

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**INVESTIGATION OF MIXING AND
COMPACTION TEMPERATURES OF ASPHALT
THROUGH DIFFERENT VISCOSITY MODELS**



by
Ali Abdulhussein Abdulridha ALMUSAWI

December, 2020

İZMİR

INVESTIGATION OF MIXING AND COMPACTION TEMPERATURES OF ASPHALT THROUGH DIFFERENT VISCOSITY MODELS

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Graduate School of Natural and Applied Sciences of Dokuz Eylül University
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**by
Ali Abdulhussein Abdulridha ALMUSAWI**

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Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**INVESTIGATION OF MIXING AND COMPACTION TEMPERATURES OF ASPHALT THROUGH DIFFERENT VISCOSITY MODELS**” completed by **ALI ABDULHUSSEIN ABDULRIDHA ALMUSAWI** under supervision of **PROF.DR. BURAK ŞENGÖZ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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ABSTRACT

The determination of mixing and compaction temperatures through the ASTM (equiviscous) method has been defined as the standard method. The implementation of the Equiviscous method for the modified bitumen results in high temperatures, which may not be required during the construction of the asphalt mixtures. This study aims to investigate several alternative methods proposed in the literature named as high shear rate method (HSR), zero shear viscosity method (ZSV), steady shear flow method (SSF), and phase angle method. For this purpose, 50/70 and 160/220 penetration grades bitumen modified with elastomeric type – Styrene Butadiene Styrene (SBS) and Reactive Elastomeric Terpolymer – Elvaloy (RET) have used. The study also aims to measure the applicability of the proposed alternative methods for the warm mix asphalt involving organic and chemical additives. The results have shown that for the polymer modified bitumen, all suggested methods resulted in lower mixing and compaction temperatures compared to the Equiviscous method. While for the warm mix asphalt, the implementation of the SSF method only resulted in lesser temperatures compared to the Equiviscous method.

Also, the asphalt mixture mechanical properties such as Marshall Mix design and Indirect Tensile Strength test (ITS) were measured based on the determined mixing and compaction temperatures through different methods. Finally, the economic impacts of the determined production temperatures for several models are evaluated by the estimation of energy consumption in terms of electricity and natural gas costs for the batch type asphalt plants. Besides, the possible environmental effects are estimated considering carbon dioxide emissions.

Keywords: Polymer bitumen, warm mix asphalt, high shear rate, zero shear viscosity, steady shear flow, phase angle

ASFALTIN KARIŐTIRMA VE SIKIŐTIRMA SICAKLIKLARININ FARKLI VİSKOZİTE MODELLERİ İLE İNCELENMESİ

ÖZ

ASTM (equiviscous) yöntemi ile karıőtırma ve sıkıőtırma sıcaklıklarının belirlenmesi standart yöntem olarak tanımlanmıştır. Modifiye bitüm için ASTM (equiviscous) yönteminin uygulanması, asfalt karıőtımlarının üretiminde istenmeyen yüksek karıőtırma ve sıkıőtırma sıcaklıklarına neden olacaktır. Bu çalışmada literatürde alternatif yöntemler olarak önerilen yüksek kesme hızı yöntemi, sıfır kesme viskozitesi yöntemi, sabit kesme akıőtı yöntemi ve faz açısı yöntemi olarak önerilen çeőtitli alternatif yöntemler araştırılmıştır. Bu amaçla, elastomerik tip - Stiren Bütadien Stiren (SBS) ve Reaktif Elastomerik Terpolimer - Elvaloy (RET) ile modifiye edilmiş 50/70 ve 160/220 penetrasyon sınıfı bitüm kullanılmıştır. Çalışma ayrıca önerilen alternatif yöntemlerin organik ve kimyasal katkı maddeleri içeren ılık karıőtım asfalt için uygulanabilirliğini ölçmeyi amaçlamaktadır. Sonuçlar, polimer modifiye bitüm için önerilen tüm yöntemlerin, ASTM (equiviscous) yöntemine kıyasla daha düşük karıőtırma ve sıkıőtırma sıcaklıklarına sahip olduğunu göstermiştir. İlık karıőtım asfalt ise, SSF yönteminin uygulanması yalnızca ASTM (equiviscous) yöntemine kıyasla daha düşük sıcaklıklarla sonuçlanmıştır.

Ayrıca Marshall tasarım yöntemi ve Dolaylı çekme mukavemeti testi (ITS) ile asfalt karıőtımın mekanik özellikleri, farklı yöntemlerle belirlenen karıőtırma ve sıkıőtırma sıcaklıklarına göre ölçülmüştür. Son olarak, birkaç modelde için belirlenen üretim sıcaklıklarının ekonomik etkileri, beç tipi plent için elektrik ve doğalgaz maliyetleri açısından enerji tüketimi tahmini yapılarak değerlendirilmiştir. Ayrıca olası çevresel etkiler karbondioksit emisyonları dikkate alınarak hesaplanmıştır.

Anahtar Kelimeler: Polimer bitüm, ılık karıőtım asfalt, yüksek kesme hızı, sıfır kesme viskozitesi, sabit kesme akıőtı, faz açısı

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CHAPTER ONE

INTRODUCTION

Over the year's base bitumen (unmodified) has been used in the construction of the asphalt pavement. The rapid growth rate in the traffic volumes showed a limitation in the performance of the base bitumen, which may be clearly noticed in the earlier failures of the pavement than what is expected. This led to a decrease in service life and an increase in maintenance costs. To overcome such problems and to enhance the performance of the asphalt pavement, in the last few decades modified bitumen with polymers has been adopted. However, selecting suitable temperatures to handle these modified bitumen has become an issue since an appropriate method has not been regulated. The equiviscous method (ASTM D 2493), which has been described and used for the determination of mixing and compaction temperatures of the base bitumen, yields high temperature when it is applied to the polymer modified bitumen. This is because the equiviscous method is established for the base (unmodified) bitumen, which exhibits Newtonian behavior at high temperatures. In such behavior, the viscosity is not shear rate dependent. In other words, in systems showing Newtonian flow, as shear stress increases, shear rate also increases and the consistency of the flow is constant. While modified bitumen exhibits a non-Newtonian behavior. The non-Newtonian flow represents the behavior of the material which its viscosity is shear dependent.

For polymer modified bitumen, implementing such high temperatures can cause serious issues such as environmental problems and the degradation of the asphalt mixtures. The insufficiency of the ASTM (equiviscous) method led the agencies and bitumen suppliers to predict the required mixing and compaction temperatures for the modified bitumen using field experiences. There is a need for a formal method to determine the mixing and compaction temperatures of the modified bitumen and must consider its behavior.

For warm mix asphalt (WMA), which requires lower temperatures than hot mix asphalt, the implementation of the ASTM (equiviscous) method does not demonstrate

a significant lowering in the determined mixing and compaction temperatures. Hence, it is likewise to investigate an alternative that can be more applicable.

Also, from the economic perspective, utilization of lower mixing and compaction temperature may reduce the energy consumption that used heating aggregate and bitumen required for construction and which may lead to reduce road construction costs. From an environmental perspective, using lower temperatures can cause less harm to the environment

1.1 Problem Statement

Most of the road network over the world has been constructed using asphaltic materials. Several types of modifiers and additives have been subjected to asphalt material in order to increase the durability and also to improve the performance of the asphalt pavement in terms of resistance to permanent deformation and fatigue cracking. During the construction of the asphalt pavement, the materials (bitumen and aggregate) must be heated and compacted at specified temperatures to reach the required performance. The required heating and laying down temperatures are determined by the ASTM (equiviscous) method. However, this method is designed only for the base (unmodified) bitumen and the application of this procedure for the modified bitumen may result in excessively high temperatures which may not be necessary for the construction of the asphalt pavement. Thus, there is a need to investigate alternative methods that can be more suitable to implement for bitumen samples involving additives and modifiers. In the thesis, alternative methods (HSR, ZSV, SSF, and Phase angle) have been investigated to determine mixing and compaction temperatures. The effect of variation in mixing and compaction temperatures on the mechanical properties of asphalt concrete samples involving base (unmodified) bitumen and polymer modified bitumen has been evaluated through Marshall mix design and indirect tensile strength tests. Besides bitumen samples involving organic and chemical WMA additives have been assessed and the applicability of the proposed methods on WMA has been examined.

1.2 Aims and Objectives

The study aims to investigate different alternative methods in order to find lower and realistic mixing and compaction temperatures of asphalt samples produced with bitumen containing several types of additives and to reveal the differences from the present method (ASTM D 2493). This can be achieved through the following objectives

- 1- Firstly, bitumen samples containing styrene-butadiene-styrene type elastomer, reactive elastomeric terpolymer, organic and chemical WMA, which utilization rates in bitumen were determined in accordance with the literature, were produced with a high shear rate mixer.
- 2- The mixing and compaction temperatures have determined by applying the equiviscous method (ASTM D 2493) for both base (unmodified) and modified samples.
- 3- The mixing and compaction temperatures of modified samples have been determined through the implementation of the alternative methods (HSR, ZSV, SSF, and phase angle) by utilizing different machines, Brookfield viscometers and Dynamic Shear Rheometer (DSR), and different loading times and temperatures.
- 4- The obtained results have been modeled in different ways and compared with the ASTM (equiviscous) method.
- 5- The applicability of the obtained temperatures has been examined for asphalt samples by the Marshall mix design method and Indirect Tensile Strength (ITS) test.
- 6- Finally, the economic impact of the determined mixing and compaction temperatures through different models is evaluated by estimating the energy consumption in terms of electricity and natural gas costs by considering asphalt batch plant type. Besides, the expected environmental impact is appraised by assessing carbon dioxide emissions.

CHAPTER TWO

BITUMEN RHEOLOGY

Rheology deals with the deformation and flow characteristics of the material. Since the bitumen is a viscoelastic material, its rheological characteristics change with the change of temperature and rate of the load. Therefore, the behavior of the bitumen depends on the load applied, the duration of the load, and the temperature during this time. All these properties of bitumen pass into the hot mixture, and therefore bituminous mixtures are also viscoelastic materials (Hunter et al., 2015).

2.1 Rheology, Deformation, Flow

The material's behavior can be recognized based on the deformation recoverability when the load is removed. If the material has the ability to recover this deformation, it would be referred to as elastic. While the material that does not return to its original shape and the deformation is irrecoverable, such material is defined as viscous. In the simplest of terms, ideal solid materials have the ability to recover the deformation when the load is removed, whereas liquids are behaving in a viscous manner and when the load is removed it results in permanent deformation. In general, most of the materials exhibit behavior between elastic solid and viscous liquid, and such behavior is referred to as viscoelastic and the bitumen at intermediate temperatures exhibits such behavior (Hunter et al., 2015).

In rheology, there are major concepts that have a major impact on the definition of the material's behavior such as the concept of deformation and flow. "Deformation is associated with solid behavior, and can be defined as an alteration in shape or size as a response to an applied load". "Flow is associated with liquids (and gases), and is a deformation that continues for as long as the load is applied". Also, there are other factors that play an important role in defining the behavior of the materials such as the effects of the loading time and the temperature. The variation of the temperature and

the load duration would generate a different range of behavior shapes (Schramm, 1994).

Bitumen is one of those materials that its rheological properties such as flow and deformation characteristics are related to the temperature and loading time. Almost all asphalt pavements are of remarkably good quality when they are constructed, but distresses such as cracks begin to appear 2-3 years later. However, deformations that asphalt pavements will undergo can be calculated in advance and if measures can be taken to prevent them, it may be possible to extend the life of the pavement. For this, firstly, it is necessary to know the behavior of asphalt under load. This is achieved by examining the rheological properties of asphalt. In other words, the strength and degree of hardness of asphalt vary depending on the temperature of the environment (Asphalt Institute, 2007)

2.1.1 Elastic Materials' Behavior

Elastic materials are deformed under the influence of the load but can be restored when the load is lifted. Ideal solids are elastic materials. They store deformation energies when stress is applied. Such materials comply with Hooke's law. There is a linear correlation between load-deformation. Hook described the linear correlation between stress and strain in 1678. He is the founder of the classical theory of elasticity and used spring models for this purpose. The Hooke body models the stress-unit strain relationship of materials with ideal rigid behavior up to certain stress levels (Choquet, 1994).

In elastic materials, all work done by external stresses during a strain increase is stored and returns when the loading is lifted. Meanwhile, there is no energy loss in the material. Elastic deformations depend not only on strain size but also on deformation and loading history. Hook law, whose equation and schematic representation are given in Figure 2.1, states that deformation is proportional to the applied stress. The elastic constant (E), also called the “Young Constant”, does not depend on the magnitude and shape of the stretched stress (Painter & Coleman, 1997).

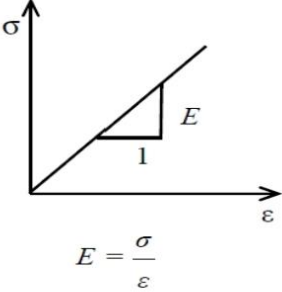
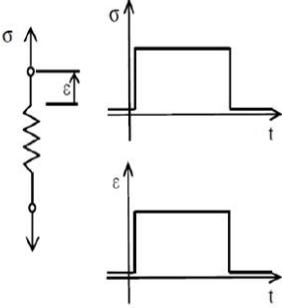
Equation	Illustration	Time dependency	Change of shape
 $E = \frac{\sigma}{\epsilon}$		Time Independent	Recoverable

Figure 2.1 Hook's law and linear-elastic model (Choquet, 1994)

2.1.2 Viscous Materials' Behavior

Viscous materials are deformed during the continuation of the load and remain deformed when the load is lifted. The deformations occurring in such material change according to the loading patterns and the duration of the loads. Dashpot models are used to determine the behavior of viscous materials. Materials in ideal gas and liquid form behave viscously and when they change shape, they cannot store energy, their shape changes are irreversible.

Newton's law states that there is a direct proportion between shear stress (τ) and shear deformation (γ) as seen in the equation below and defines a proportionality constant (η) called viscosity. In Newton law, some of the features of which are given in Figure 2.2, a linear relationship similar to Hook's law is obtained at low strain rates. However, at high strain rates, deviations from the linear relationship are expected. Like the loss of energy in the flow event, which results in permanent deformation, over time, the strain increases continuously and linearly in pure Newtonian viscous fluids (Choquet, 1994).

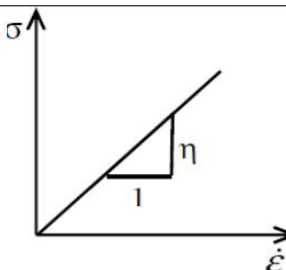
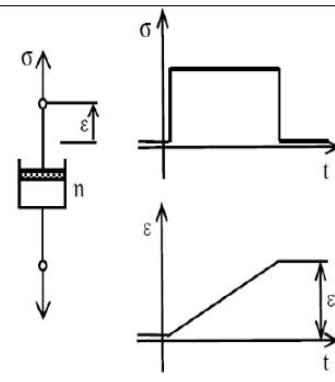
Equation	Illustration	Time dependency	Change of shape
 $\frac{d\varepsilon}{dt} = \dot{\varepsilon} = \frac{\sigma}{\eta}$		Time Dependent	Non-Recoverable

Figure 2.2 Newton's law and linear-viscous model (Choquet, 1994)

2.1.3 Viscoelastic Materials' Behavior

Ideal elastic and ideal viscous materials are two endpoints and many materials show both properties. The behavior of viscoelastic materials can be modeled by connecting the dashpot and spring in various ways. Creep and relaxation behaviors can also be examined with these models. These materials, in particular, exhibit elastic behavior when they are loaded faster and viscous when loaded slowly. During the normal application of the load, they have a behavior suitable for the combination of these two behaviors (viscoelastic) (Choquet, 1994).

The bitumen is a viscoelastic material which means that its behavior is time-temperature dependent as shown in Figure 2.3. The behavior of the bitumen under different temperatures is changing which is affecting the performance of the asphalt pavement. In the hot climate or slow loading conditions, the bitumen show a viscous behavior. While at low temperatures or cold weather and fast applied loads, the bitumen is more like an elastic solid. In general, the climate conditions are mostly in between cold and hot conditions, and in such situations, the bitumen is acting like both a viscous liquid and elastic solid. Also, the bitumen is shear rate-temperature dependent and based on that it can be distinguished as a Newtonian or Non-Newtonian material (Asphalt Institute, 2007).

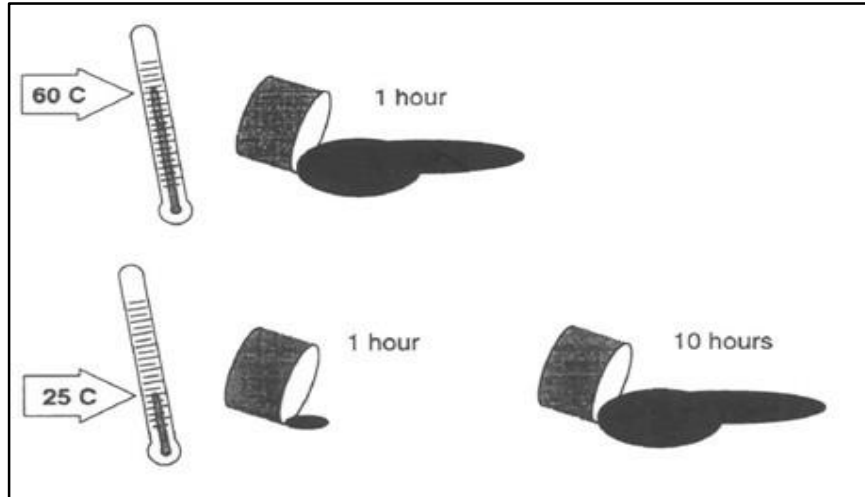


Figure 2.3 Bitumen behavior at different temperatures (Asphalt Institute, 2007)

2.2 Shear-Related Flow Behavior

Viscosity describes the fluidity of the bitumen at any particular temperature. In other words, the viscosity measures the bitumen resistance to flow. Since the bitumen is a viscoelastic material, its viscosity changes with the temperature. Therefore, to compare the consistency of the bitumen the test must be conducted at the same conditions (temperature and shear rate). There are two types of viscosity; dynamic viscosity and kinematic viscosity.

Dynamic viscosity: which may be called as the absolute viscosity or only as viscosity to recognize from the kinetic viscosity. The dynamic viscosity can be calculated through shear stress over shear rate (Equation 2.1).

$$\text{Dynamic viscosity} = \frac{\text{Shear stress}}{\text{Shear rate}} = \frac{\text{Pa}}{\text{s}^{-1}} = \text{Pa s} \quad (2.1)$$

Kinematic viscosity: is represented as the ratio of the dynamic viscosity of the fluid to its density (Equation 2.2).

$$\text{Kinematic viscosity} = \frac{\text{Dynamic viscosity}}{\text{Density}} = \frac{\text{mm}^2}{\text{s}} \quad (2.2)$$

2.2.1 Newtonian Behavior

In systems showing Newtonian flow, as the shear stress increases, shear deformation also increases. η is the viscosity coefficient and is generally defined as viscosity (Schramm, 1994). The flow curve is called a rheogram. The rheogram is obtained by plotting the shear rate ($\dot{\gamma}$) against shear stress (τ). A system showing Newtonian flow is presented in Figure 2.4. In the rheogram of a Newtonian flow system, the flow curve is a line that passes through the origin. Base bitumen or unmodified bitumen at high temperature behaves as a Newtonian fluid (Schramm, 1994).

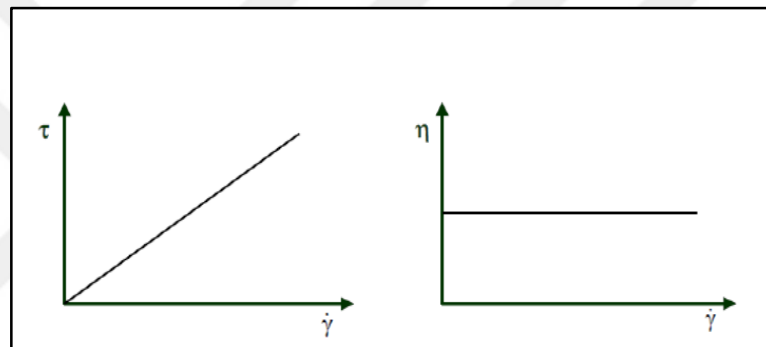


Figure 2.4 Newtonian flow rheogram (Choquet, 1994)

2.2.2 Non-Newtonian Behavior

Non-Newtonian represents the behavior of the material which its viscosity is shear dependent. When the viscosity is decreasing with the increase of the shear rate, the fluid is considered as “shear-thinning liquid”. While if the viscosity is increasing with the increase of the shear rate, the fluid is considered as “shear thickening liquid”. Most of the polymer modified bitumen are non-Newtonian (shear-thinning liquid). Also, at an intermediate temperature, the base bitumen behaves as non-Newtonian (shear-thinning liquid). Systems with non-Newtonian flow are divided into three groups: plastic flow, pseudoplastic flow, and dilatant flow (Schramm, 2000).

