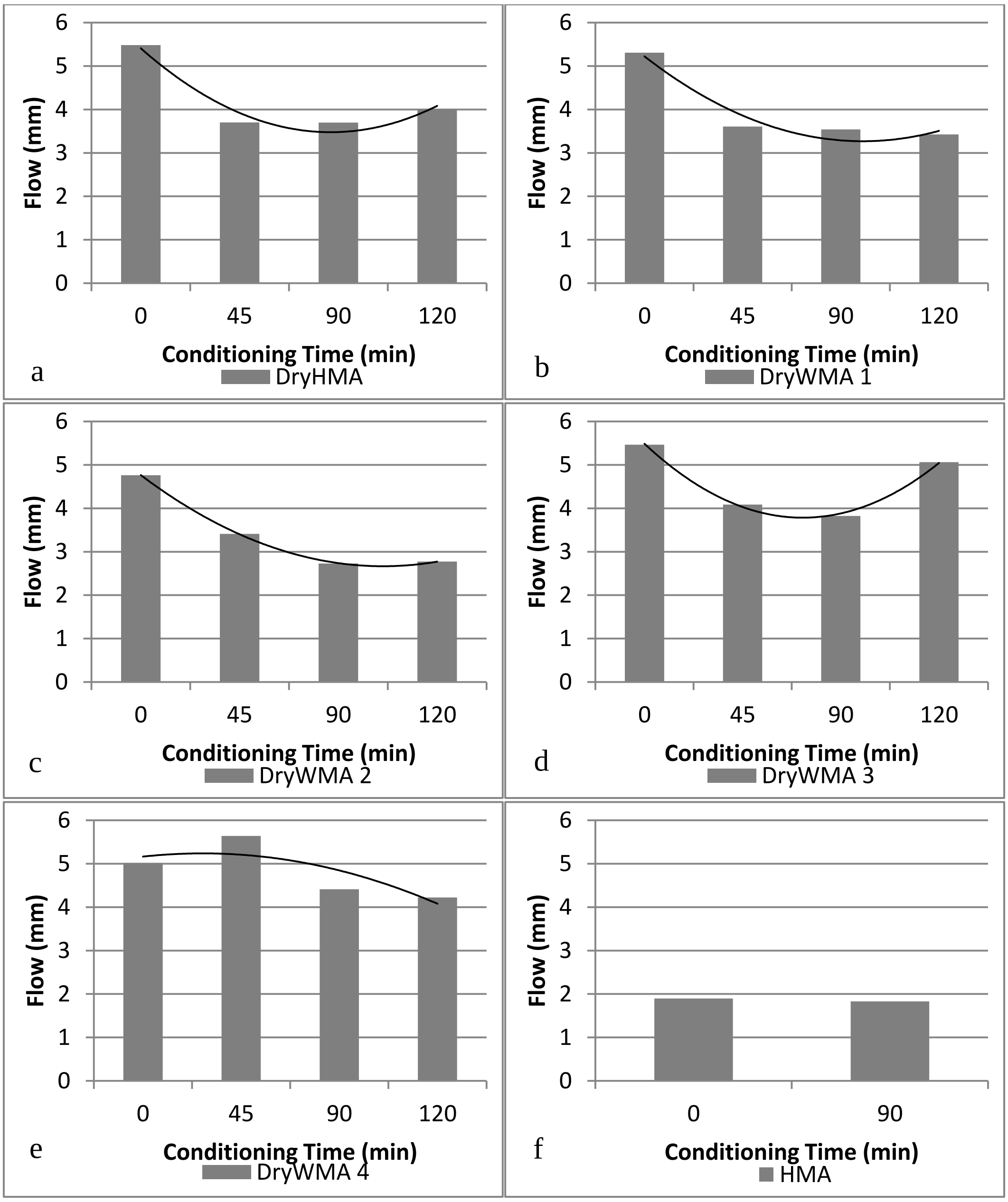


Figure 4.5 Flow of mixtures with respect to conditioning time

4.4 Indirect Tensile Test

Three mixtures (DryHMA, DryWMA 3, DryWMA 4), which were discussed in the previous sections, were selected to perform IDT tests, in order to evaluate the low-temperature cracking performance of the samples using 3 replicates at 3 different temperatures for each testing sets. At this point DryWMA 1 was excluded since lower additive dosage did not significantly affect the volumetric properties of the mixtures. In addition, DryWMA 2 was also excluded due to low air void content, since the comparison of results would not be possible. On the other hand, another mixture, named as DryWMA 5, was added to the experimental matrix. DryWMA 5 was prepared similar to DryWMA 2 (i.e. mixing and compaction temperatures), but the compaction effort was reduced to 50 blows per each side. As shown in Figure 4.1c, the air void percentage of DryWMA 2 was as low as 3.76% when compacted at the level of 75 blows per side. Therefore, with less compaction effort the air void level was increased to the same level with the other samples. All IDT samples had an air void of 5.5% ± 0.5. It was recommended to use the similar range of air voids in the IDT test to better compare the results. Average of air voids was determined as 5.63, 5.53, 5.38 and 5.52 for DryHMA, DryWMA 3, DryWMA 4 and DryWMA 5, respectively.