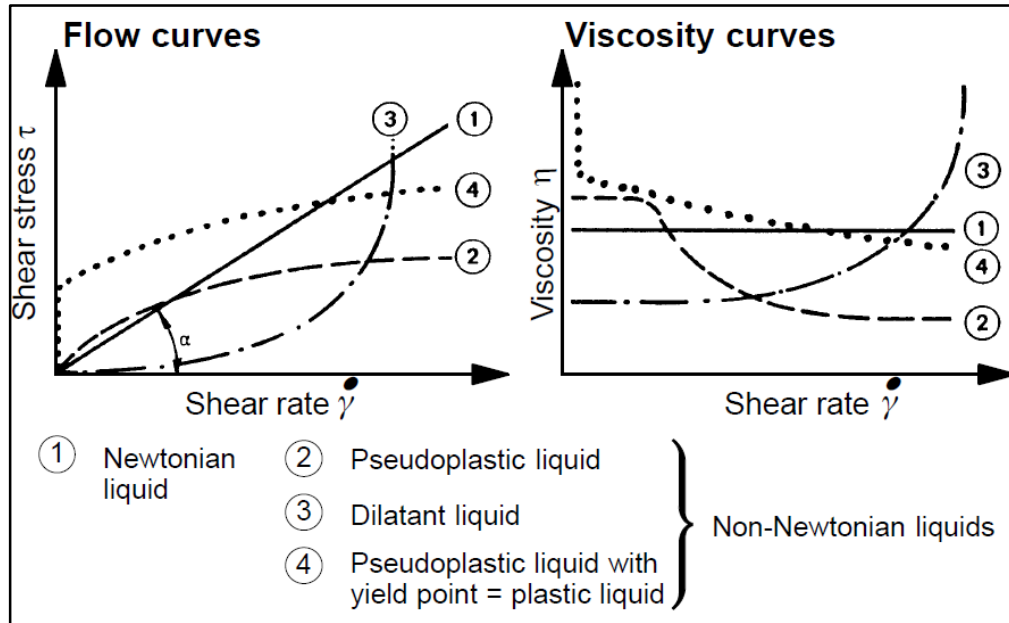


Figure 2.5 Materials behavior (Schramm, 1994)

Plastic liquid, this flow type is called Bingham flow, in the name of Bingham, one of the researchers of modern rheology. As presented in Figure 2.5, non-Newtonian liquids showing plastic flow cannot start flowing instantly. A certain threshold must be exceeded for the flow to start. The material shows an elastic behavior when a stress is applied below the threshold value. The increase in shear stress increases in proportion to the shear rate from the moment the stress exceeds the threshold value. They act as the flow of Newtonian systems after the threshold value (Schramm, 1994).

Pseudoplastic liquid, as seen in Figure 2.5, there is no threshold value in the pseudoplastic flow and the flow rheogram is a curve starting from the origin. As the shear rate of a pseudoplastic substance increases, its viscosity decreases. Semi-solid systems including yogurt, tomato paste, polymer solutions, and polymers also show pseudoplastic flow.

Dilatant flow; the behavior is the opposite of pseudoplastic flow. The dilatant flow diagram is presented in Figure 2.5. In a dilating material, the viscosity increases as the shear stress increases. That is, as the material is mixed, it becomes darker or thicker.

CHAPTER THREE

MODIFICATION

Modification is defined as the mixing of various additives in certain ratios and conditions into the base bitumen in order to increase the performance of the mixture used in road pavements (Malkoç, 2002).

3.1 Purpose of Modification

Bitumen is a viscoelastic material and shows rheological behavior. Bitumen is also a thermoplastic material and its consistency changes when heated. This is one of the properties that make bitumen used as a binder. The viscoelastic character of the bitumen is reflected exactly in the bituminous hot mixture. Viscoelastic materials exhibit more elastic behavior and high strength at higher loading rates (fast vehicles). In contrast, they exhibit viscous behavior and low strength at low loading rates (slow or stationary vehicles). They exhibit common elastic and viscous behavior at moderate speeds. Bitumen also shows low mechanical strength at high temperatures and high strength at low temperatures because of its thermoplastic properties. Deformations occurring in bituminous layers largely depend on these properties of bitumen and mixture.

Research in recent years has revealed that the addition of some polymers and additives affects the rheological behavior of the bitumen, improves its properties and brings superior properties to the bitumen. Therefore, the main purpose of adding polymer to bitumen is to change the viscoelastic behavior of bitumen and to reduce its temperature sensitivity, especially without affecting its behavior at low temperatures.

The effects of modification on bitumen and bituminous mix can be summarized as follows (Asphalt Institute, 2007; Hunter et al., 2015).

1. Increase the pavement's service life
2. Reduce the maintenance cost

3. Increase the pavement's resistance to permeant deformation (rutting) and thermal cracking
4. Increase the pavement's durability
5. Reduce the risk of the early pavements distresses.
6. Increases the stability of the asphalt mixtures.
7. Increase the adhesion between the bitumen and aggregate particles.

3.2 Polymer Types and Applications

Various bitumen modification applications are carried out to provide the above-listed requirements. These applications include sulfur addition, rubber addition, even organic or inorganic sulfides, and bitumen modification by adding polymer. The most commonly used of these additives is polymers. Polymers are made up of chemically connected long molecular chains. Based on the physical properties, polymers are classified into plastomers (plastics) and elastomers (elastic). Under load, plastomers will stretch, but will not return to their original form. While elastomers, when the load released will return to the original shape (Asphalt Institute, 2007).

The behavior of the bitumen, when the polymer added, generally can be described in two ways. If the bitumen becomes thicker and the viscosity increased, then the polymers form discrete particles in the bitumen material. In this case, the low-temperature properties of the obtained polymer bitumen samples will not significantly have influenced. If the polymer work on forming a continuous network and homogenous blend in the bitumen, then both high and low-temperature properties of the bitumen would be affected (Hunter et al., 2015). Table 3.1 shows the polymer types used in bitumen modification, their common names, and some usage areas.

Table 3.1 Example of different polymer types (Hunter et al., 2015)

Type	Example	Usage purpose
Rubber	Natural latex Synthetic latex Reclaimed rubber Polyethylene	Decrease HMA stiffness at low temperatures to resist thermal cracking, Rutting resistance, Improving cohesion of mixture
Polymer	Elastomer (SBS)	High temperature performance, Surface treatment and isolation, Improving cohesion of mixture, HMA rutting resistance, Crack filling
	Plastomers (EVA EBA)	
Reactive polymers	Elvaloy 4170	Increase fatigue resistance, resulting polymer modified asphalt is very stable, and can be stored for extended periods.
Fiber	<i>Natural:</i> Asbestos Rock wool <i>Manufactured:</i> Polypropylene Polyester Fiberglass	Increase stiffness
Chemical modification	Polyphosphoric acid (PPA)	Increase high temperature stiffness.

3.2.1 Elastomers

The most common molecules to form a styrene polymer is butadiene. During the polymerization process, if the butadiene and styrene forming a random arrangement, this polymer is referred to as Styrene-Butadiene Rubber (SBR). This kind of polymers may also be referred to as synthetic latex. On the other hand, if butadiene and styrene are formed in discrete, would be called Styrene-Butadiene-Styrene (SBS) (Asphalt Institute, 2007).

Elastomers obtain strength and elasticity by physically crosslinking three-dimensional networks. This is because polystyrene end blocks are collected in separate environments and form the three-dimensional polybutadiene or polyisoprene rubber system. Even polystyrene end blocks, which add strength to the polymer, provide superior flexibility to the material in the middle blocks (Vonk & Gooswilligen, 1989).

Although the quality of the elastomer is affected by many factors, the most important of these factors is the amount of shearing (shear force) applied by the mixer. When the polymer is added to the hot bitumen, the bitumen starts to penetrate rapidly into the polymer particles. In order to obtain a satisfactory level of distribution within a realistic mixing period, the amount of shear force on the particles is important. Therefore, medium or high shear mixers are required to distribute the elastomers properly into the bitumen.

3.2.2 Plastomers

Plastomers are a kind of polymers utilized in bitumen samples. The major characteristics of this type are that when stretched will remain in the same position when the load is released. One of the most popular plastomers types is Ethylene Vinyl Acetate (EVA). EVA copolymers are easily dissolved in bitumen and provide good compatibility. During storage, some discrimination may occur. Therefore, the modified product must be thoroughly mixed before use (Asphalt Institute, 2007; Hoban, 1987).

The utilization of EVA to modify bitumen samples is not only applied to improve the performance of the pavement. It is also utilized for cold weather applications. EVA enhances the workability of asphalt mixtures due to its sensitivity against shear force (Woolley, 1986).

3.2.3 Thermosetting

International Union of Pure and Applied Chemistry (IUPAC) define a thermosetting resin as a petrochemical in a soft solid or viscous state that changes irreversibly into an infusible, insoluble polymer network by curing. Curing can be induced by the action of heat or suitable radiation, or both. A cured thermosetting resin is called a thermoset. Curing can be induced by the action of heat or suitable radiation or both. A cured thermosetting polymer is called a thermoset (Nic et al., 2005).

Epoxy resins are used in a variety of special applications in pavements such as airport and bridge surfacing. Blended with asphalts, the bitumen displays the behavior of thermosetting resins rather than those of asphalts. Asphalt pavements designed using epoxy modified bitumen (EMB) do not exhibit viscous flow, exhibit resistance against chemical attack, and are less temperature susceptible. They exhibit higher cracking resistance and better adhesion (Giavarini et al., 1993).

CHAPTER FOUR

WARM MIX ASPHALT

4.1 Warm Mix Asphalt Technology

The first studies that led to the emergence of WMA additives started in the 1950s. In early studies, researchers generally tried direct water injection into the bitumen to recycle existing asphalt pavements. However, it was understood in these first trials that the service life of the pavement was not long due to the low mixing and compaction temperatures.

The idea of producing bituminous mixtures at lower temperatures has been an issue that has been studied for many years. The first study was made Csanyi in 1956 at Iowa State University (Chowdhury & Button, 2008). In this study, Csanyi designed a metal conditioning cabinet on the field. This cabin has two entrances and one exit section. Hot bitumen injection is made from the upper entrance, and cold water is added to the cabinet from the other entrance. Cold water sprayed into the cabin foamed hot bitumen, causing a decrease in its viscosity. The foamed bitumen obtained from the outlet in the cabin was mixed with aggregate and paved.

Other studies were carried out by Chevron in the early 1970s by developing asphalt emulsions and some mixture and thickness design methods. Chevron has determined some important rules to be followed in the design and production works of bituminous mixtures prepared with asphalt emulsions (Chevron, 1977). In the ongoing studies, it was stated that the mixes prepared by using asphalt emulsions are prepared at a lower temperature and that they are easy to transport and can be used easily on rural roads, and the investment costs are very low in the plants where asphalt emulsions are produced (Kuennen, 2004).

The first modern WMA studies have started from the second half of the 90s and the findings have been published in the German Bitumen Forum (GBF) held in 1997. In the organization, it was aimed to introduce bitumen producers and academicians with WMA technology and direct the works in line with the requirements of the contractor

companies. In the process that followed, Shell Bitumen Company implemented trial ways and laboratory experiments with WMA in Norway, England and the Netherlands (Koenders et al., 2000). Shell Bitumen Company has developed a WMA additive named WAM - Foam in the light of the data obtained from Koenders' experimental studies using intensive gradation. In the subsequent works, Sasol Wax International AG in Europe introduced Sasobit®, a fully organic wax-based WMA additive, to the market in 1997. As of this date, this process has started to be called WMA technology (Button et al., 2007).

Jenkins et al. (1999) have tried the semi-warm foamed bitumen method. In this method, they mixed aggregates heated at different temperatures with foamed bitumen not to exceed 100 ° C. The obtained results showed that when the aggregates are mixed with foamed bitumen, the aggregates in the mixture are better coated with bitumen, increasing the cohesion, and tensile strength of the mixture.

The aforementioned studies have started to be applied primarily in regions around the world such as Europe, South Africa, and Australia where fossil fuels are costlier (Button et al., 2007). Today, although warm mix asphalt additives are available in the market, it is not a technology used as intensely as HMA. However, its potential effects are being investigated. Recently, in many states of the USA, both laboratory experiments and field studies are applied intensely on a bituminous mixture prepared with WMA additives (Zettler, 2006). Studies have shown that it is possible to use WMA additives for applications with different aggregate gradations such as open gradation, gap gradation, and stone mastic asphalt (SMA), although it is generally utilized with dens gradation mixtures (Koenders et al., 2000).

4.2 Classification of WMA

WMA additives are classified according to different production and application methods and are generally divided into three groups:

- Organic additives
- Chemical additives

Foaming methods (additives containing water and direct water injection).

4.2.1 Organic Additives

Organic WMA additives are amide or wax containing additives that can be easily dissolved in nature. When added directly to the bitumen, they are completely melted at melting temperatures and distributed homogeneously in the bitumen. As a result of this melting cause a significant decrease in the viscosity of the bitumen (Rubio et al., 2012). Organic WMA additives increase the hardness of the mixture by activating the lateral crystalline structure they contain when they are cooled to service temperature (Shang et al., 2011).

Organic WMA additives are high molecular hydrocarbon chains with a melting temperature of 80-120 ° C, improving the properties of base bitumen. There is a direct relationship between the length of the chains in their structures and the melting temperature of the additives. Organic WMA additives with a relatively long carbon chain melt at higher temperatures, while those with a short carbon chain melt at low temperatures (Bueche, 2009). In general, by adding 2-4% (by weight of the bitumen) to the base bitumen, they provide a 20-30 ° C drop in mixing temperature (Rubio et al., 2012). The organic additive manufacturing process has been used since the 1980s and has three different methods: (i) Fischer-Tropsch waxes, (ii) fatty acid amides, (iii) Montan waxes.

4.2.2 Chemical Additives

In general, chemical WMA additives are a combination of emulsification additives, surface improvers, polymers, and additives that enable aggregate to be coated with bitumen, increasing workability, compaction, and adhesion. Chemical WMA additives are added directly to the bitumen and then this mixture is mixed with aggregate. They provide a 15-75 ° C decrease in the mixing temperature to the ingredients of the product used (Barthel et al, 2004).

Chemical WMA additives are generally between 1.5% and 3.0% by weight of the bitumen in the mixture according to the manufacturer's recommendations and experimental studies. Chemical additives do not require any plant modification during production and mixing processes (Prowell et al., 2011). However, it is not necessary to add any anti-peel additive in bituminous mixtures prepared with chemical WMA additives (Chowdhury & Button, 2008).

4.3.3 Foaming Technologies

Water is an important agent in increasing the coating potential of the bitumen. Based on this principle, foaming technologies have been developed in two ways. One is to inject fine water particles directly into the mixture during the mixing process. In this method, water particles turn to steam after being sprayed into the hot environment of the mixture. This causes an expansion for water volume by a factor of 1.673. This expansion results in a reduction of the mix viscosity and help coating. WAM-foam is a patented foaming technology developed based on this theory by the cooperation of Shell Global Solutions and Kolo Veidekke. Within the WAM-foam process, the aggregates are mixed with soft bitumen firstly, and then harder bitumen foamed with wet filler is added to the mix (D'Angelo et al., 2008).

Another method of foaming technology is to add an additive that contains a particular amount of water. A pre-moistened additive releases its moisture when added to the hot mixture. This acts as the same system of the injection method. Released steam results in a more lubricant mix and correspondingly increases the workability. Advera® and Aspha-min® (both are synthetic zeolites) have been developed based on this theory. Zeolites are minerals with a micro-porous structure that can absorb and maintain moisture (D'Angelo et al., 2008). More examples of foaming technologies are shown in Table 4.1.

Table 4.1 Example of existing WMA foaming technologies (D'Angelo et al., 2008)

Technology	Company	Production Temperature (at plant) °C	Reported Field Practice
WAM-Foam	Shell Global Solutions and Kolo Veidekke	110–120 °C	Many European Countries and Canada
Advera® (Synthetic zeolite)	PQ Corporation	20–30 °C (Drop from HMA) 130–170 °C (German guideline Recommendation)	U.S.
Aspha-min® (Synthetic zeolite)	Eurovia and MHI	20–30 C° (Drop from HMA) 130–170 °C (German guideline Recommendation)	Germany
LT Asphalt	Nynas	90 °C	Netherlands and Italy
Double-Barrel Green	Astec	116–135 °C	U.S.
ECOMAC	Screg	Placed at about 45 °C	France
LEA, EBE and EBT	LEACO, Fairco and EIFFAGE Travaux Publics	<100 °C	France, Spain, Italy and U.S.
LEAB®	BAM	90 °C	Netherlands

CHAPTER FIVE

MIXING AND COMPACTION TEMPERATURES DETERMINATIONS

5.1 Background

In 1962 the Asphalt Institute's Mix Design Methods for Asphalt Concrete Manual suggested specifying mixing and compaction temperatures based on viscosity measurements. The viscosity limits were 85 ± 10 seconds Saybolt Furol for mixing the bitumen with aggregate and 140 ± 15 seconds Saybolt Furol for compaction. By 1974 the Asphalt Institute changed the units of the viscosity to more practical units of centistokes and suggested the viscosity limits to be 170 ± 20 centistokes and 280 ± 30 centistokes for mixing and compaction respectively. Twenty years later, Superpave mix design (SP-2) Manual suggested using the same mixing and compaction limits only the viscosity unit has been changed to become Pa s. The manual has stated that the suggested limits are not applicable for the modified bitumen and proposed that users must contact the supplier for appropriate mixing and compaction temperature values (Azari et al., 2003). American Society for Testing and Materials (ASTM) has released a special standard to calculate mixing and compaction temperatures of asphalt mixture (ASTM D2493). In this standard, the viscosity measurement must be conducted at specified temperatures (135°C and 165°C) and the obtained viscosities in log scale are drawn against the temperature. The mixing and compaction temperatures limits are 0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s, respectively.

Since the Equiviscous method is based on viscosity measurement for unmodified bitumen, the increase in viscosity in polymer modified bitumen will affect mixing and compaction temperatures determination and may result in excessive temperatures. In other words, the application of the Equiviscous method may not present realistic approach regarding mixing and compaction of modified bitumen. So it is necessary to investigate alternative methods that must be reliable and more applicable (Khatri, 2005; West et al., 2010).

Some studies have suggested measuring the viscosity of the asphalt mastic (bitumen and filler) rather than the base bitumen to determine the mixing and compaction temperatures. The reason to use asphalt mastic is to better simulate the mixing of aggregate and bitumen during the construction. Zeng and Wu investigated the effect of the mineral filler on the viscosity of the bitumen and also on the mixing and compaction temperatures. They believed that the viscosity of the asphalt mastic must be considered rather than the bitumen itself. They suggested new viscosity rang for mixing and compaction for unmodified bitumen 0.576 ± 0.071 Pa. s. and 0.968 ± 0.107 Pa. s, respectively (Zeng & Wu, 2008).

Other studies have demonstrated the effects of the compaction temperature on the properties of the asphalt mixtures. Azari et. al evaluated the optimum compaction temperature for Novophalt modified bitumen using four temperatures (119, 139, 159, and 179 °C). They found that increasing the compaction temperature to some degree improves the shear properties of the mixture and the optimum compaction temperature range is between 139 to 159 °C (Azari et al., 2003). Lee et. al investigated the effects of using different compaction temperatures on the volumetric properties of the modified bitumen. Two modification types (crumb rubber and SBS) have been used to prepare the modified bitumen samples and have been compacted over a range of temperatures (116, 135, 154, 173 °C). The results have shown that for SBS modified bitumen the variation of the compaction temperatures does not affect the volumetric properties. While for the crumb rubber modified bitumen the volumetric properties have influenced by the variation of the compaction temperatures. Also, it has been noticed that the air void content has increased with decreasing the compaction temperature (Lee et al., 2008).