All samples were subjected to conditioning in the environmental chamber in order to reach the desired core temperatures and each sample was tested within 2 minutes frame according to the ASTM D6931. In this study, 20˚C, 5˚C and -10˚C were the temperatures selected to run the IDT tests based on the literature, to evaluate the low temperature properties of the samples (See Figure 4.7). According to literature, the samples that were tested at 20˚C conditioned for 4 hours and the other sets (at 5˚C and -10˚C) were conditioned overnight in the environmental chamber. Load-Deformation graphs were given from Figure 4.6 to Figure 4.9 according to testing temperature.

Figure 4.6 illustrated the IDT test results for DryHMA, DryWMA 2, DryWMA 3, DryWMA 4 and DryWMA 5 at the 20˚C. Since DryWMA 2 had lower air voids, it was intentionally eliminated from the test matrix, though one sample set was used only at 20˚C to relate compaction energy and air voids. Unexpectedly, less compaction when compared with DryWMA 2 resulted in slight reduction in the indirect tensile strength for DryWMA 5. It indicated that decreasing the number of blows resulted in lower load bearing capacity. Except DryWMA 5, all other sets of samples could bear the load about 14-16kN. This issue was discussed further in the following parts.

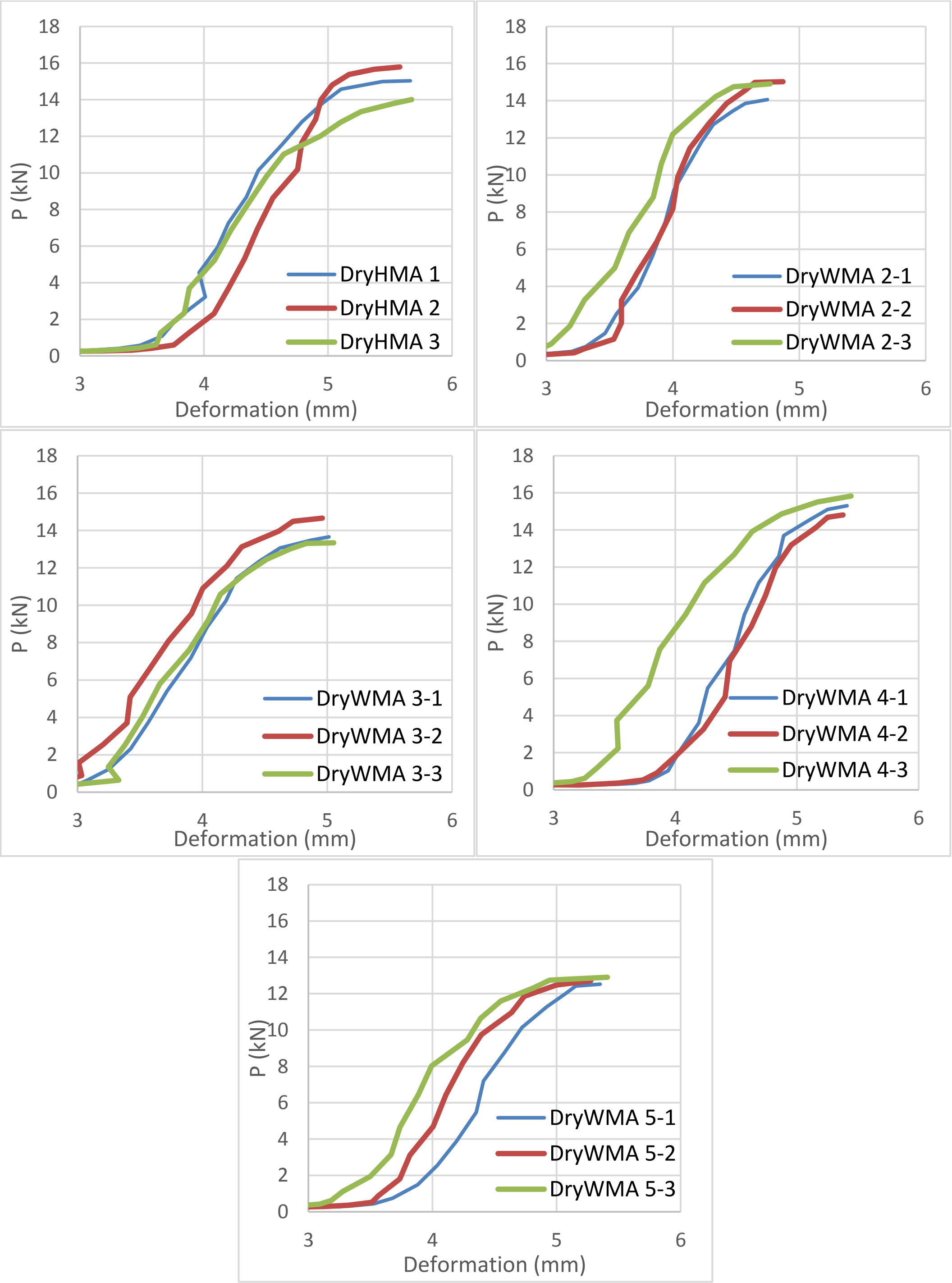


Figure 4.6 IDT load - deformation ratio at 20˚C

Figure 4.7 IDT tested samples

Figure 4.8 presented the load – deformation results at 5˚C. DryHMA, DryWMA 3, DryWMA 4 and DryWMA 5 samples were conditioned as it was discussed before at specified temperature and tested immediately. Results indicated a value range between 25kN and 30kN for all samples with semi smooth failure.