5.2 Effect of Mixing and Compaction Temperatures On the Asphalt Characteristics

There have been numerous studies that investigate the effect of the mixing and compaction temperatures on the asphalt mixture characteristics. Fink and Letter evaluated the characteristics of asphalt prepared with unmodified bitumen. Their

research demonstrated that lower compaction temperature had a direct impact on the density. Besides the Marshall stability increases with the increase in compaction temperature. While the flow values have not been affected by the compaction temperature (Fink & Lettier, 1951). Huner and Brown investigated the effect of variation of compaction temperatures on the mechanical properties of asphalt mixtures using Superpave gyratory compactor for two different aggregate types. They concluded that none of the asphalt mixtures were affected by the reduction of compaction temperatures for the unmodified samples (Huner & Brown, 2001). Bahri and Rader reported that significant changes have been detected in Marshall stability, flow, air voids, and density with the variation of mixing and compaction temperatures. Rahmat et al. evaluated the effect of compaction temperature on the dense graded asphalt mixtures performance. They concluded that the raise in compaction temperature increased voids in mineral aggregate value (VMA) while the voids filled with asphalt value (VFA) have decreased. Also, they found that increasing compaction temperature has a positive impact on the asphalt mixture performance in terms of increasing Marshall stability, creep modulus and resilient modulus (Rahmat et al., 2019).

In the case of modified asphalt mixtures, recent studies have indicated that mixing and compaction temperatures may have a direct effect on the properties of asphalt mixture. The increase in mixing and compaction temperatures lead to an increase in the modified asphalt mixture performance in terms of resilient modulus and resistance to permanent deformation (Aschenbrener & Far, 1994; Newcomb et al., 1992). Moreover, several authors have recognized the effect of using different mixing and compaction temperatures on the volumetric properties of asphalt concrete samples (Aschenbrener & Far, 1994; Azari et al., 2003; Newcomb et al., 1992). It has been noticed that the variation in volumetric properties for modified asphalt samples is greater than the samples prepared with unmodified bitumen (Lee et al., 2008). Also, several studies have shown that the utilization of high temperatures has serious consequences on the bitumen rheological characteristics in terms of aging of bitumen and degradation of polymer modified bitumen. Airey and Brown indicated that the bitumen storage at high temperatures can cause damage to long-chain polymers and

by that, the benefits of modified bitumen are revoked (Airey & Brown, 1998). Therefore, many agencies and bitumen suppliers do not apply the ASTM (equiviscous) method when it comes to the modified bitumen because of the excessive resulted temperatures which may not be necessary when the traditional method is applied.

5.3 Recent Methodologies

In the last few years, there are several attempted by many researchers to specify more practical approach to determine mixing and compaction temperatures of modified bitumen than the ASTM (equiviscous).

5.3.1 High Shear Rate Method (HSR)

Solaimanian and Kennedy presented a method that considers the viscosity of the bitumen at a higher shear rate than the ASTM (equiviscous) method using Brookfield rotational viscometer measurements for the determination of mixing and compaction temperatures (Yildirim et al., 2000). The shear rate of 500 1/s was adopted based on experimental work with mixtures compacted in a Superpave gyratory compactor (SGC). The same mixtures were prepared with four different bitumen and then compacted in the SGC over a range of low temperatures (between 50°C and 95°C) to evaluate the effect of temperature on mixture density. It was speculated that equivalent mix densities would emerge when the viscosities of bitumen were the same. Therefore, to find the point where unmodified and modified bitumen viscosities were the same, the bitumen sample was tested in a Brookfield viscometer over shear rates ranging from 0.1 1/s to 93 1/s. The hypothesis was that the shear rate at which the viscosities of bitumen samples intersect is high. So, the viscosity data were extrapolated using the Power-law model to find the shear rate where the unmodified bitumen and the modified bitumen had the same viscosity as shown in Figure 5.1. The obtained shear rates range between 399 and 638 1/s and the average is about 490 1/s. The proposed shear rate to be utilized was 500 1/s. They determined mixing and compaction temperatures for four modified bitumen samples to be 10°C to 40°C below the temperatures from the ASTM (equiviscous) method. This method has two forms,

original and evolution, and the difference between them is the proposed mixing and compaction temperatures limits (Yildirim et al., 2006).

The application of this method was tested by Micaelo using SBS polymer modified bitumen samples at rates of 2 to 4%. The results showed that the utilizing of the high shear method in the original form resulted in excessive temperatures, above 180 °C, which may reduce polymer modification benefits and increase risks to workers and the environment. While the high shear rate in the evolution form determined mostly mixing temperatures and compaction temperatures below the ASTM (equiviscous) method results (Micaelo et al., 2012).

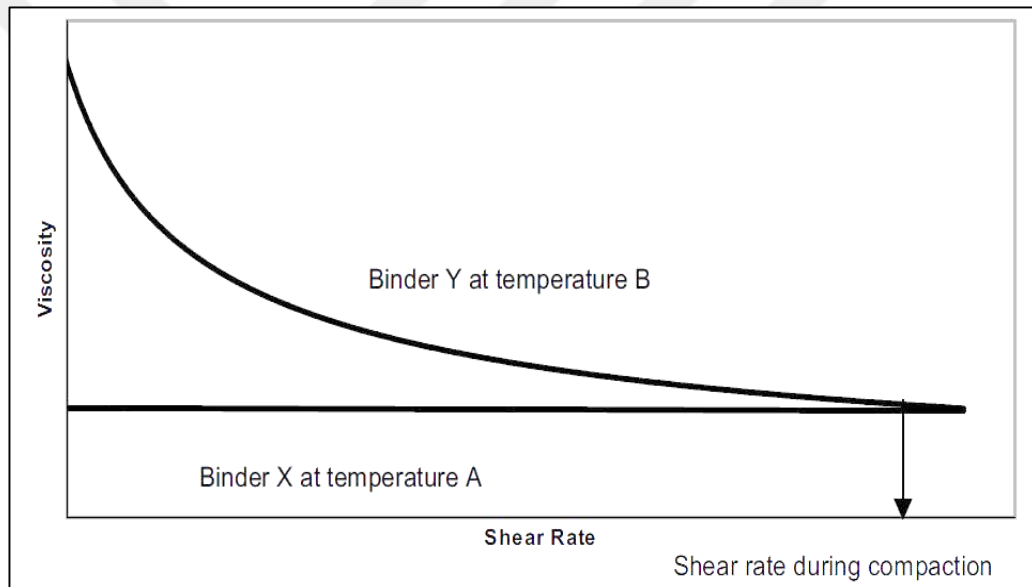


Figure 5.1 HSR hypothesis (Yildirim et al., 2000)

5.3.2 Zero Shear Viscosity method (ZSV)

The hypothesis of this method was built on the fact that most of the polymer modified bitumen samples are sensitive to shear rate and therefore did not meet the current assumption that bitumen samples are Newtonian fluids. Based on that, Khateria presented the concept of Zero Shear Viscosity (ZSV) and suggested its use for calculating mixing and compaction temperatures for polymer modified bitumen (Khatri, 2005). The researcher reasoned this was due to the lower vertical compression

rate developed during the compaction process of the Superpave gyratory compactor (SGC). Therefore, the measurement of the viscosity should be performed at a very low shear rate. Also, it has been noticed that low shear viscosity data for the asphalt correlated better to air voids in SGC-compacted specimens compared with high shear. In order to find the zero shear viscosity, it is proposed that to use the cross Williamson model which resulted in better curve fitting compared to other models as shown in Figure 5.2. The mixing and compaction criteria at this shear rate were set at 3.0 Pa s and 6.0 Pa s, respectively.

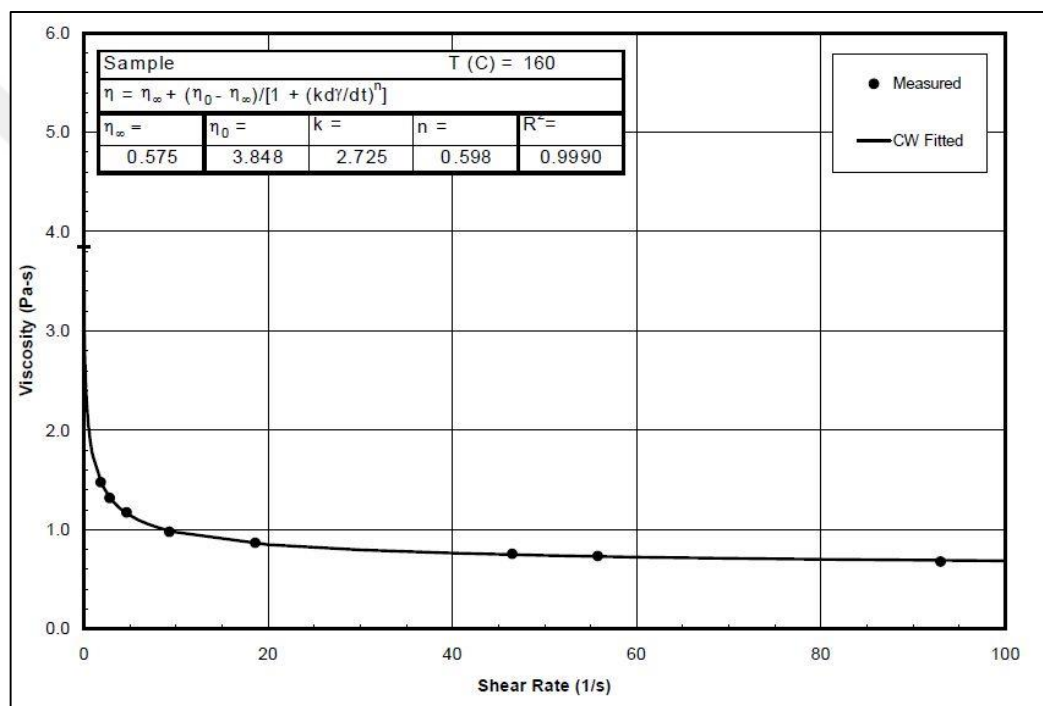


Figure 5.2 Example of ZSV (Khatri, 2005)

A couple of research studies have been conducted to evaluate the ZSV method. Grover determined the mixing and compaction temperatures based on the ZSV method and the ASTM (equiviscous) method for modified and unmodified bitumen samples. The data showed that the ASTM (equiviscous) method required excessive heating of the modified bitumen samples. The ZSV method yielded mixing and compaction temperatures that were 35°C to 40°C lower than those determined by the ASTM (equiviscous) method.

Tang and Haddock evaluated seven modified and unmodified mixtures and one SMA mixture obtained from Indiana DOT projects. Four of the mixtures were prepared using unmodified bitumen (Newtonian) and their mixing and compaction temperatures were determined by the ASTM (equiviscous) method (Tang & Haddock, 2006). All bitumen samples also were tested to determine their ZSV mixing and compaction temperatures following the procedure developed by Khatri. They found that the ZSV mixing and compaction temperatures resulted in the same optimum bitumen content as was used on the project. Also, the research results showed that the ZSV temperatures were about 40°C below the ASTM (equiviscous) temperatures. They suggested that the ASTM (equiviscous) method be used to specify mixing and compaction temperatures for unmodified bitumen samples (Newtonian) and the ZSV method be utilized for modified bitumen samples (non-Newtonian).

5.3.3 Steady Shear Flow Method (SSF)

This method is developed based on the fact that at different shear stresses the bitumen behavior is changing accordingly in terms of viscosity value. The viscosities of most modified bitumen samples approach a steady-state condition when the shear stress is around 500 Pa as illustrated in Figure 5.3. This method is conducted using a Dynamic Shear Rheometer (DSR). The viscosity values of modified bitumen samples were measured over a range of shear stresses and temperatures. The mixing and compaction temperatures determined using viscosity results at 500 Pa shear stress using a log viscosity versus log temperature chart. The mixing temperature was selected at a viscosity of 0.17 ± 0.02 Pa s, which is consistent with the ASTM (equiviscous) method. However, compaction temperature was selected at a viscosity of 0.35 ± 0.03 Pa s (West et al., 2010).

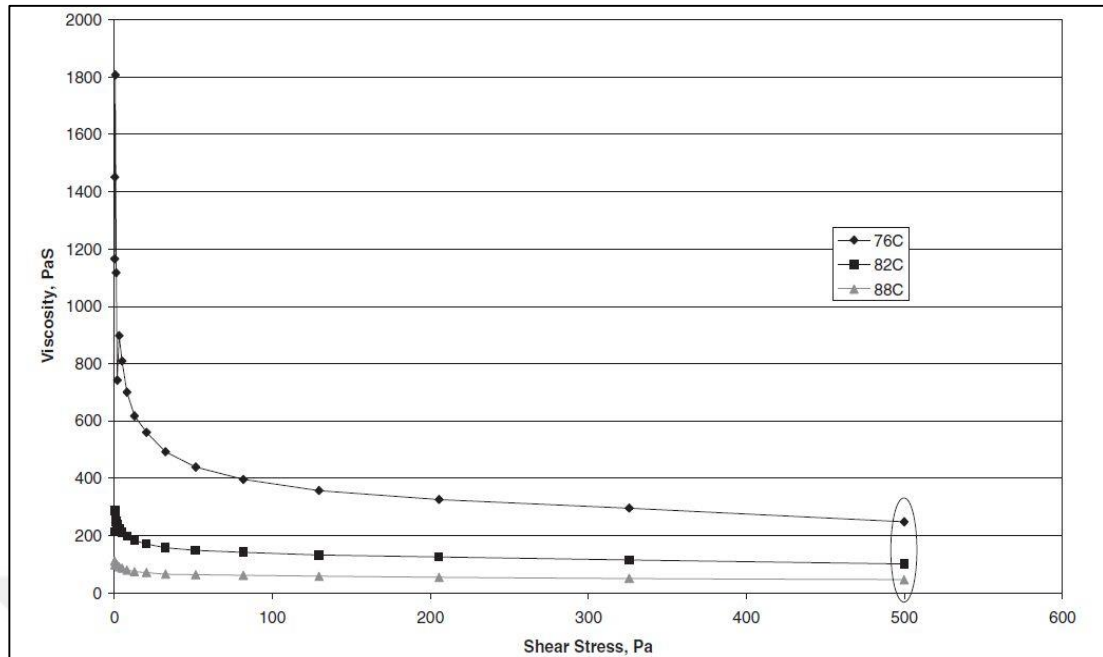


Figure 5.3 SSF method example (West et al., 2010)

The implementation of this method was examined as a part of the National Cooperative Highway Research Program. Mixing and compaction temperatures calculated with the SSF method for different PMB samples were significantly lower than the equiviscous results (West et al., 2010).

5.2.4 Phase Angle Method

This method is developed under the National Cooperative Highway Research Program (NCHRP 648) (West et al., 2010). This technique considers the non-Newtonian viscoelastic behavior of bitumen samples as measured using Dynamic Shear Rheometer (DSR) equipment. In dynamic testing, the phase angle is the measure of the time lag between the applied stress and the resulting measured strain. The phase angle can be measured over a range of temperatures and frequencies as illustrated in Figure 5.4. Accordingly, it was logical to adopt the phase angle as an alternate consistency parameter that could be utilized to determine mixing and compaction temperatures. Although phase angle is a fundamental material property, its relationship to coating and lubricating aggregate particles is empirical. However, this is also the case for viscosity at any shear rate.

The mixing and compaction temperatures determined by the Phase Angle method are lower than the ASTM (equiviscous) method. For base bitumen samples, the Phase Angle method yielded temperatures within a few degrees of the ASTM (equiviscous) method results. However, some mixing and compaction temperature results were also more than 10°F (12 °C) above or 10°F (12 °C) below the results from the ASTM (equiviscous) method (West et al., 2010).

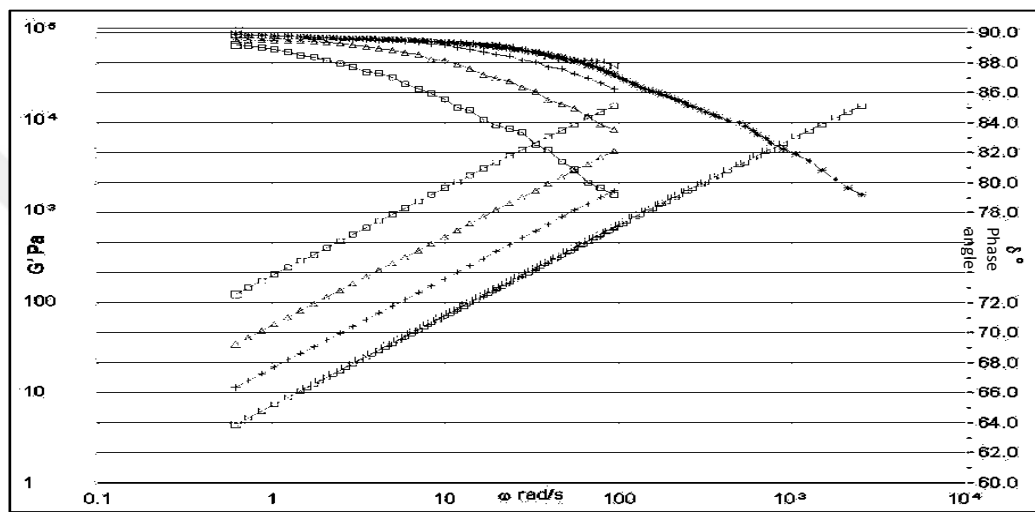


Figure 5.4 Example of Phase angle (West et al., 2010)

CHAPTER SIX

EXPERIMENTAL

6.1.1 Base Bitumen

6.1.1 Base Bitumen

In this study 50/70 and 160/220 base bitumen penetration grades supplied by Dere Group were used. Some of the conventional tests have been conducted for the base bitumen such as penetration test, softening point test, and Rolling thin film oven test to measure the bitumen characteristics. Table 6.1 shows the test results according to the ASTM specification.

Table 6.1 Properties of the base bitumen

Test	Specification	Results		Specification limits	
		50/70	160/220	50/70	160/220
Penetration (25 °C; 0.1 mm)	ASTM D5 EN 1426	65	190	50-70	160-220
Softening point (°C)	ASTM D36 EN 1427	51	41	46-54	35-43
Penetration index (PI)	-	0.35	0.123	-	-
Rolling thin film oven test (RTFOT)	ASTM D2872-12				
Change of mass (%)	-	0.160	0.94	0.5 (max.)	0.5 (max.)
Penetration (25 °C; 0.1 mm)	ASTM D5 EN 1426	53	97	50 (min.)	50 (min.)
Retained penetration (%)	ASTM D36 EN 1427	82	51	50 (min.)	50 (min.)
Softening point after RTFOT (°C)	ASTM D36 EN 1427	58	50	48 (min.)	48 min.)

6.1.2 Polymer Modifiers

With the aim of preparing polymer modified bitumen, two different polymers type— Styrene Butadiene Styrene (SBS Kraton® D 1101), and Reactive Elastomeric Terpolymer type – (Elvaloy® 4170), have been employed. The polymer modifiers play a major role in improving the asphalt mixture characteristics and increase the service life of the flexible pavement.

6.1.2.1 SBS Kraton® D 1101

The SBS polymer was Kraton D-1101 (powder form) supplied by the Shell Chemicals Company. Kraton® D 1101 is a linear SBS polymer consisting of 31% styrene and high amount of polybutadiene blocks (Shell Tech. Bulletin, 1995). Physical properties of Kraton® D 1101 are given in Table 6.2. Figure 6.1 shows Kraton® D1101 additive in powder form.

Table 6.2 The properties of Kraton D-1101 polymer

Composition	Specification	Kraton D 1101
Molecular structure	-	Linear
Physical properties		
Specific gravity	ASTM D792	0.94
Tensile strength at break (MPa)	ASTM D 412	31.8
Shore hardness (A)	ASTM D 2240	71
Physical form	-	Powder, pellet
Melt flow rate	ASTM D-1238	<1
Processing temperature (°C)	-	150–170
Elongation at break (%)	ASTM D 412	875
Density	-	-



Figure 6.1 SBS Kraton® D-1101 (Powder Form) (Personal archive, 2018)

6.1.2.1 Elvaloy® 4170

Elvaloy® 4170 plastomer modification additive was obtained from DuPont. Elvaloy® 4170 is a reactive ethylene Terpolymer used for modification of bitumen. Its composition and physical properties are given in Table 6.3. Physical view of Elvaloy® 4170 presented in Figure 6.2.