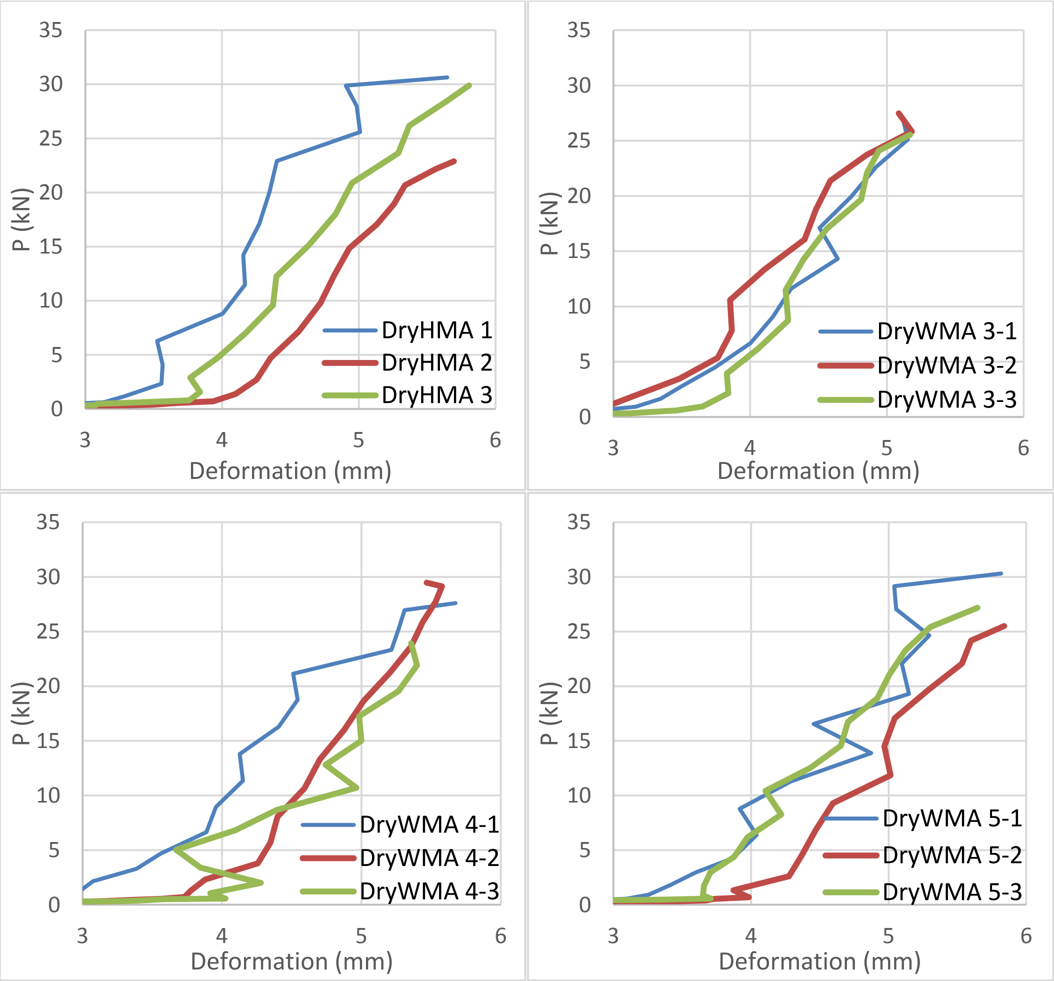


Figure 4.8 IDT load - deformation ratio at 5˚C

For -10˚C testing temperature, total increase in the IDT strength was observed as expected before, as given in Figure 4.9. Since the test temperature was lower than the previous experiment sets, the samples were more brittle, but carried more load.

IDT strength was calculated according to the Equation (2-2) with respect to the height of each sample. The strength and loads of sample sets were provided in Table 4-1. Also, from Figure 4.10 to Figure 4.12, the IDT strengths of mixtures were illustrated with respect to testing temperature.

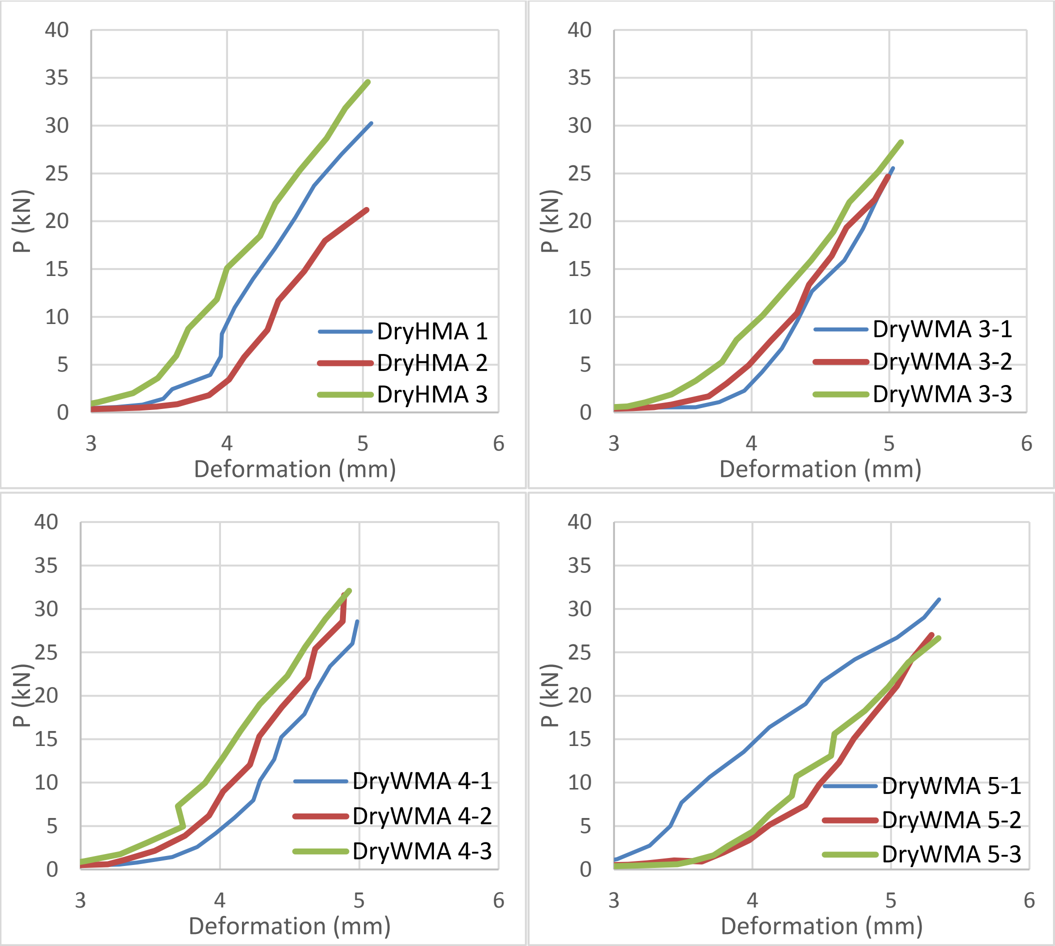


Figure 4.9 IDT load - deformation ratio at -10˚C

According to Figure 4.10, IDT strength at 20˚C significantly differed according to mixture type. DryHMA and DryWMA 4 had the highest strength, which indicated that the compaction temperature could be reduced without compromising the performance. On the other hand, DryWMA 3 had the lowest strength, which also overlapped with stability results. The reduction in mixing temperature could not be compensated by extending the conditioning period. In addition, the IDT strength of DryHMA was slightly higher than DryWMA 2, though DryWMA 2 had lower air void content. Additionally, the comparison of the DryWMA 2 and DryWMA 5, showed great strength loss by decreasing the number of blows even with the same conditions and temperatures.

Figure 4.11 provided the IDT strength results for same sets of samples at 5˚C and this graph indicated an improvement in the strength of the samples in lower temperatures about 75-100%. Strength of the samples examined in the range of 2.6-2.8 MPa and concluded to be almost equal. Noticeably, the IDT strength of DryWMA 5 improved by 117.7% and it was as high as the other mixtures when tested at -10 °C as given in Figure 4.12. Therefore, the slightly low strength value at 20 °C may be misleading when the stability and other IDT test at low temperatures taken into account.