Table 6.3 The properties of Elvaloy® 4170 polymer

Composition	Specification	Elvaloy 4170
Molecular structure	-	Linear
Physical properties		
Tensile strength at break (MPa)	ASTM D 412	31.8
Physical form	-	Powder, pellet
Melt flow rate	ASTM D-1238	8
Density	-	0.557



Figure 6.2 Elvaloy® 4170 (Personal archive, 2018)

6.1.3 Warm mix additives

In this study, warm mix additives utilized are categorized into two types, organic and chemical additives. For organic additives, Sasobit® has been used to produce WMA samples. While Rediset® additives were utilized as a chemical additive to produce WMA samples.

6.1.3.1 Organic WMA additive (Sasobit®)

The organic WMA additive (Sasobit), which has been supplied from a South African Company, is a long-chain aliphatic polymethylene hydrocarbon produced from the Fischer–Tropsch chemical process with a melting temperature of 120°C. The longer chains help keep the wax in solution, which reduces bitumen viscosity at typical asphalt production and compaction temperatures. Sasobit® should be added 3% to provide the desired viscosity to the mixture, and no more than 4% should be added to the bitumen to prevent the low temperature effect (Corrigan, 2008). Sasobit® is produced both in pellets and flakes. Figure 6.3 shows Sasobit® additive in pellets form.

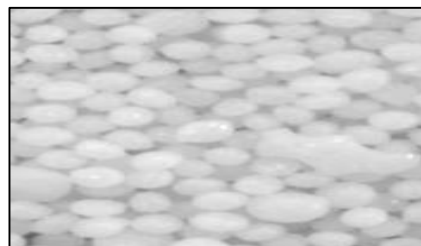


Figure 6.3 Sasobit® pellets (Personal archive, 2018)

6.1.3.2 Chemical WMA additive (Rediset®)

Chemical WMA additive (Rediset) is a combination of cationic surfactants and organic additive-based rheology modifier. The additive chemically modifies the bitumen and obtains active adhesion force that improves coating of aggregates with bitumen. Rediset® can also encourage both processing of asphalt mixture at lower temperatures and combination with high contents of Reclaimed Asphalt Pavement.

Rediset® usually does not require any additional antistripping agent in the mixture due to this product provides anti-stripping properties. Rediset® can be blended with bitumen or can be added to the mixture right after the addition of bitumen. If it is directly blended with bitumen at the refinery, it does not require any modification at the plant. Rediset® sample is given in Figure 6.4.

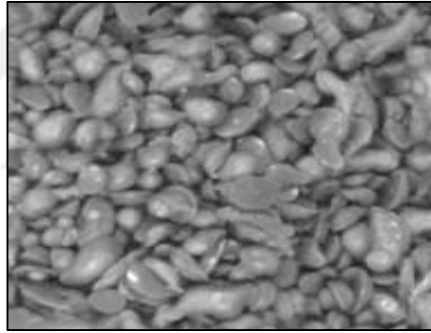


Figure 6.4 Rediset® sample (Personal archive, 2018)

6.1.4 Aggregate

The asphalt mixtures were produced with limestone aggregate collected from the Dere Beton/Izmir quarry. The physical properties of the aggregate are given in Table 6.4. The aggregate gradation has been chosen as a Type 1 wearing course based on the Turkish Specifications.

Table 6.4 Gradation and properties of the aggregate

Test	Specification	Selected gradation	Specification limits
Sieve analysis	ASTM C 136		
Sieve no			
3/4 in.		100	100
1/2 in.		92	88-100
3/8 in.		73	72-90
No. 4		44.2	42-52
No. 10		31	25-35
No. 40		12	10-20
No. 80		8	7-14
No.200		5.3	3-8
Bulk Specific gravity (coarse aggregate)	ASTM C 127	2.686	
Bulk Specific gravity (fine aggregate)	ASTM C 128	2.687	
Specific gravity (filler)		2.725	
Los Angeles abrasion (%)	ASTM C 131	24.4	Max 45
Flat and elongated particles (%)	ASTM D 4791	7.5	Max 10
Sodium sulfate soundness (%)	ASTM C 88	1.47	Max 10-20

6.2 Preparation of bitumen samples involving additives

To prepare the polymer modified bitumen PMB samples SBS® and Elvaloy®, have been added into the base (unmodified) bitumen. While for warm mix asphalt, organic and chemical additives have been incorporated into the base bitumen.

6.2.1 Preparation of PMB samples

Based on the past researches the SBS Kraton D 1101 concentration in the base bitumen is chosen 5% as optimum content (Sengoz & Isikyakar, 2008). A high shear

laboratory mixer is used to prepare the SBS polymer modified bitumen. The base bitumen has been first heated to (180-185 °C) and has been poured into 600 ml glass beakers. Based on several past researches, the base bitumen and the polymer are heated at such temperature to ensure that the base bitumen and polymer are above their softening points. Also, it is necessary to heat the bitumen at high temperatures to allow the polymer particles to become soluble during production (Kök et al., 2013; Larsen et al., 2009; Munera & Ossa, 2014; Schaur et al., 2017). The SBS was then added gradually to the base bitumen and the rotating speed was kept at 2000 rpm for 1 hour.

The Elvaloy content is 1.5 % of the bitumen weight as recommended in the literature to achieve optimum performance (Topal, 2010). Laboratory mixer is used to prepare the modified bitumen samples and following the procedure recommended by the DuPont company. The bitumen is heated at 185 °C to become fluid enough and then the modifier is gradually added while the rotating speed is set at 200 rpm for 2 hours. The viscosity must be measured immediately after the finishing of the production and the sample must be cured in the oven for 24 hours at 190 °C to allow the reaction to complete (Bulatović et al., 2014).

6.2.2 Preparation of Bitumen Samples With WMA Additives

The concentration of both organic and chemical is specified based on the recommendations by the suppliers as well as literature (Oliveira et al., 2013). The concentration of both organic additive (Sasobit®) and the chemical additive (Rediset®) is chosen as 3% to produce warm mix asphalt samples. The base bitumen is heated until it becomes fluid and has been poured into a 500 ml glass beaker. The Sasobit® is then added gradually and the rotating speed was maintained at 1000 rpm for 10 minutes. While for the chemical additive the rotating speed was 1000 rpm for 15 minutes. These values were taken into account based on past researches which indicate that the production process of the warm mix asphalt does not require a high shear rate and the required production time should be maintained at the minimum so the warm mix additives would more effective and the aging effect would be avoided (Kanitpong et al., 2008; Sengoz et al., 2013).

6.3 Conventional Properties of Bitumen Involving Additives

Conventional bitumen tests such as penetration test (ASTM D5- 06), softening point test (ASTM D36-95) and rolling film thin oven test (ASTM D2872-12) have been subjected on both PMB and WMA samples. Tables 6.5 and 6.6 present the properties of the polymer modified bitumen and bitumen involving WMA additives.

Table 6.5 Properties of the 50/70 penetration bitumen grade involving different additives

Test	Polymer		WMA additives	
	% 5 SBS	% 1.5 Elvaloy	% 3 Organic	% 3 Chemical
Penetration (25 °C; 0.1 mm)	48	49	37	40
Softening point (°C)	49	65	69	58
Flash Point (° (°C)	260+	260+	260+	260+
Ductility (25°C, cm)	100+	100+	100+	100+
Rolling thin film oven test (RTFOT)				
Change of mass (%)	0.07	0.03	0.07	0.06
Retained penetration (%)	21	25	13	17
Softening Point Difference(°C)	3	0	4.0	2.1
Penetration index (PI)	-2.18	1	1.95	0.09
Storage Stability (°C)	3	1.92	1.6	0.6

Table 6.6 Properties of the 160/220 penetration bitumen grade involving different additives

Test	Polymer		WMA additives	
	% 5 SBS	% 1.5 Elvaloy	% 3 Organic	% 3 Chemical
Penetration (25 °C; 0.1 mm)	119	105	95	98
Softening point (°C)	59	71	77	79
Flash Point (° (°C)	260+	260+	260+	260+
Ductility (25°C, cm)	100+	100+	100+	100+
Rolling thin film oven test (RTFOT)				
Change of mass (%)	0.141	0.097	0.090	0.075
Retained penetration (%)	21	24	11	15
Softening Point Difference(°C)	6	3	5.6	7.9
Penetration index (PI)	5.30	3.50	2.33	1.2
Storage Stability (°C)	6	4.32	2.7	0.96

According to Tables 6.5 and 6.6, SBS Kraton® D 1101 and Elvaloy® 4170 polymers have reduced penetration values compared to base bitumen; however, an increase in softening point is observed. Penetration is an indicator of consistency and its value is inversely proportional to consistency. The decrease in penetration and increase in softening point means that the hardness of polymer modified bitumen increases. In addition to the increase in hardness, the increase in the penetration index of the polymer modified bitumen indicates that the modified bitumen, especially with a high polymer rate, significantly reduces its temperature sensitivity. The age hardening of the bitumen during bulk storage is evaluated by the mass loss, penetration, retained penetration, and softening point temperature in the RTFOT. The bitumen modified with SBS Kraton® D 1101 and Elvaloy® 4170 polymers in terms of storage stability can be said to be suitable for long-term storage as it remains within specification limits (maximum 4 ° C).

Similar statements can be made for organic and chemical WMA additives. When Tables 6.5 and 6.6 are examined, reduction of penetration values compared to polymer additive bitumen samples with the addition of organic (Sasobit) and chemical (Rediset) warm mix asphalt additive; however, an increase in softening point values is observed. The increase in the softening point means that the mixtures prepared with these additives may be resistant to rutting. Also, it is seen that the storage stability of bitumen samples prepared with organic and chemical WMA additives gives very good results and this shows that bitumen containing organic and chemical WMA additives is quite suitable for storage.

6.4 Mixing and Compaction Temperatures Determination Methods

In the last few years, there are several attempts by many researchers to specify a more practical approach to determine mixing and compaction temperatures for modified bitumen rather than the ASTM (equiviscous) method. Below are the detailed information and procedures regarding the proposed as well as the ASTM (equiviscous) method.

6.4.1 Equiviscous Method (ASTM D 2493)

Based on ASTM D 2493, this method is conducted to measure the viscosity of the bitumen at two temperatures 135°C and 165 °C at a constant shear rate of 6.8 1/s (ASTM, 2016). Brookfield viscometer is the most common machine that is utilized to measure the bitumen viscosity for this method. The measured viscosity results are then drawn versus the temperature. The temperatures corresponding to bitumen viscosities 0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s were chosen as mixing and compaction temperatures, respectively. The mixing and compaction temperature determinations are illustrated in Figure 6.5.

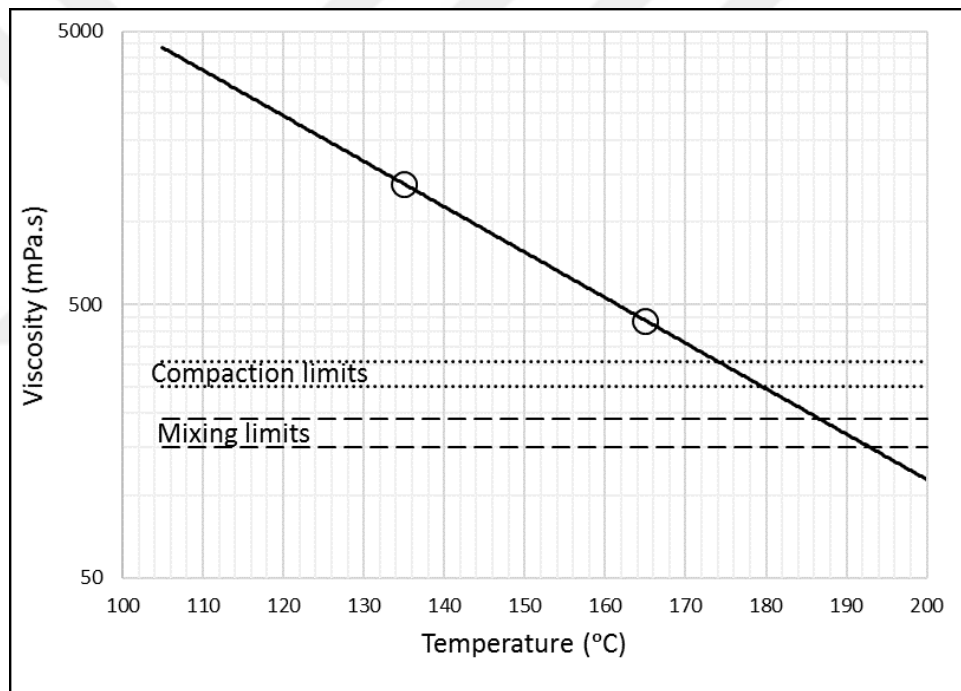


Figure 6.5 Temperature viscosity plot showing mixing and compaction temperatures ASTM (equiviscous) method

6.4.2 High Shear Rate Method (HSR)

This approach has been introduced by Solaimanian and Kennedy based on the shear rate- temperature behavior dependency of the bitumen. In this method, Brookfield viscometer is used to find the viscosity of the bitumen at different shear rates and then drawn and extrapolated using the power-law model to 500 1/s shear rate as shown in

figure 6.6. This is performed because such a high shear rate cannot be measured directly using Brookfield viscometer. Based on the bitumen viscosity range used to estimate mixing and compaction temperatures, this method can be classified into two forms named high shear rate original (HSR-O) and high shear rate evolution (HSR-E). In HSR-O method the obtained viscosity values at 135 °C and 165 °C are plotted against the temperature. Mixing and compaction temperatures are determined by using the same viscosity limits used in the Equiviscous method (0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s) (Yildirim et al., 2000). While for HSR-E method the authors have suggested a higher viscosity range for mixing and compaction to be used which are 0.275 ± 0.03 Pa. s and 0.550 ± 0.06 Pa. s, respectively (Yildirim et al., 2006).

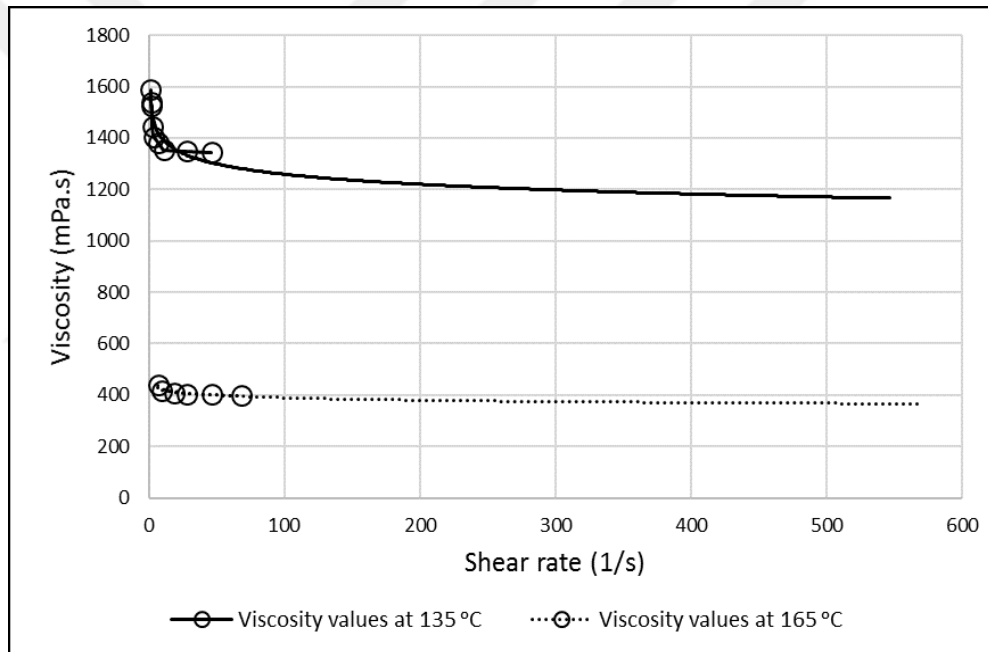


Figure 6.6 Example data from high shear rate for PMB samples

6.4.3 Zero shear Viscosity Method (ZSV)

Zero shear viscosity (ZSV) is the viscosity measured in shear deformation at a shear rate approaching zero. Khateria et al. proposed the zero shear viscosity concept to be implemented for the determination of mixing and compaction temperatures of modified bitumen using Brookfield viscometer (Khatri, 2005). In order to find the zero shear viscosity, the Cross Williamson model has been proposed to be used in a solver

program. Accordingly, unlike the ASTM (equiviscous) method, different shear rate values are required to measure the viscosity of the modified bitumen at two temperatures 135 °C and 165 °C as illustrated in Figure 6.7. The required mixing and compaction temperatures are then found by plotting the log-log of viscosity as a function of log temperature in degrees Kelvin ($273 + ^\circ\text{C}$). The proposed bitumen viscosity ranges to estimate mixing and compaction is 3.0 Pa. s and 6.0 Pa. s, respectively. The Cross Williamson model is given as in Equation (6.1).

$$\eta = \eta_{\infty} + (\eta_0 - \eta_{\infty}) / (1 + [(k\dot{\gamma})]^n) \quad (6.1)$$

where,

η_0 = the zero shear viscosity

η_{∞} = the terminal viscosity at infinite shear rate,

$\dot{\gamma}$ = the shear rate, and

k, n = model constants.

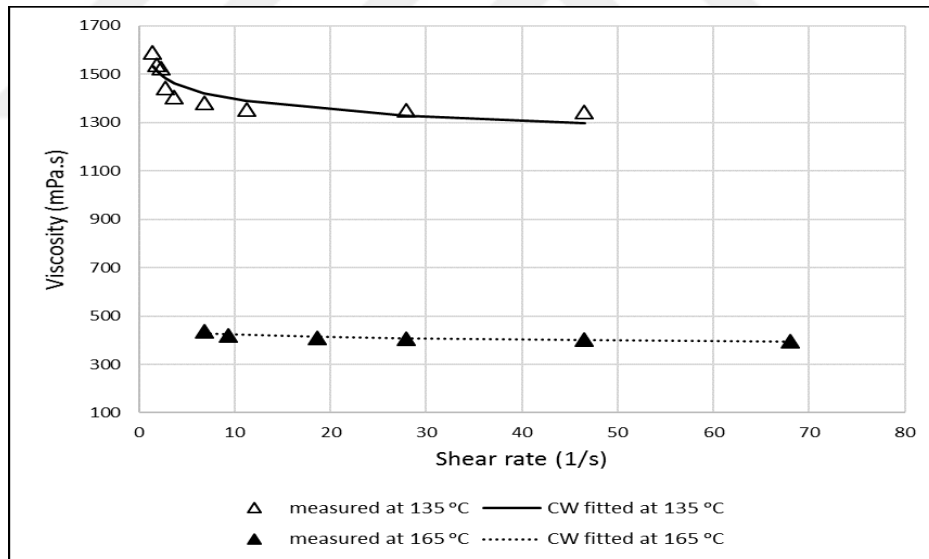


Figure 6.7 Example data from zero shear viscosity method for PMB samples

6.4.4 Steady Shear Flow Method (SSF)

This method which is recommended by Reink is based on the shear dependency of the bitumen (West et al., 2010). The steady shear flow test is conducted using Dynamic Shear Rheometer (DSR). The target shear stress of 500 Pascal is chosen as a

value where the viscosity measurements appeared more stable and the bitumen sample reaches the steady-state condition. In this method, Viscosities are measured at three temperatures (76°C, 82°C, and 88°C) over a series of stress levels from 0.33 Pa to 500 Pa as shown in Figure 6.8. The measured viscosity values at steady state-condition (500 Pa) are then plotted using a log viscosity versus log temperature chart and extrapolated to determine the mixing and compaction temperatures based upon specified viscosity ranges of 0.17 ± 0.02 Pa. s and 0.35 ± 0.03 Pa. s, respectively.