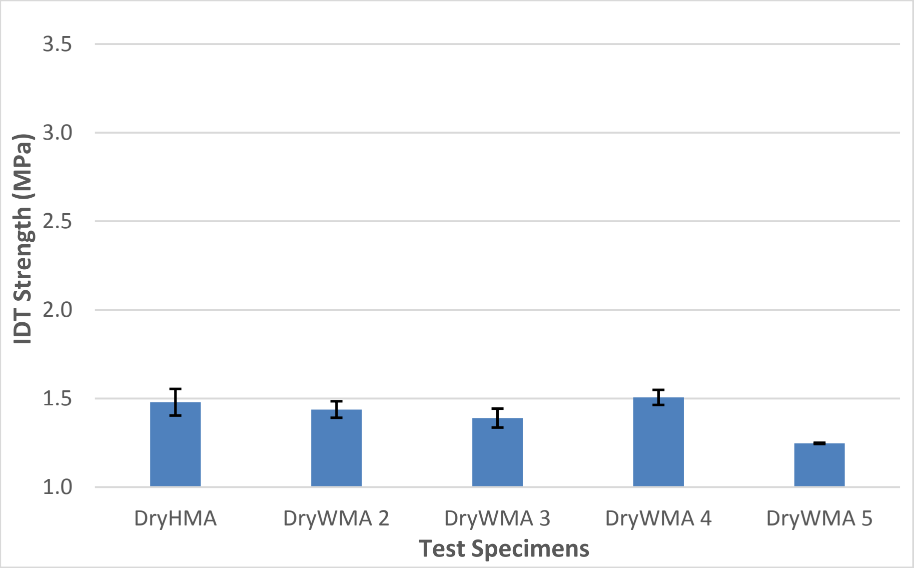


Figure 4.10 IDT strength for different mixtures 20˚C

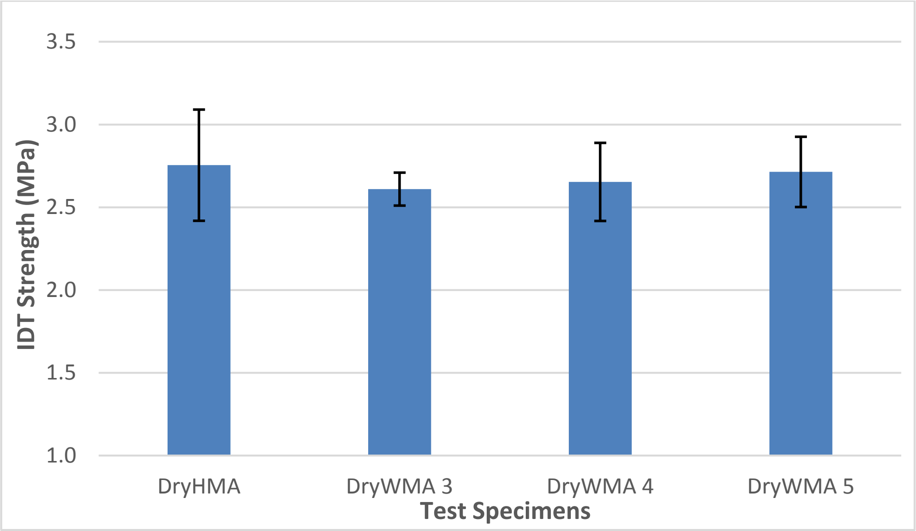


Figure 4.11 IDT strength for different mixtures 5˚C

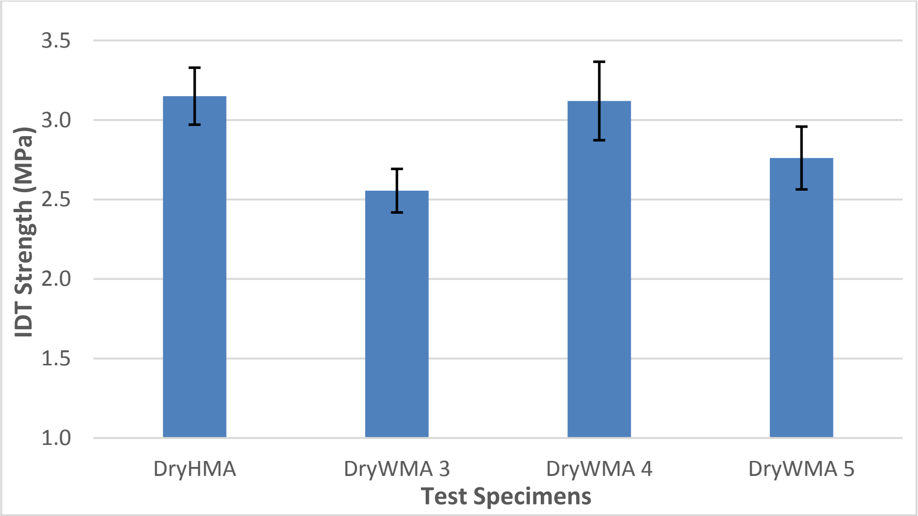


Figure 4.12 IDT strength for different mixtures -10˚C

As given in Figure 4.12, the improvement in IDT strengths of the mixtures at -10˚C continued, when compared to mixtures tested at 20 °C. 112.9%, 83.9%, 107.1% and 121.4% of strength gain was calculated in the DryHMA, DryWMA 3, DryWMA 4 and DryWMA 5, respectively. However, IDT strength loss was observed in DryWMA 3 when the strengths were compared at 5˚C and -10 ˚C. The 87.8% strength gain at 5˚C was decreased to 83.9% at -10˚C when compared to the results at 20˚C. In other words, 4.5% of strength lost was observed while lowering the test temperature. This indicated that poor binder-CR interaction resulted in a more brittle mix structure.

Table 4-1 Load and strength value for IDT samples (improvements are given with respect to 20˚C)

	Sample sets	IDT Strength (MPa)	P (kN)	Improvement (%)
20 °C	DryHMA	1.479	14.941	-
	DryWMA 2	1.438	14.664	-
	DryWMA 3	1.389	13.887	-
	DryWMA 4	1.506	15.313	-
	DryWMA 5	1.247	12.715	-
5 °C	DryHMA	2.755	27.811	86.2
	DryWMA 3	2.610	26.603	87.8
	DryWMA 4	2.653	27.005	76.2
	DryWMA 5	2.714	27.669	117.7
-10 °C	DryHMA	3.150	31.889	112.9
	DryWMA 3	2.556	26.162	83.9
	DryWMA 4	3.120	31.618	107.1
	DryWMA 5	2.761	28.245	121.4

According to aforementioned experiments (both volumetric and performance), it was concluded that the inclusion of WMA additive has various positive effects on the mixture performance such as improvement in workability, compactibility, and reduction in the compaction temperatures. On the other hand, it was proven that the mixing temperatures could not be lowered.

4.5 Cooling Curve predictions

The mixing and compaction temperatures are important parameters that influence the change in the air voids as it was presented in Figure 4.1. During the pavement lay down, it is important to control the temperatures in order to achieve the targeted air voids and as well the required performance. Compacting the pavements before temperature drops below the optimized temperature is a crucial problem and it is too difficult to compact the mixture to the targeted air voids, no matter how much energy is going to be applied. In addition, compacting the flexible pavements at lower temperatures than the compaction temperature make the pavement susceptible to moisture damage, prone to fatigue and permanent deformation. So it is important to predict the cooling rates of asphalt mixture for the construction and the maintenance phases of the actual field projects. Besides, the estimation of cooling rate based on the experience may result in irreparable consequences.

In this study, DryHMA and DryWMA 4 were selected to be analyzed using the Multicool program. Assumptions on existing surface properties, construction conditions and weather parameters were given in the Table 4-2. As tabulated, these parameters were varied to evaluate the effect of each parameter on the cooling rate of the pavements. In the last two column of the table, the cooling rates of WMA and HMA were given. It was clearly proven that the compaction frame had significantly expanded, although this data was not validated in the field as part of this study.