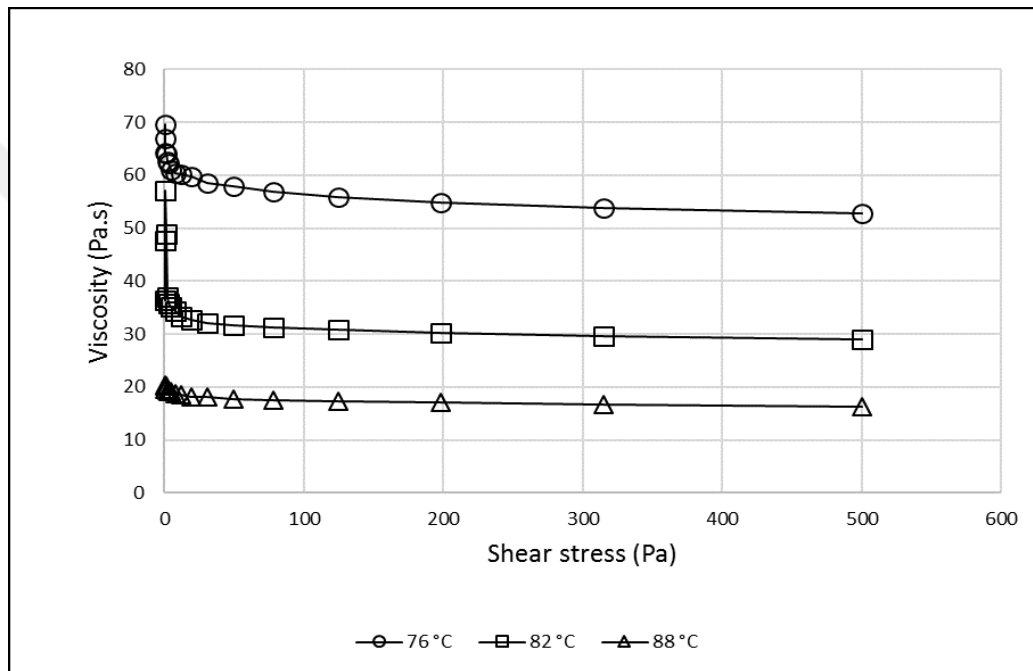


Figure 6.8 Example data of steady shear flow method for PMB

6.4.5 Phase Angle Method

This method is based on non-Newtonian viscoelastic behavior of the bitumen. In this method, the bitumen sample is tested using the frequency sweep module of DSR. Based on the penetration grade of the bitumen as well as the concentration of polymer, different test temperatures varying from 40 °C to 100 °C can be applied. Frequency ranges are 0.1 rad/sec to 100 rad/sec and the strain level is maintained at 12%. Phase angle master curves are developed from the obtained data using a reference temperature of 80 °C through the Time-Temperature Superposition (TTS) procedure as illustrated in Figure 6.9. The phase angle of 86° is recommended since the values

between 85° to 90° exhibits the viscous behavior of bitumen sample. As indicated in Equations 6.2 and 6.3 the frequency value which corresponds 86° phase angle is used in an empirical equation that has been established by Casola to determine mixing and compaction temperatures of the bitumen (West et al., 2010).

$$\text{Mixing Temperature} = 325 (\text{freq.})^{-0.0135} \quad (6.2)$$

$$\text{Compaction Temperature} = 300 (\text{freq.})^{-0.012} \quad (6.3)$$

where the frequency, is in radians/sec.

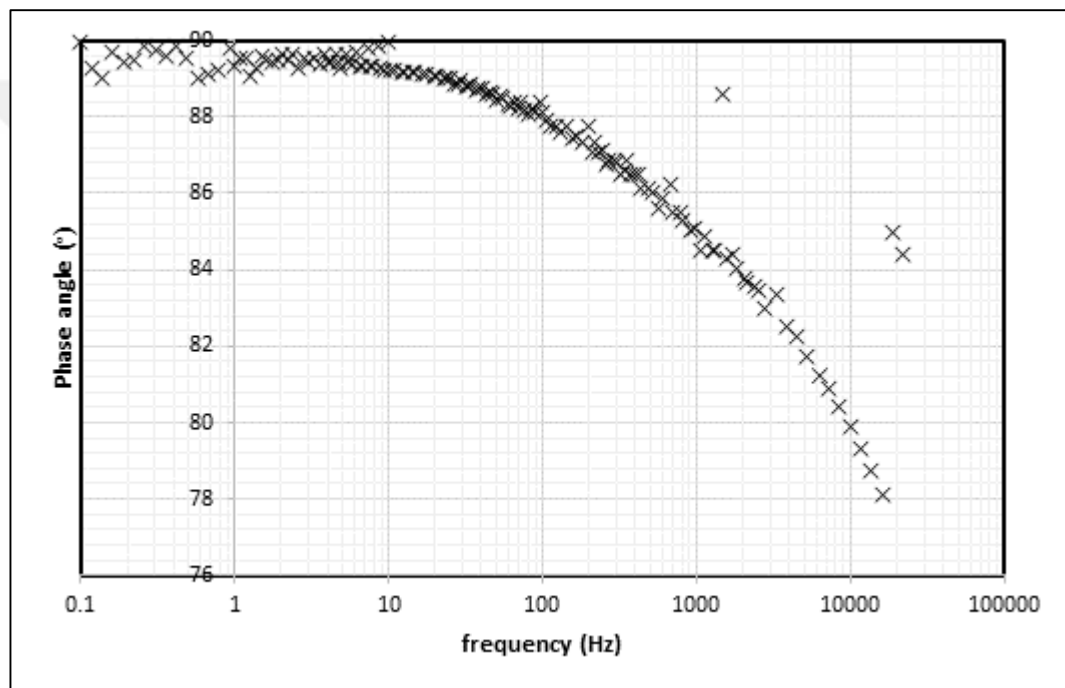


Figure 6.9 Example of master curve for phase angle

6.5 Marshall Mix Design

In order to determine the optimum bitumen content (OBC) for asphalt mixtures, there are several design methods such as Marshall mix design and Super pave methods. In this study, the Marshall method of mix design (ASTM D 1559) has been adopted to find the required OBC for each asphalt mixture. A series of test specimens were prepared over a range of bitumen contents varying from 3.5% to 5%. For each bitumen content, three samples were prepared so it will provide adequate data. The aggregate weight in each sample is 1150 grams. The bitumen and aggregate were heated based

on the lowest and highest determined mixing temperatures for each asphalt type. The samples are then mixed and placed in the preheated mold as illustrated in Figure 6.10.



Figure 6.10 Mixing the bitumen and the aggregate at the desired temperature (Personal archive, 2019)

To prevent adhesion between the mixture and the mold, the filter paper was inserted into the bottom of the mold. Compaction temperatures were also specified based on the lowest and highest determined for each asphalt type. Asphalt concrete specimens were prepared with a compaction effort of 75 blows (wearing course) simulating the heavy traffic loading conditions as shown in Figure 6.11.

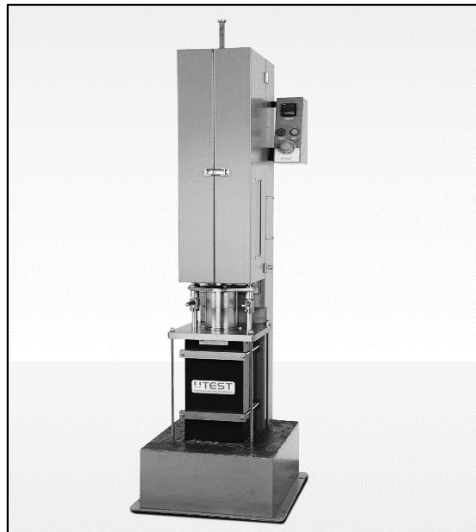


Figure 6.11 Marshall compactor (Personal archive, 2018)

The stability of compacted samples was measured as shown in figure 6.12. Marshall stability can be described as the maximum compressive load that a compacted Marshall specimen can endure before it breaks at 60°C and a loading rate of 51 mm/min. Marshall stability measures the mass viscosity of the aggregate bitumen mixture.



Figure 6.12 Marshall machine (Personal archive, 2018)

Finally, the values of stability, flow, VMA, and VFA has been plotted against the bitumen content. The optimum bitumen content for wearing course is calculated as the content corresponding to 4% air voids.

6.6 Indirect Tensile Strength Test

The indirect tensile strength test is used to determine the tensile properties of the asphalt concrete which can be indicated to the cracking properties of the pavement. The ITS test is performed by loading the specimens at a constant rate (50 mm/min vertical deformation at 25 °C) and the force required to break the specimen is measured following ASTM D6931-07. The procedure of the method is given below:

- ☒ Bitumen and aggregate are mixed and compacted based on the determined mixing and compaction temperatures.
- ☒ The obtained asphalt samples were then extracted and the heights of each specimen were measured.
- ☒ The asphalt specimens were placed in plastic bags and then place in a water bath for 2 hours at 25 °C.
- ☒ After 2 hours, the specimens were removed from the bath, and the plastic bag.
- ☒ Before starting the test, the loading strips should be parallel and centered on the vertical diametric as shown in Figure 6.13.

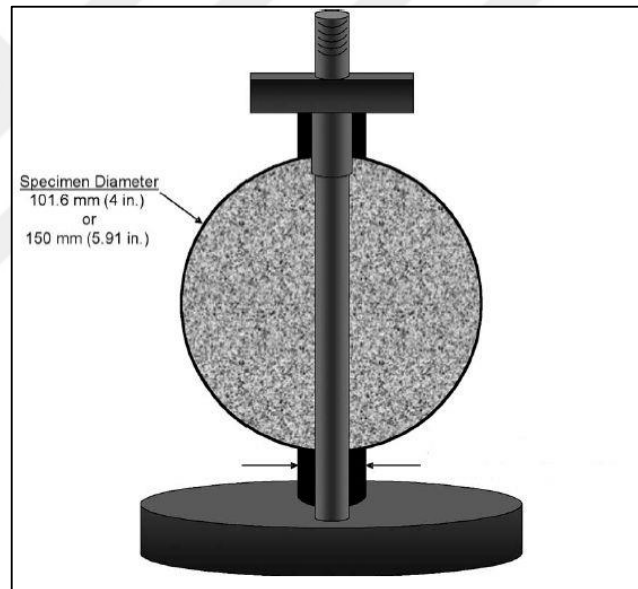


Figure 6.13 Setting the asphalt sample in ITS

- ☒ A vertical compressive ramp load was applied until the maximum load is reached.
- ☒ Finally, the indirect tensile strength was calculated using the following equation:

$$St = \frac{2P}{\pi} * D * t \quad (6.4)$$

Where;

S_t = Horizontal tensile stress at centre of specimen, kPa.

P = Applied load, kg.

D = Diameter of specimen, cm.

t = Thickness of specimen, cm.



CHAPTER SEVEN

RESULTS AND DISCUSSION

7.1 Mixing and Compaction Temperatures Determination

7.1.1 Equiviscous Method Results

Figures 7.1 to 7.2 illustrate the measured viscosity at 135 °C and 165 °C regarding SBS and Elvaloy polymer modified bitumen as well as bitumen samples involving WMA additives (organic and chemical).

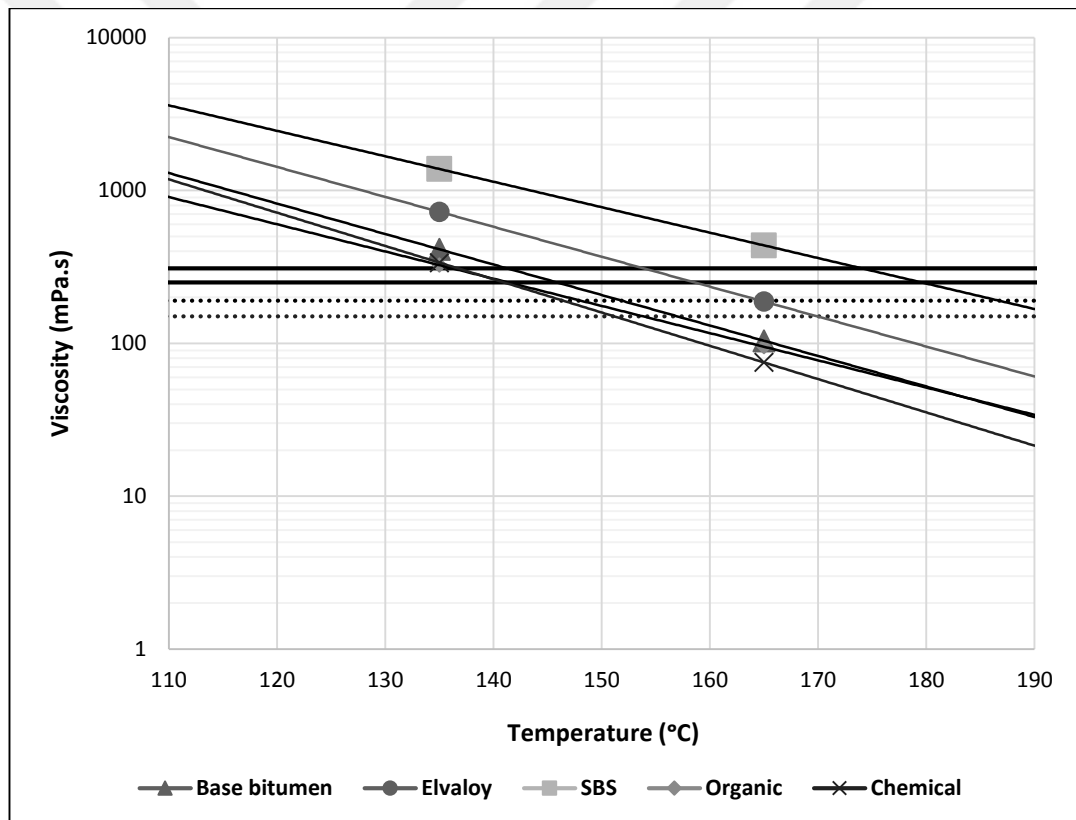


Figure 7.1 Mixing and compaction temperatures (50/70 bitumen) determined according to ASTM (equiviscous) Method

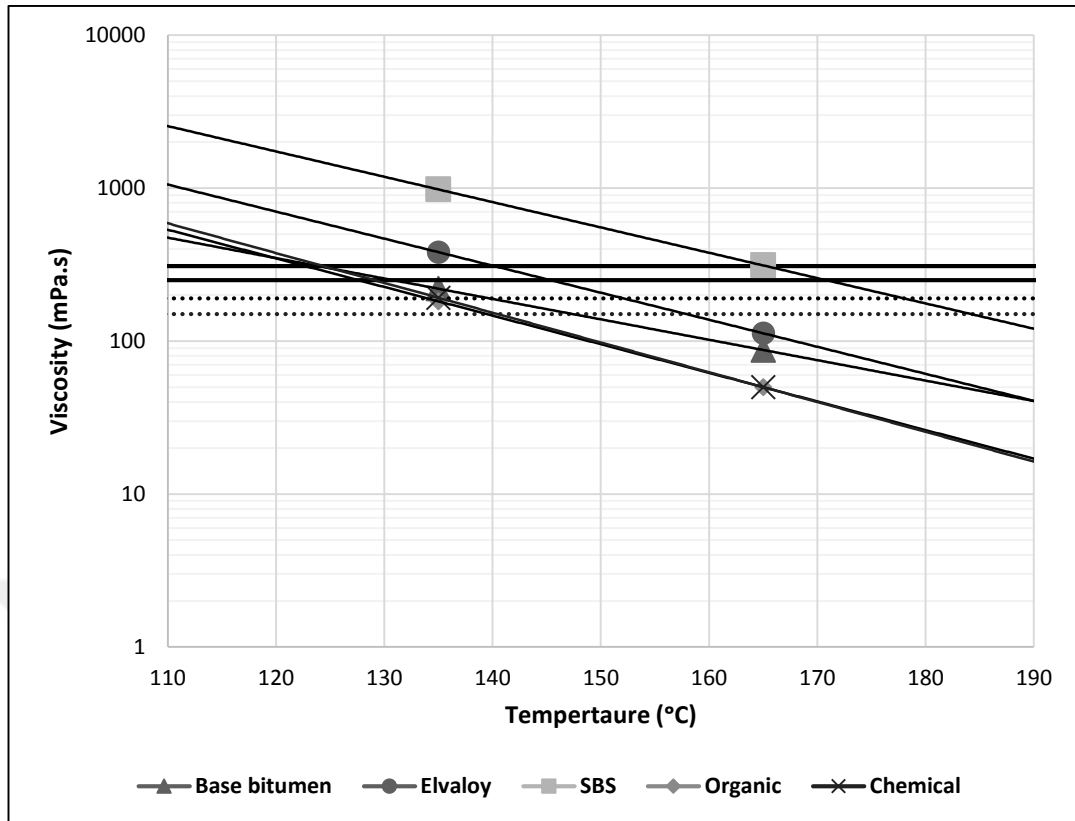


Figure 7.2 Mixing and compaction temperatures (160/220 bitumen) determined according to ASTM (equiviscous) Method

The mixing and compaction temperatures corresponding to 0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s are presented in Table 7.1. The results showed that the polymer modified bitumen samples tend to have a higher mixing and compaction temperatures than the base bitumen. This can be attributed to the significant physical changes when the polymer is added to the base bitumen. The polymer absorbs the oily constituents and especially at higher concentrations, the bitumen becomes stiffer and more viscous. On the other hand, both warm mix asphalt additive work on reducing the viscosity of the bitumen samples so the required mixing and compaction temperatures become lesser than the base bitumen.

Table 7.1 ASTM (equiviscous) method results

Material	50/70		160/220	
	Mixing Temperature (°C)	Compaction Temperature (°C)	Mixing Temperature (°C)	Compaction Temperature (°C)
Base bitumen	152-158	141-146	140-147	125-131
PMB (SBS)	186-192	174-180	177-184	165-171
PMB (Elvaloy)	165-170	154-158	157-165	140-145
WMA (Organic)	146-153	135-140	134-140	123-128
WMA (Chemical)	146-151	136-141	135-140	124-128

7.1.2 High Shear Rate Method Results

Figures 7.3 to 7.12 present the viscosity values plotted against shear rate related to base bitumen, polymer modified bitumen and bitumen samples produced with WMA additives for both 50/70 and 160/220 penetration grades. The measured viscosity values are then extrapolated using power law model.