Table 4-2 Summary of Multicool Program Inputs and Outputs

Air Temp. (˚C)	Avg. Wind Speed (km/hrs)	Sky Condition	Surface Material Type	Surface Temp. (˚C)	HMA Cooling (min.)	WMA Cooling (min.)
Influence of Ambient Air Temperature and Surface Temperature to Cooling						
20	8	Clear and Dry	Granular Base	25	102	80
30	8	Clear and Dry	Granular Base	35	126	84
40	8	Clear and Dry	Granular Base	45	166	130
Influence of Average Wind Speed to Cooling						
20	8	Clear and Dry	Granular Base	25	102	80
20	12	Clear and Dry	Granular Base	25	93	73
20	16	Clear and Dry	Granular Base	25	85	68
Influence of Sky Condition to Cooling						
20	8	Clear and Dry	Granular Base	25	102	80
20	8	Partly Cloudy	Granular Base	25	88	70
20	8	Overcast	Granular Base	25	79	62
Influence of Base Material to Cooling						
20	8	Clear and Dry	Granular Base	25	102	80
20	8	Clear and Dry	AC	25	94	75

Different agencies allowed minimum temperature to stop the compaction at 80˚C. Compacting the mixture below this temperature is not suggested since it would cause adverse problems in pavements. Since compacting process is energy consuming, getting to the targeted air voids below this temperature is not so easy. This compaction effort even could reduce the density or start the fracture in aggregates which is not appropriate in the pavements. The stop temperature (85˚C) in this study is selected 5˚C more than the suggested minimum temperature since dry process CR modified mixtures are harder to compact, comparing to traditional HMA mixtures. Therefore, the delivery temperature was determined as the compaction temperatures and 85˚C was selected as the stop temperature with respect to various studies.

Low temperatures at night and high wind speed are the most considerable parameters during the night construction. In order to evaluate these cases, air temperatures in this study were selected as 20, 30 and 40˚C, also surface temperature for the pavement were increased for 5˚C according to the air temperatures, respectively. Wind speeds for this project were assumed to be 8, 12 and 16km/hrs, by keeping the other values constant to evaluate the wind speed variation effects on the cooling time. Sky condition for the project was varied as clear and dry, partly cloudy and overcast also with keeping other variables constant. Additionally, two major surface materials were selected as the input parameters. Table 4-2 was prepared to evaluate the results of the Multicool program at the above-mentioned conditions. Data provided in this table indicated that 20 minutes difference between HMA and WMA cooling durations were observed under any condition.

In addition to the cooling rate during the compaction, the cooling rate of the mixtures during the hauling time till the project location should be determined to manage the construction. This period of the project has no simulation method to calculate, so Multicool program was also used to estimate the cooling rate in this study. At this phase, the starting temperature was selected as the mixing temperature where the mixture was loaded to the carrier and stopping temperature was estimated as compaction temperature, which is the starting time of compaction during the unloading of mixtures. For both mixtures 160˚C was selected as the mixing temperature as indicated before. The compaction temperatures are defined 150 and 135˚C for DryHMA and DryWMA 4, respectively, as illustrated in Figure 4.13. In order to simulate the thickness of the material behind the carrier, the maximum thickness for the program (254mm) was selected. The thickness and the depth of the pavement had great influence on the cooling rate. In order to take into account the cover on the mixture during the hauling, the wind speed was assumed as 0km/hrs, In addition, the ambient air and surface temperature were assumed 48.89˚C and 73.89˚C, respectively. Unfortunately, these selected temperatures were the maximum available values in the Multicool software. Figure 4.14 was prepared according to the output results of Multicool with the above-mentioned conditions. Cooling time for DryHMA and DryWMA 4 was determined as 35 and 158 minutes, respectively, though it was underestimated because of the limitations in the inputs. However, it was concluded that at least two hours of extra time is provided by using the DryWMA method comparing to the DryHMA, as presented in Figure 4.13. Therefore, it is possible to construct the roads at low temperatures. Moreover, lower temperature behind the paver provides safe and comfortable working environment.