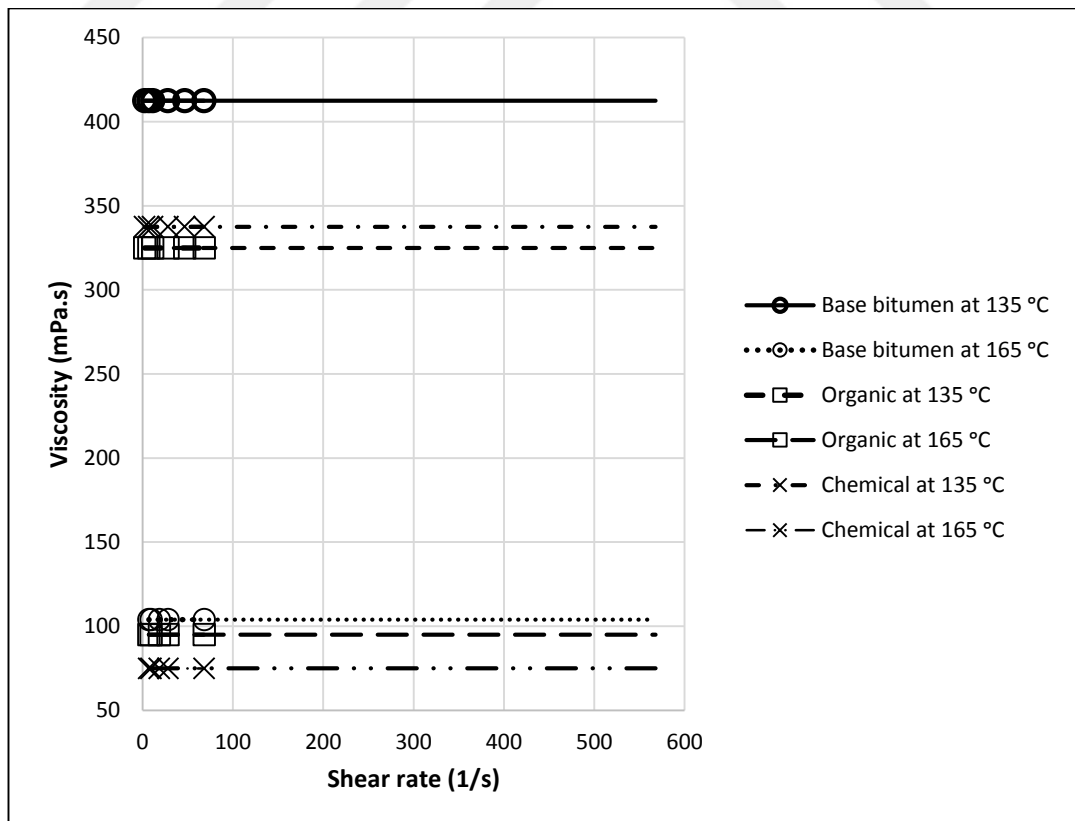


Figure 7.3 High shear rate for 50/70 base bitumen and WMA

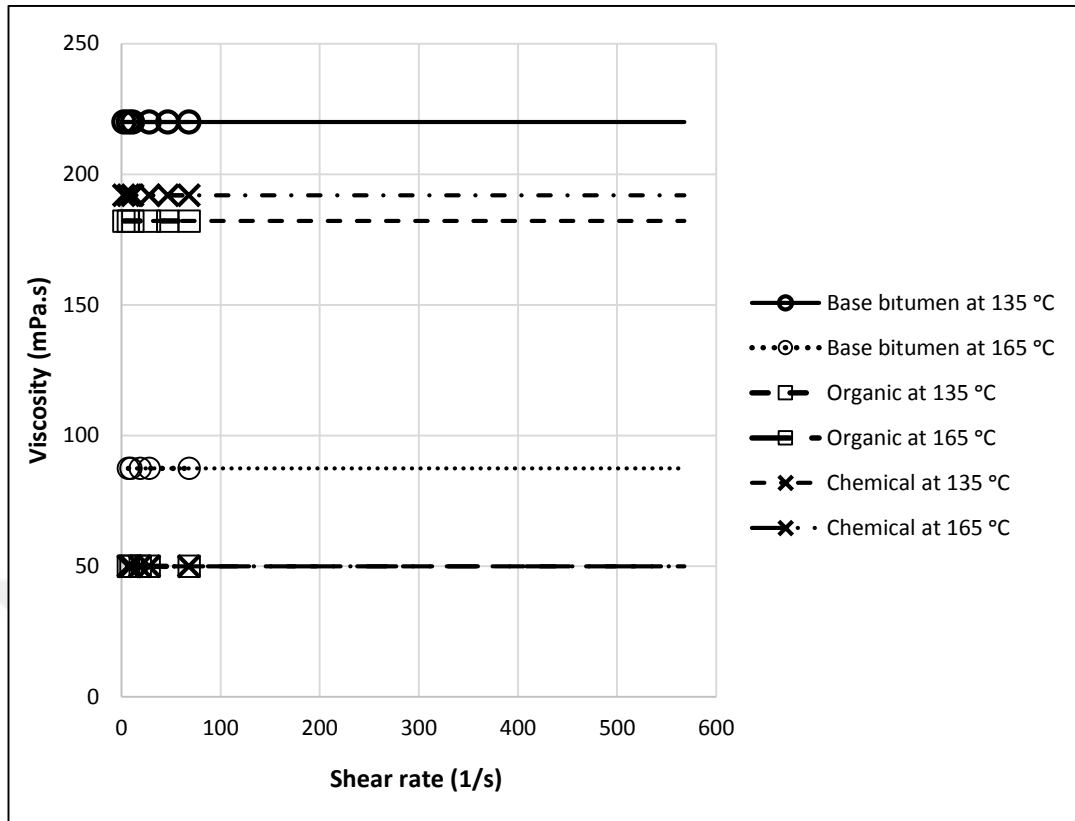


Figure 7.4 High shear rate for 160/220 base bitumen and WMA

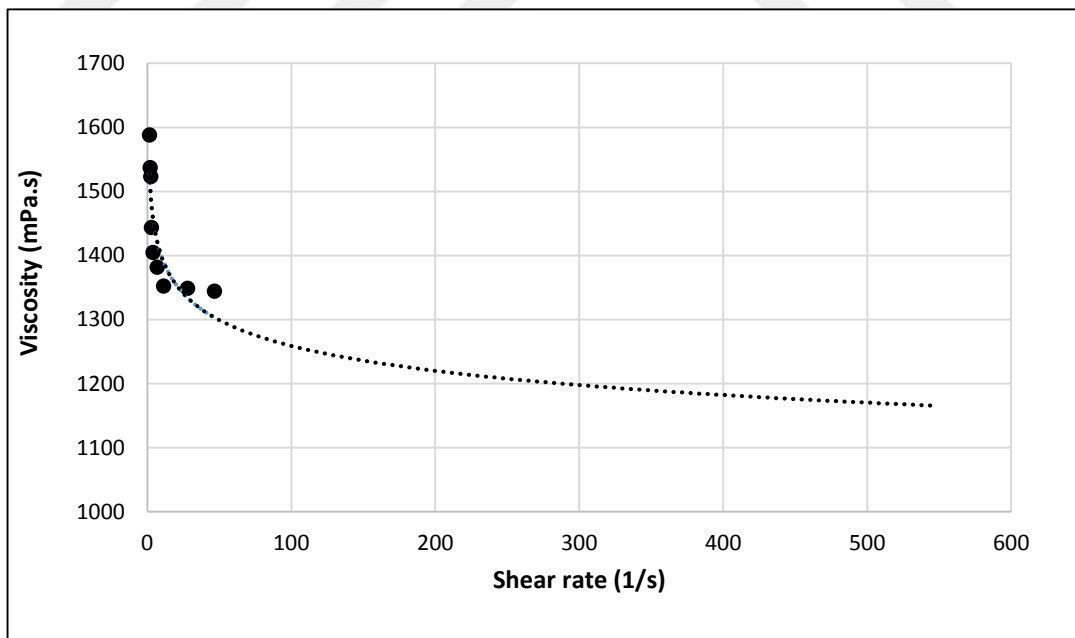


Figure 7.5 50/70 PMB (SBS): viscosity measurement at 135 °C

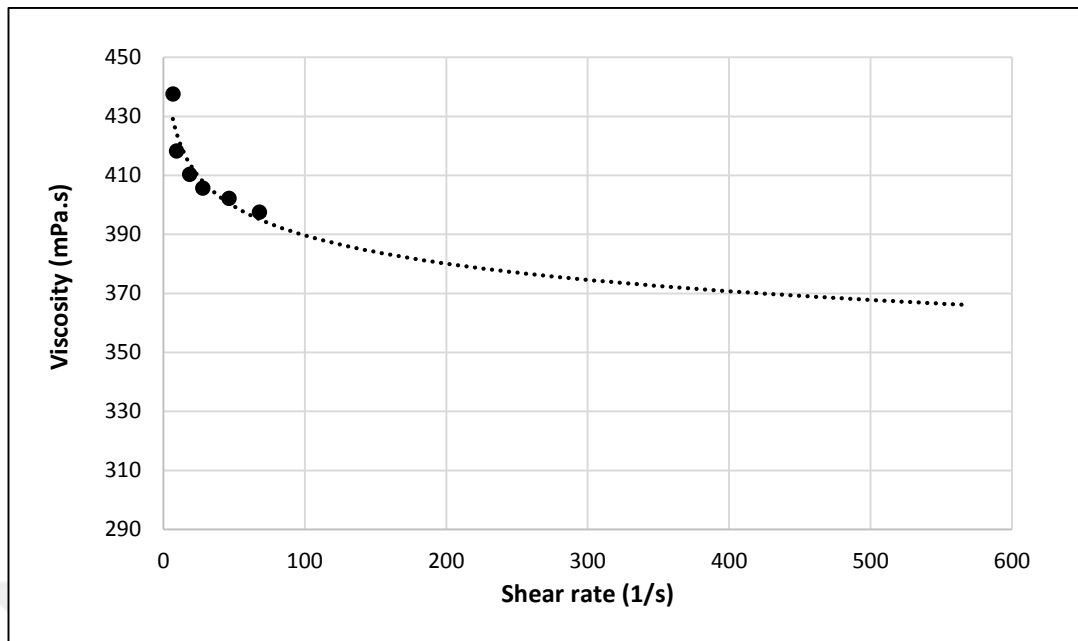


Figure 7.6 50/70 PMB (SBS): viscosity measurement at 165 °C

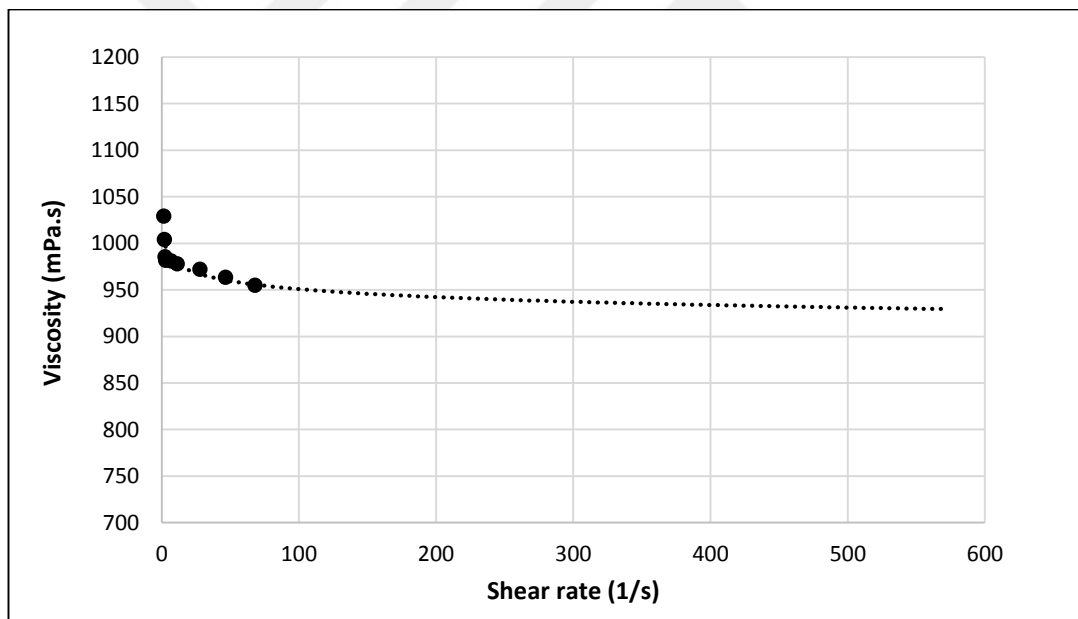


Figure 7.7 160/220 PMB (SBS): viscosity measurement at 135 °C

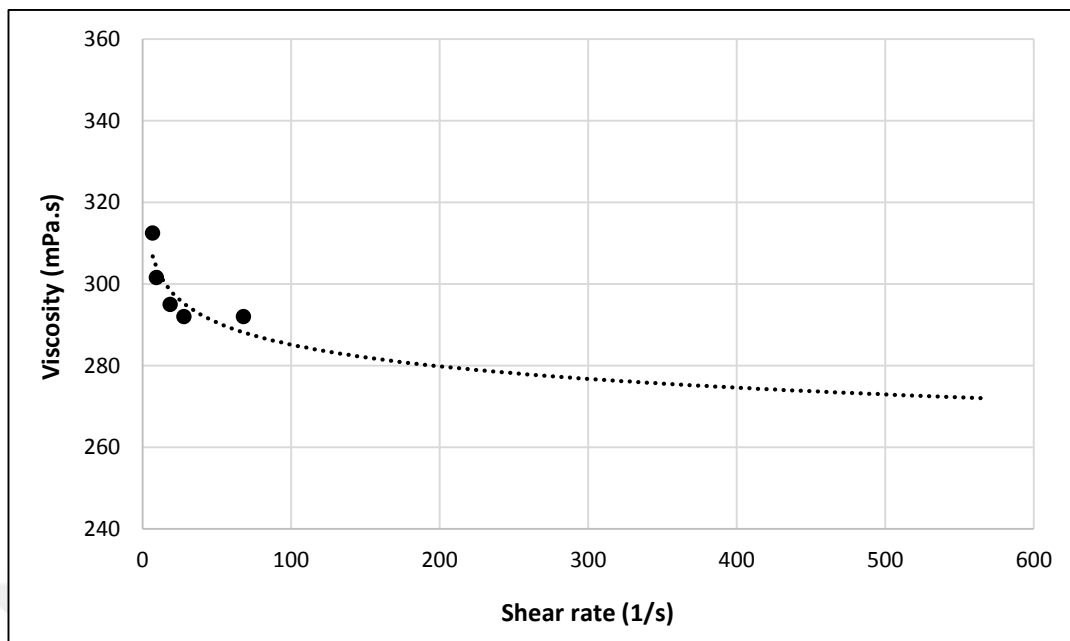


Figure 7.8 160/220 PMB (SBS): viscosity measurement at 165 °C

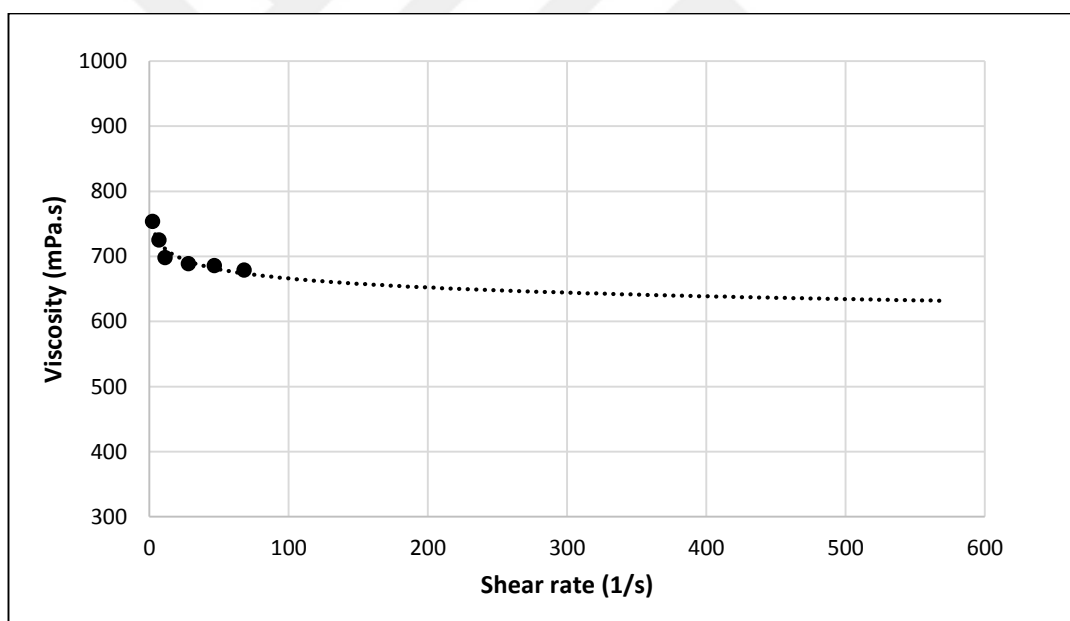


Figure 7.9 50/70 PMB (Elvaloy): viscosity measurement at 135 °C

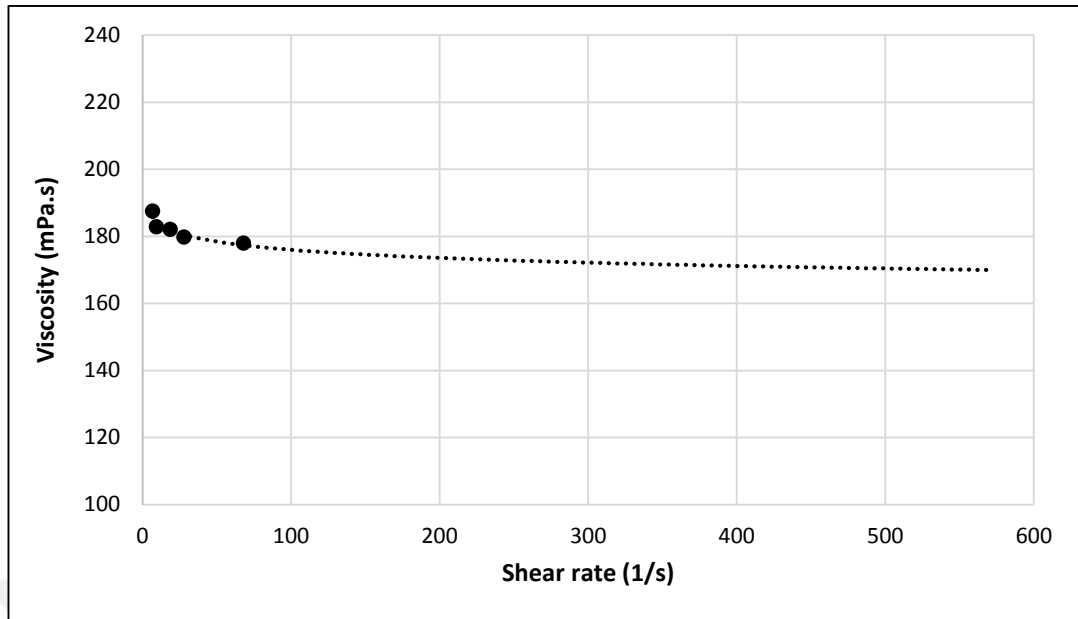


Figure 7.10 50/70 PMB (Elvaloy): viscosity measurement at 165 °C

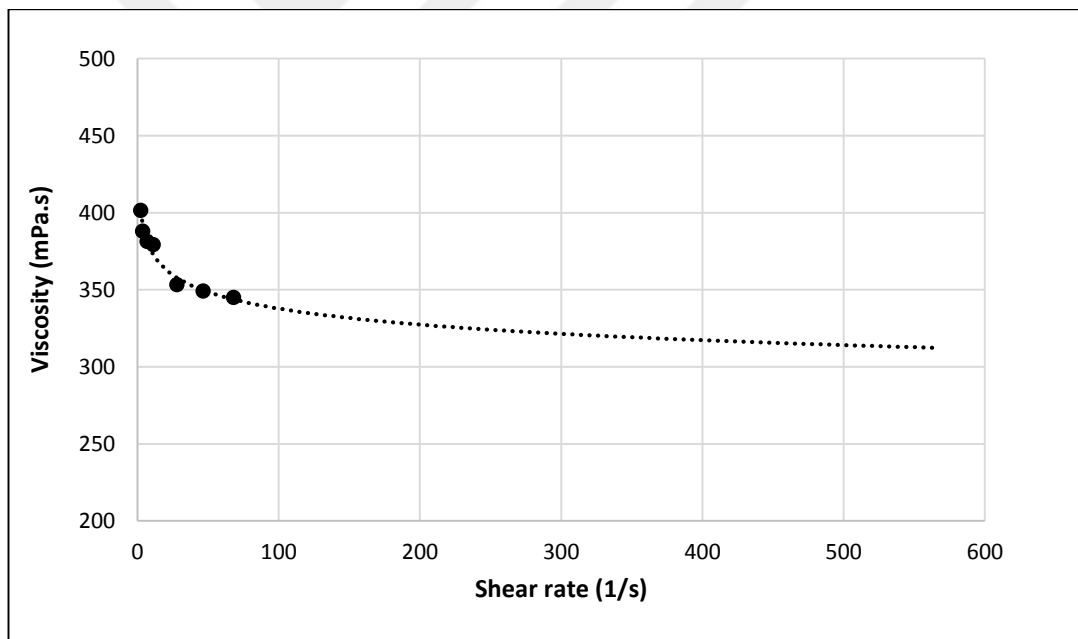


Figure 7.11 160/220 PMB (Elvaloy): viscosity measurement at 135 °C

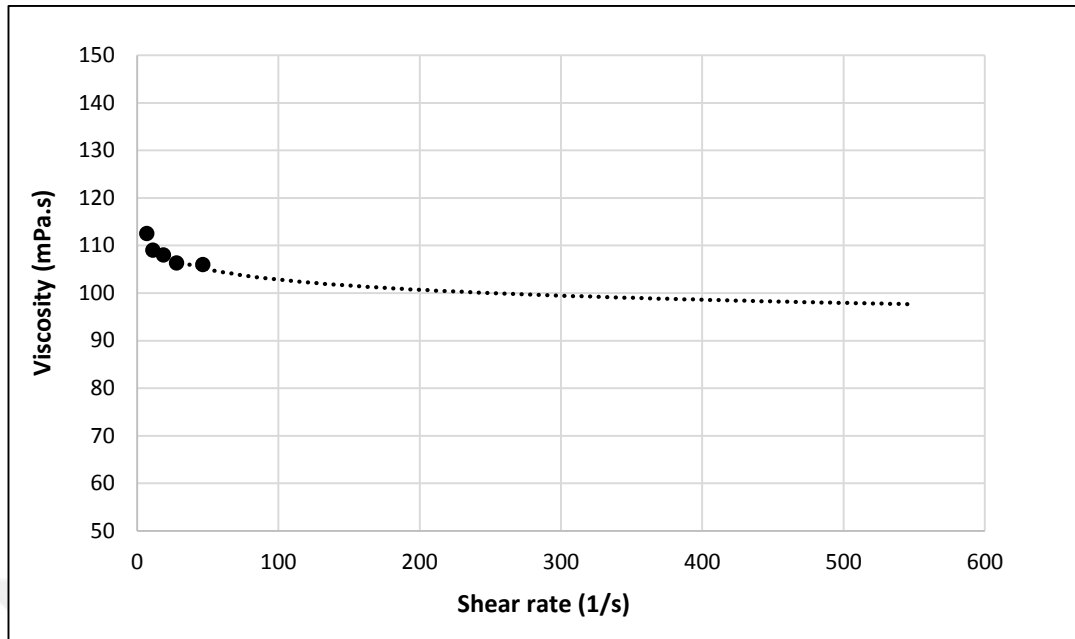


Figure 7.12 160/220 PMB (Elvaloy): viscosity measurement at 165 °C

To determine mixing and compaction temperatures, the extrapolated viscosity values at 500 1/s shear rate are drawn against the temperature as demonstrated in Figures 7.13 to 7.16 for both original and evolution form of high shear rate method.

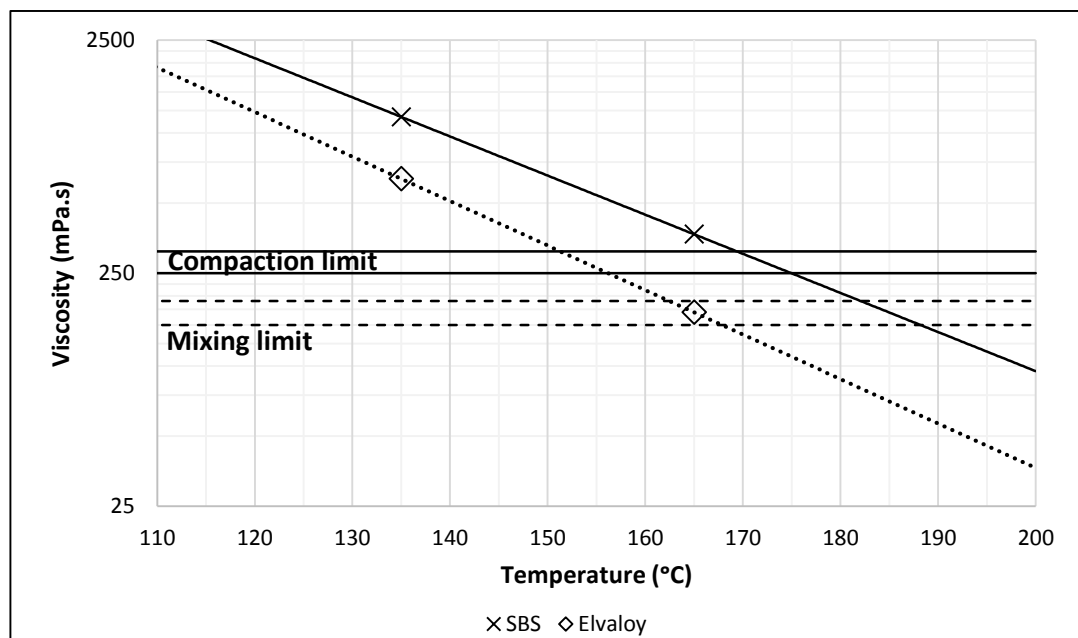


Figure 7.13 High Shear Rate Method for 50/70 (Original form)

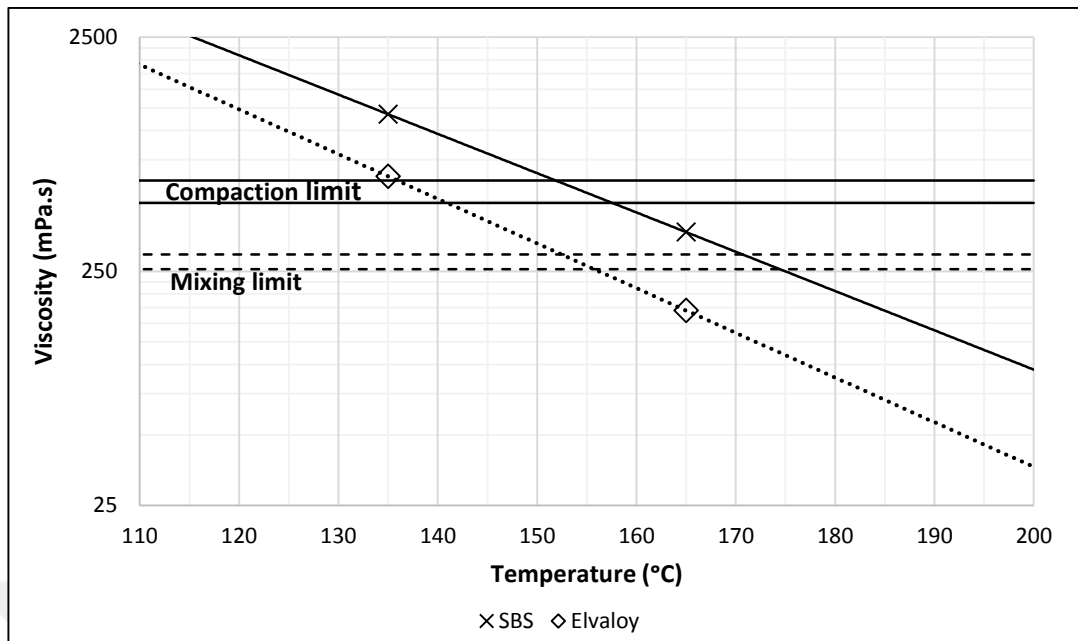


Figure 7.14 High Shear Rate Method for 50/70 (Evolution form)

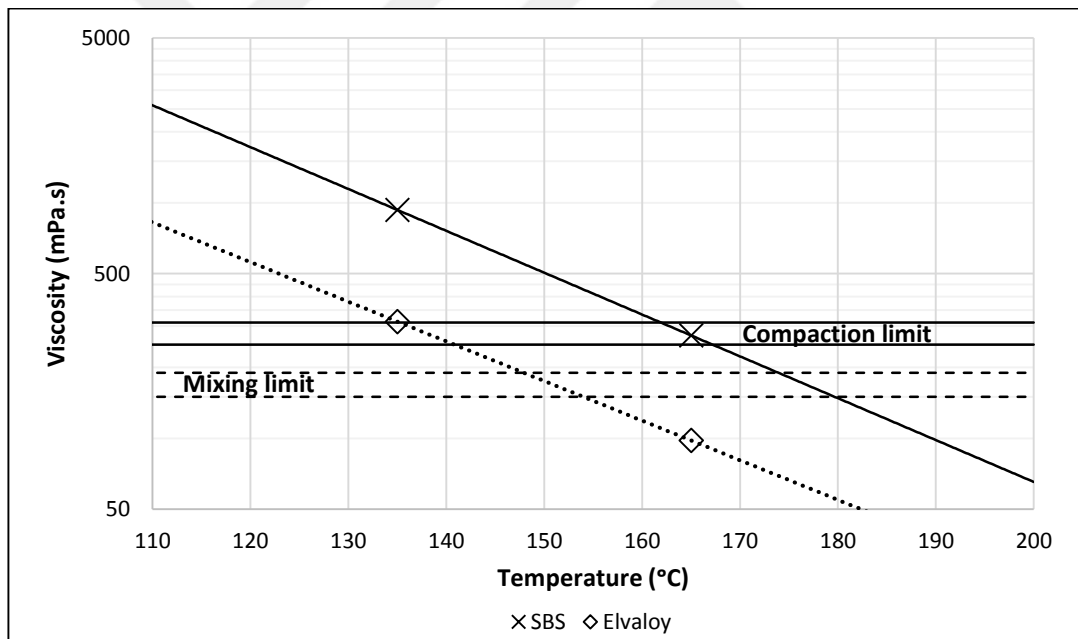


Figure 7.15 High Shear Rate Method for 160/220 (Original form)

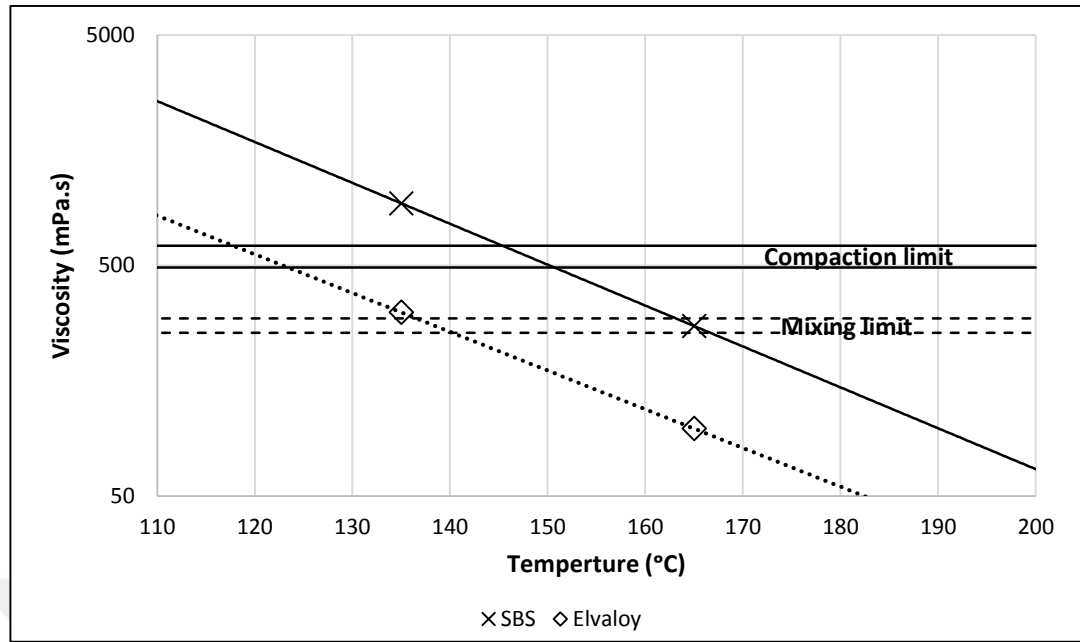


Figure 7.16 High Shear Rate Method for 160/220 (Evolution form)

The above-mentioned method is based on the variation in viscosity with a change in shear rate. In other words, this method is more suitable for non-Newtonian materials like polymer modified bitumen. This method is not applicable on base bitumen and on bitumen involving WMA additives since they all depict Newtonian behavior at high temperatures.

It can be noticed that the original form of the method resulted in close results with a slightly different compare to the ASTM (equiviscous) method. While utilizing the evolution form exhibited lower mixing and compaction temperatures. Among the polymer modified samples, SBS polymer depicted the highest mixing and compaction temperatures. This method is not applicable on base bitumen and on bitumen involving WMA additives since they all depict Newtonian behavior. Based on Figures 7.13 to 7.16, the determined mixing and compaction are presented in Table 7.2.

Table 7.2 HSR method results

Material	50/70				160/220			
	Original		Evolution		Original		Evolution	
	Mixing Temp. (°C)	Comp. Temp. (°C)	Mixing Temp. (°C)	Comp. Temp. (°C)	Mixing Temp. (°C)	Comp. Temp. (°C)	Mixing Temp. (°C)	Comp. Temp. (°C)
Base bitumen	N B*	N B*	N B*	N B*	N B*	N B*	N B*	N B*
PMB (SBS)	181-187	170-175	170-175	152-158	174-180	162-167	163-167	145-151
PMB (Elvaloy)	162-167	152-157	152-155	136-141	147-154	135-141	136-140	118-124
WMA (Organic)	N B*	N B*	N B*	N B*	N B*	N B*	N B*	N B*
WMA (Chemical)	N B*	N B*	N B*	N B*	N B*	N B*	N B*	N B*

N B* Newtonian Behavior

7.1.3 Zero Shear Viscosity Method Results

Similar to the high shear rate method the viscosity values are measured at different shear rates at two temperatures 135 °C and 165 °C. Figures 7.17 to 7.20 illustrate the measured and the fitted (obtained from Cross-Williamson model) viscosity values at different shear rates for base bitumen and SBS and Elvaloy polymer modified samples as well as to the WMA bitumen samples.

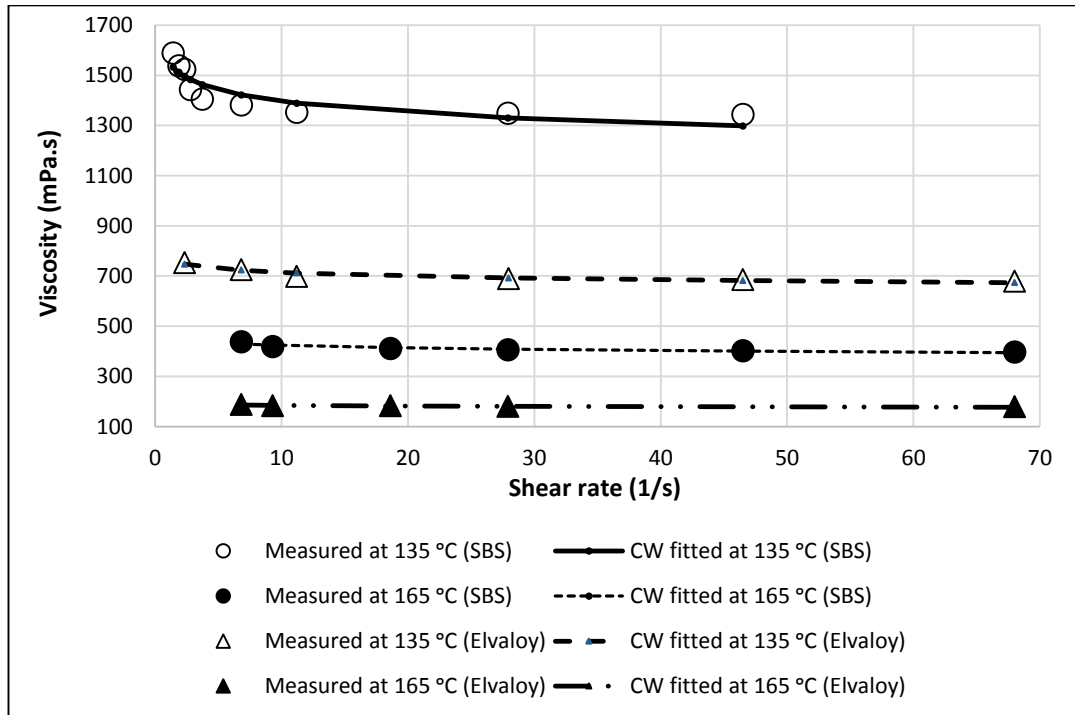


Figure 7.17 Zero Shear Viscosity measurements for 50/70 (PMB)

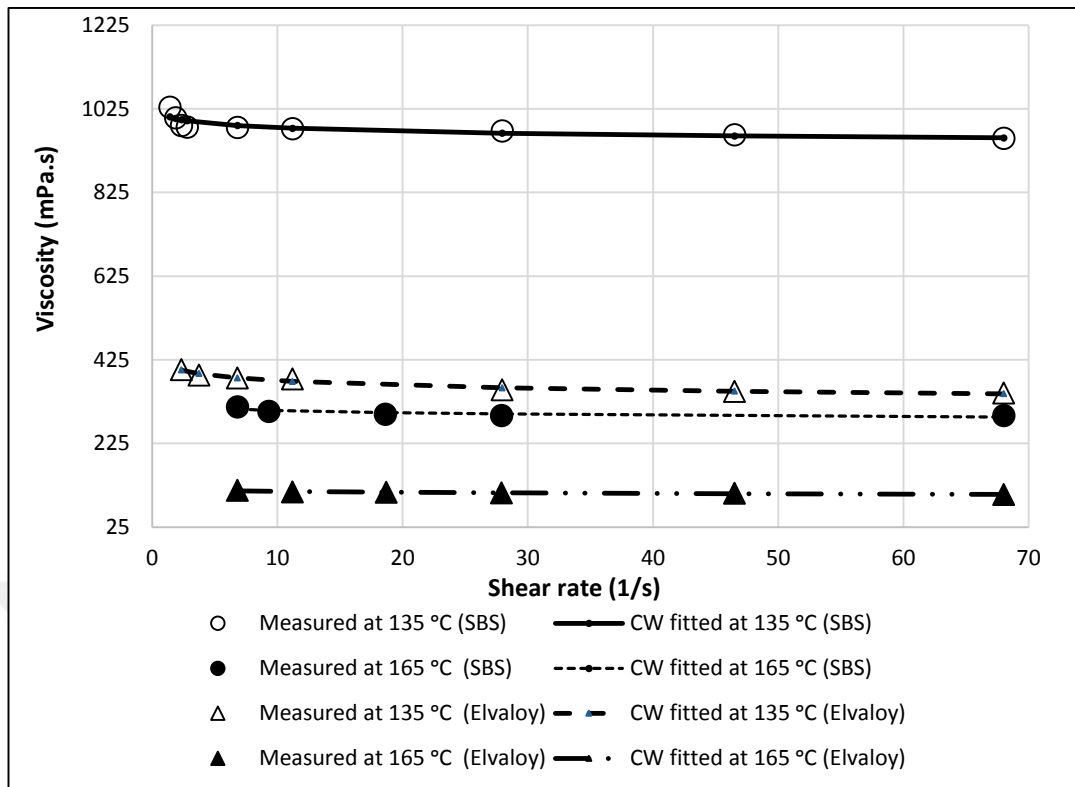


Figure 7.18 Zero Shear Viscosity measurements for 160/220 (PMB)

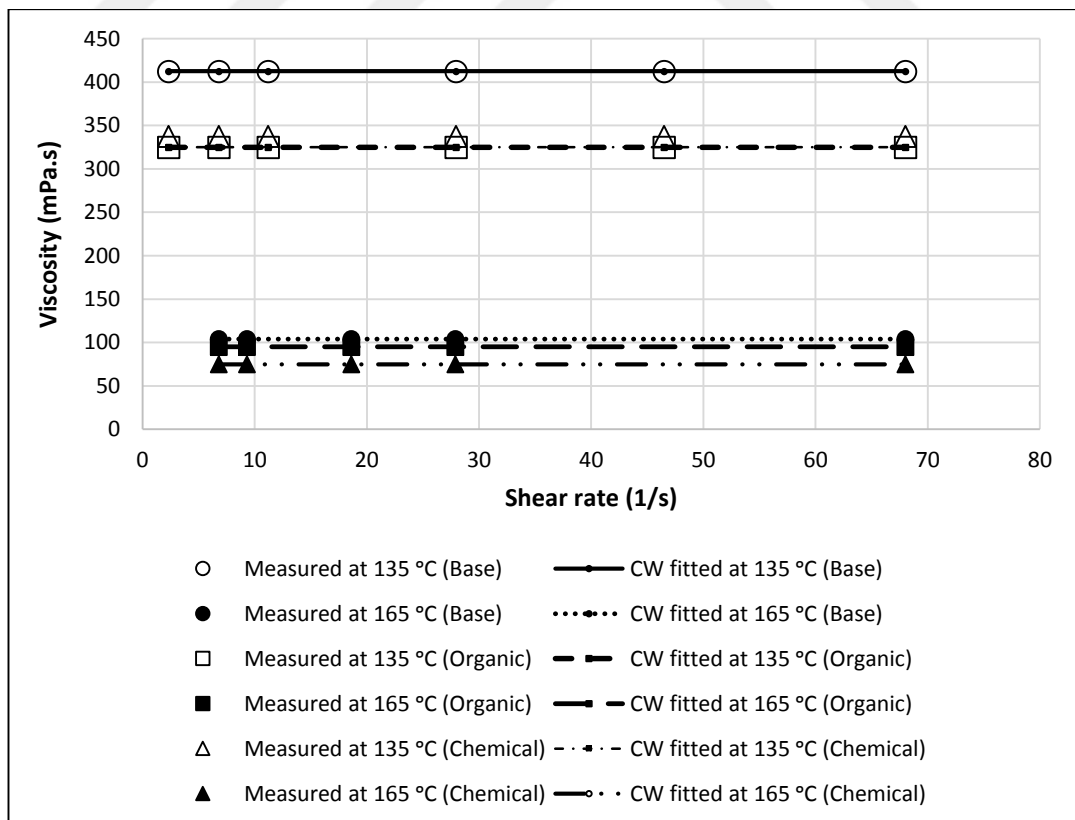


Figure 7.19 Zero Shear Viscosity measurements for 50/70 (Base and WMA)