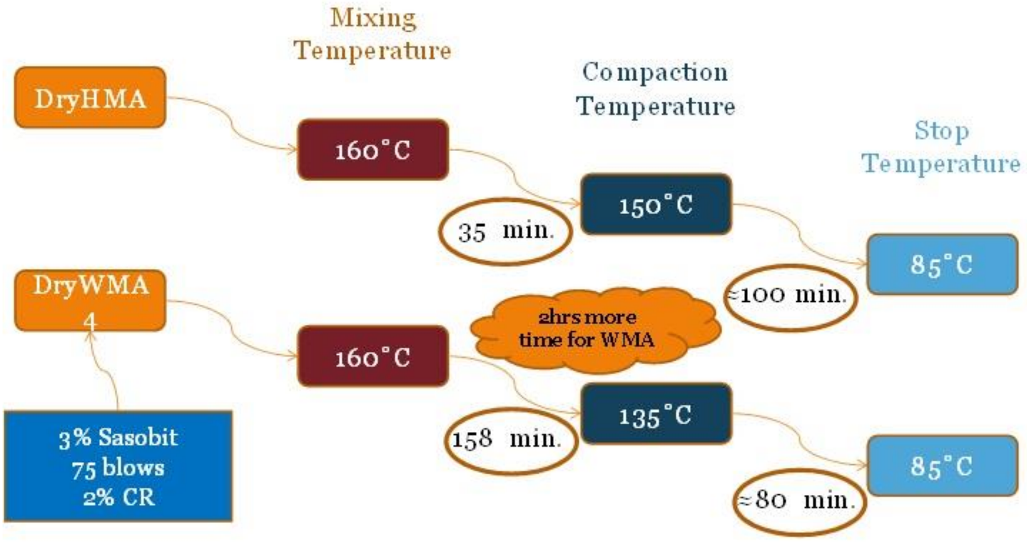


Figure 4.13 Illustration of cooling rates

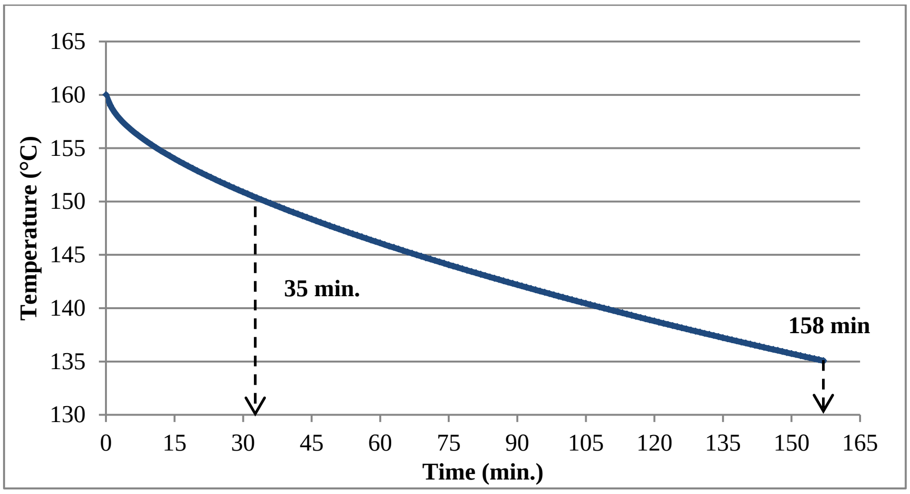


Figure 4.14 Cooling rate of asphalt mixture from mixing to compaction

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

In this chapter, the outcomes of the study are summarized and some recommendations for future studies are provided. To interpret the asphalt mixture physical and performance properties, several parameters including the additive dosage, compaction temperature, mixing temperature, and conditioning time were varied throughout the study. On the other hand, there were some limitations including the single aggregate source, single binder type and source, one crumb rubber dosage, and one type of WMA additive. Therefore, several DryHMA and DryWMA samples were prepared to evaluate the volumetrics, stability and indirect tensile strength of these mixtures. Furthermore, in order to demonstrate the advantages of WMA on crumb rubber modification, cooling curves were also analyzed.

5.2 Conclusions

This study associates many design parameters to the physical and performance properties of the mixtures. Based on the comparison of the traditional HMA and DryHMA to several DryWMA mixtures, the following major conclusions are drawn:

- The compactibility and workability of asphalt mixtures with the addition of WMA additive improve, regardless of any changes in the mixture preparation plan.

- WMA additive dosage has a considerable effect on the compactibility and stability of the dry CR modified mixtures. Therefore, proper amount for WMA additive should be determined for successful implementation.

- Mixing temperature has significant effect on the stability of the mixtures, regardless of compaction temperature since it is a significant parameter for the CR-binder interaction. For DryWMA3, the highest measured stability was about 820 kgf at 90 minutes conditioning time. This reveals that the decrease in the mixing temperatures could not be compensated by extending the conditioning time.

- Conditioning time allows better CR-binder interaction, which results in the improvement of stability and mixture binding properties.

- Lower compaction temperature of DryWMA mixtures increases the health and safety of workers and provides a comfortable working condition, due to exposure to lower carbon emission.

- Reduction in the compaction temperature has not significantly altered the performance of mixtures. Thus, it can be concluded that this method helps to compact the mixtures at lower temperatures. Accordingly, the hauling distance could be longer and it is possible to work at lower ambient temperatures.

- According to the stability and volumetric results, the conditioning time has significant effect on performance properties of DryWMA. However, this conditioning should be limited to 90 minutes.

- Addition of WMA additive to asphalt mixtures did not significantly affect the IDT strength (Refer to Figures 4.9 to 4.11).

- WMA additives could be used as compaction aid for Dry process CR modified mixtures.

- Despite the IDT results at 20°C, it is concluded that reducing the compaction effort is possible for dry process CR modified WMA at the similar temperatures with the DryHMA mixtures.

- According to cooling rate analysis, it is concluded that WMA additives increase the hauling frame and compaction time for the dry processed CR mixtures. It is anticipated that it provides approximately 2 hours of extension in this time frame.

By considering the world pollution and necessity of more environmentally friendly methods in pavement engineering, WMA method and CR modifications are the mostly used techniques in pavement construction, separately. According to this study, it is concluded that the association of these two methods might be successfully used in the actual field projects.

5.3 Recommendations

Considerable findings of this study are discussed in section 5.2. Also, further studies are needed to improve these results and extend the current research. Permanent deformation and moisture susceptibility tests should be performed to ensure the rutting resistance of CR modified mixtures. Additionally, the findings of this research should be verified in the field. In addition, the CR dosage might be varied in order to come up with the optimum dosage. Moreover, these findings are limited with one type of WMA additive. Therefore, these analyses could be repeated by using other WMA technologies in order to validate the research outcomes.

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APPENDIX A: IDT test literature review

Table A-1 Summary of IDT test literature review

Title	Sample Dia. (mm)	Sample Height(mm)	Temp.	Conditioning	Air Voids	Load (mm/min)	
D6931	100	38	25	4h Air			
Islam et al. (2015a)	100	50	20		5.4	50	AASHTO T283-03
Fedrigo et al. (2018)	102	65				50	ASTM D6931
Lusher (2017)	150	38-50	-10	3-1 hours	vary	12.5	T322-07 NCHRP 530
Cerni et al. (2017)	100	60	10,20,30		4 or 8	50	EN 12697-26 EN 12697-23
Richardson & Lusher (2008)	150	50	-10,4.4,21	3 ± 1 hours	4,6.5,9	12.5	T 322-07 NCHRP 530
Islam et al. (2015b)	150	50			5.8		
Yin et al. (2017)	150	50	25		vary	0.5, 50	
Corradini et al. (2017)	100	60					EN 12697-24

Table A-1 (Continued)

Title	Sample Dia. (mm)	Sample Height(mm)	Temp.	Conditioning	Air Voids	Load (mm/min)	
Šimun et al. (2014)	100	60-65	5,15,25, 35		vary		EN 12697-26
Modarres & Alinia (2017)			20	5 hours			ASTM D6931
Zhang et al. (2016)	100		-10		4	50	
Zhao et al. (2018)	101.6	63.5	-10		3.5,3.6, 4.1,4.3, 4.8	1	ASTM D4123
Fu et al. (2017)	101.6	40	25				
Dan et al. (2018)	150	32				51	
Yin et al. (2018)	150	40-50	10,17.5, 25	2h	7	0.5,5,50	
Liu et al. (2015)	150	130	15				
Karakas et al. (2015)			25		Around 8	50	
Peng et al. (2017)	101.6	63.5	20		2.42 till 4.88	50,60	DEM

APPENDIX B: Heights and air voids for IDT test samples

Table 0-1 Sample Heights and air voids

	Sample	H1	H2	H3	Average Height	Total Average	Air voids
20 °C	HMA 1	64.5	64.3	65.0	64.6	64.3	5.709
	HMA 2	64.0	64.2	63.8	64.0		5.272
	HMA 3	64.6	64.1	64.3	64.3		5.884
	DryWMA 2-1	63.1	63.0	63.1	63.1	63.6	4.025
	DryWMA 2-2	64.0	63.9	63.9	63.9		4.219
	DryWMA 2-3	64.0	64.2	63.4	63.9		4.147
	DryWMA 3-1	64.6	65.0	64.6	64.7	64.7	5.815
	DryWMA 3-2	64.9	64.9	64.7	64.8		5.195
	DryWMA 3-3	65.0	64.5	64.4	64.6		5.542
	DryWMA 4-1	65.2	64.7	65.6	65.2	64.9	5.209
	DryWMA 4-2	64.6	64.1	64.8	64.5		5.618
	DryWMA 4-3	65.0	65.4	65.1	65.2		5.440
	DryWMA 5-1	64.2	64.0	64.5	64.2	64.9	5.391
	DryWMA 5-2	64.2	65.0	65.1	64.8		5.675
	DryWMA 5-3	65.9	65.8	65.6	65.8		5.467
5 °C	HMA 1	64.9	64.4	64.8	64.7	64.2	5.937
	HMA 2	64.2	63.8	63.7	63.9		5.129
	HMA 3	63.9	64.3	64.2	64.1		5.812
	DryWMA 3-1	64.0	64.5	65.0	64.5	64.8	5.780
	DryWMA 3-2	64.5	64.9	64.8	64.7		5.261
	DryWMA 3-3	65.4	65.4	64.9	65.2		5.522
	DryWMA 4-1	64.1	64.2	64.8	64.4	64.9	5.384
	DryWMA 4-2	65.3	65	65.5	65.3		5.118
	DryWMA 4-3	65.2	65.4	64.9	65.2		5.842
	DryWMA 5-1	64.3	64.2	64.5	64.3	64.9	5.139
	DryWMA 5-2	64.5	64.1	65.4	64.7		5.889
	DryWMA 5-3	65.4	65.8	66.0	65.7		5.554
-10 °C	HMA 1	64.2	63.6	64.6	64.1	64.4	5.407
	HMA 2	64.6	64.2	64.8	64.5		5.849
	HMA 3	64.5	64.8	64.7	64.7		5.665
	DryWMA 3-1	65.1	65.2	64.7	65.0	64.6	5.327
	DryWMA 3-2	64.2	64.0	63.9	64.0		5.811
	DryWMA 3-3	64.5	64.4	65.0	64.6		5.538

Table B-1 (continued)

Sample	H1	H2	H3	Average Height	Total Average	Air voids	Sample
-10 ˚C	DryWMA 4-1	64.8	65.4	65.2	65.1	65.1	5.447
	DryWMA 4-2	64.9	65.1	65.3	65.1		5.374
	DryWMA 4-3	65.3	65.6	64.6	65.2		5.575
	DryWMA 5-1	64.5	64.3	64.5	64.4	65.2	5.501
	DryWMA 5-2	65.7	64.8	65.3	65.3		5.710
	DryWMA 5-3	65.9	65.8	65.6	65.8		5.363