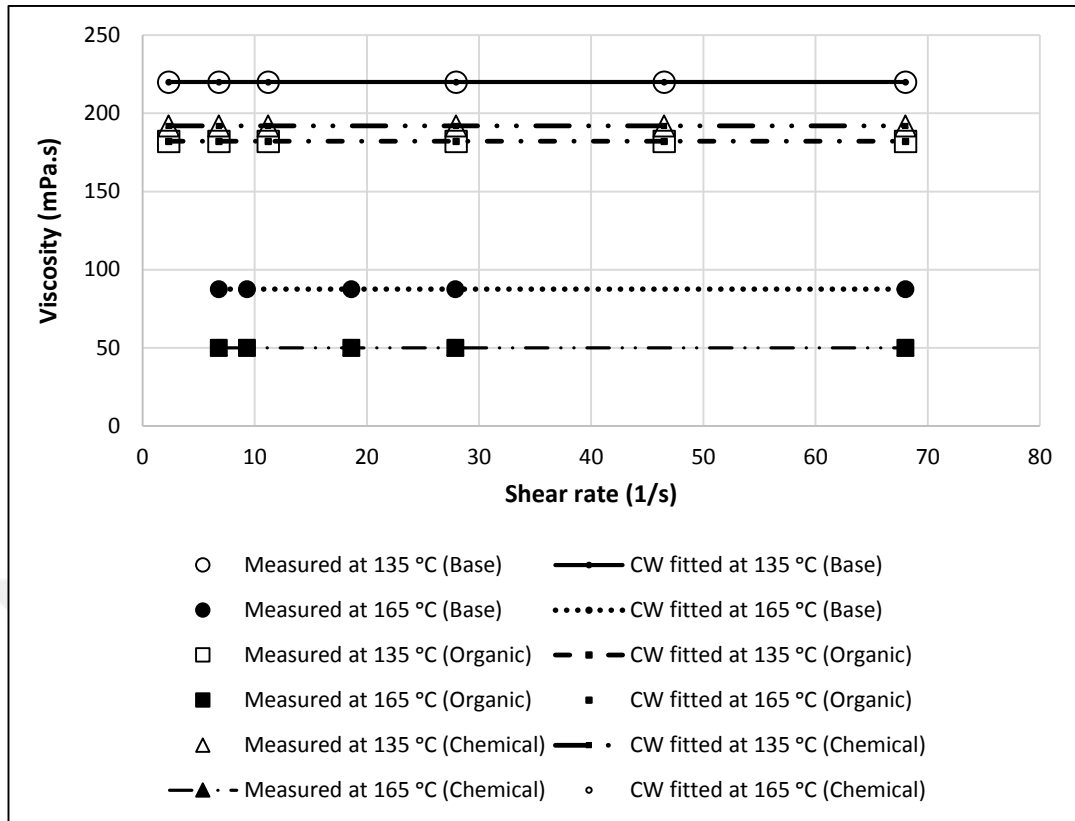


Figure 7.20 Zero Shear Viscosity measurements for 160/220 (Base and WMA)

The resulted zero shear viscosity is plotted on a log-log scale as a function of log temperature in Kelvin units as illustrated in Figure 7.21. The mixing and compaction temperatures corresponding to 3 ± 0.3 Pa s and 6 ± 0.6 Pa s, respectively.

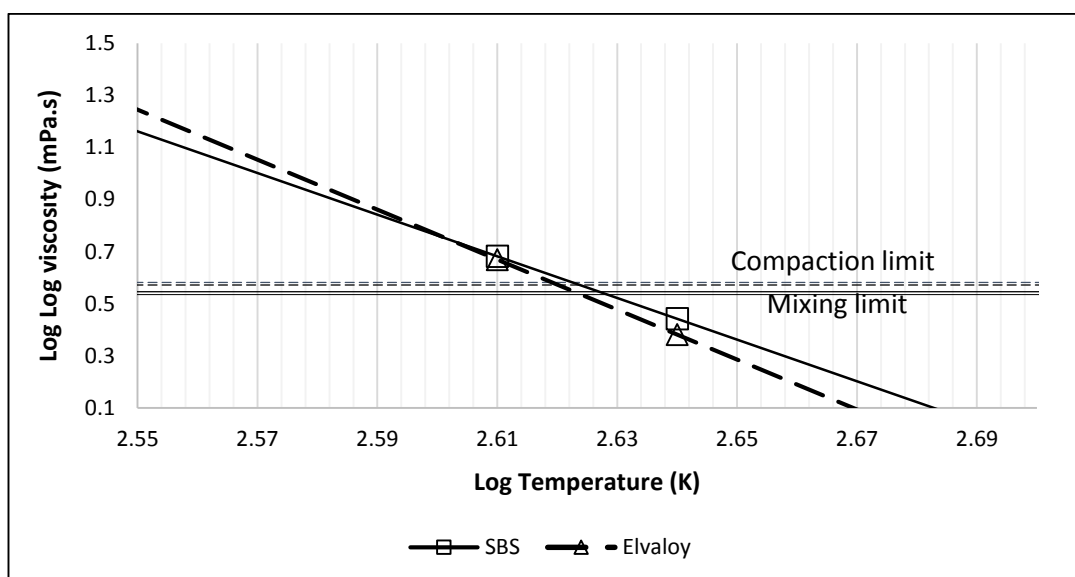


Figure 7.21 Mixing and compaction determination for ZSV method

The determined mixing and compaction temperatures results based on the zero shear viscosity method are presented in Table 7.3.

Table 7.3 ZSV method results

Material	50/70		160/220	
	Mixing Temp. (°C)	Comp. Temp. (°C)	Mixing Temp. (°C)	Comp. Temp. (°C)
Base bitumen	N B*	N B*	N B*	N B*
PMB (SBS)	151.5	145.5	148.6	143.8
PMB (Elvaloy)	148.7	141.9	125	116
WMA (Organic)	N B*	N B*	N B*	N B*
WMA (Chemical)	N B*	N B*	N B*	N B*

N B* Newtonian Behavior

The expression stated in Table 7.3 as NB showed that base bitumen exhibits Newton's behavior. In other words, the viscosity does not show any change at different shear rates (Figure 7.18-7.19). Thus, the Zero Shear Viscosity method is not suitable for base bitumen samples. A similar statement can be made for bitumen samples involving organic and chemical additives.

When the mixing and compaction temperatures for 50/70 and 160/220 penetration bitumen containing SBS and Elvaloy are compared, as expected, 50/70 samples resulted in the higher temperatures. This is because the 50/70 is stiffer than 160/220 and therefore the handling temperature are substantially high.

It can be noticed that mixing and compaction temperatures for 50/70 samples modified with SBS and Elvaloy are very close. However, similar statements cannot be made for polymers added to 160/220 penetration. Thus, SBS polymer added to base bitumen with 160/220 penetration gave 148.6 °C mixing temperature value, while Elvaloy polymer addition to the same bitumen showed 125 °C mixing temperature. This means that there is no significant increase in viscosity with the addition of Elvaloy type polymer to high-penetration bitumen (i.e. soft bitumen).

However, when ASTM (equiviscous) method and zero shear viscosity methods were evaluated on the basis of SBS and Elvaloy polymer additives, it was observed that the ASTM (equiviscous) method produced higher temperature values.

7.1.4 Steady Shear Flow Method Results

Figures 7.22 to 7.31 present the test results for different bitumen samples at a different set of temperatures (76 °C, 82 °C, and 88 °C). All the bitumen samples have reached a steady-state condition (no variation in the viscosity readings) when the stress level is about 500 Pa.

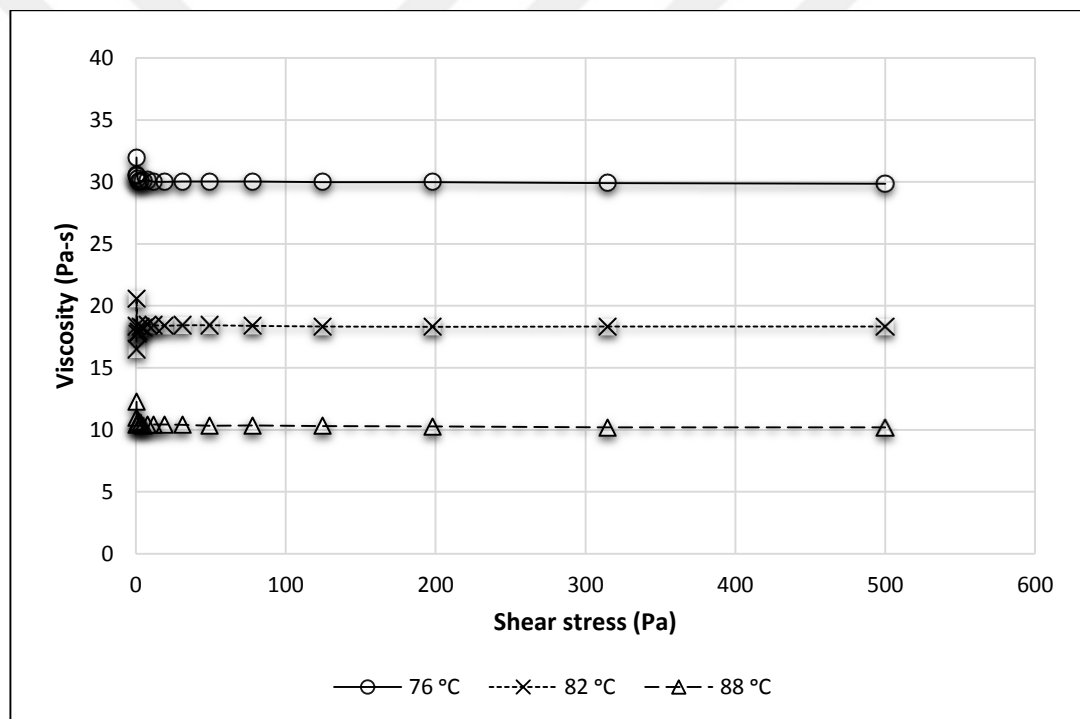


Figure 7.22 Steady Shear Flow measurements for 50/70 (Base)

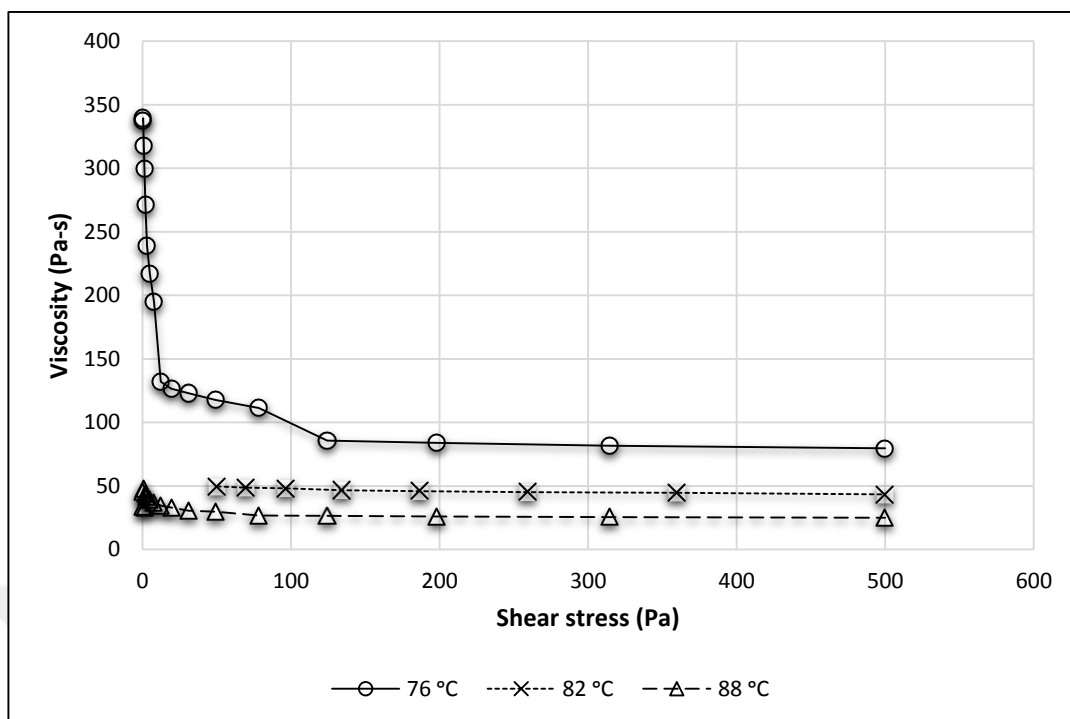


Figure 7.23 Steady Shear Flow measurements for 50/70 (SBS)

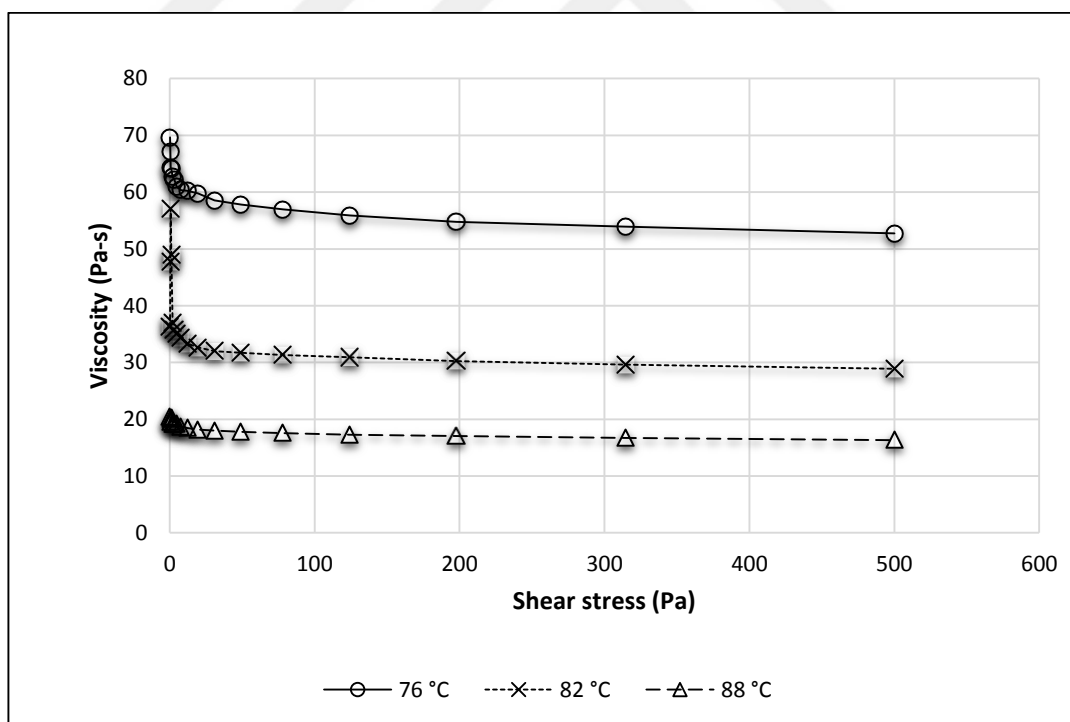


Figure 7.24 Steady Shear Flow measurements for 50/70 (Elvaloy)

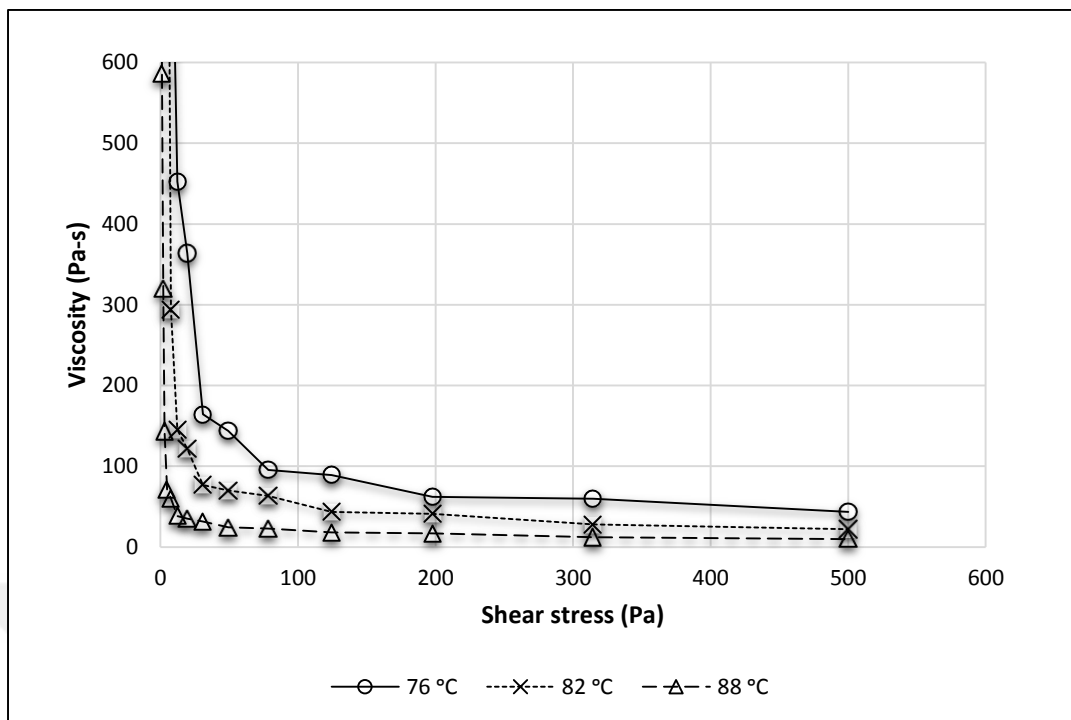


Figure 7.25 Steady Shear Flow measurements for 50/70 (Organic)

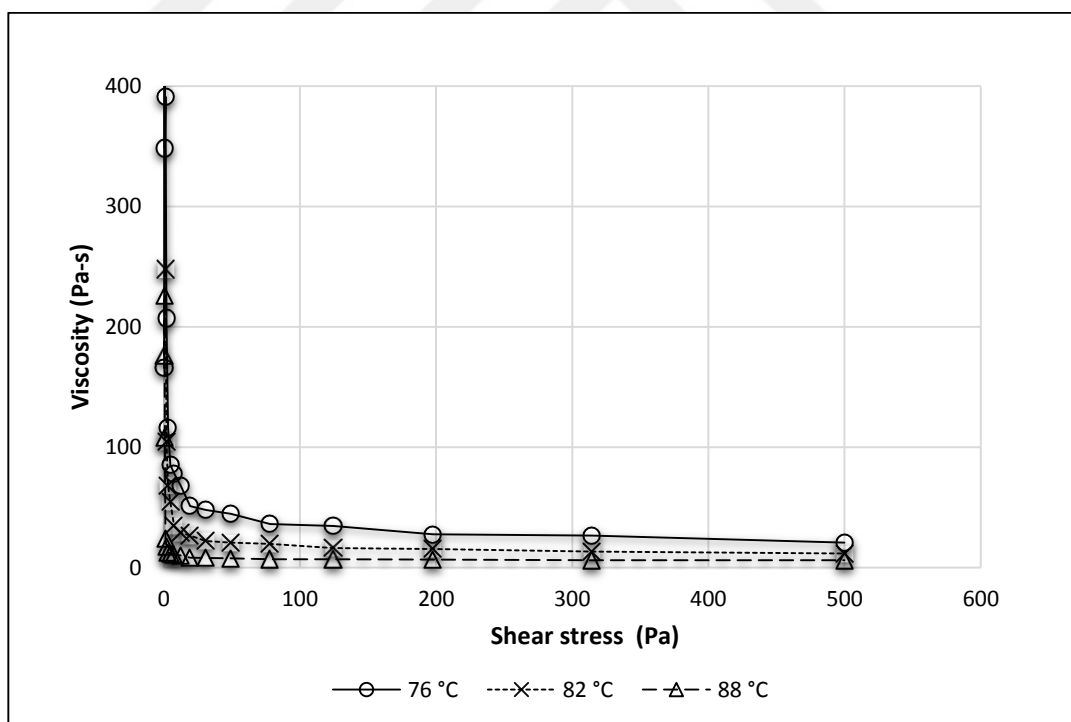


Figure 7.26 Steady Shear Flow measurements for 50/70 (Chemical)

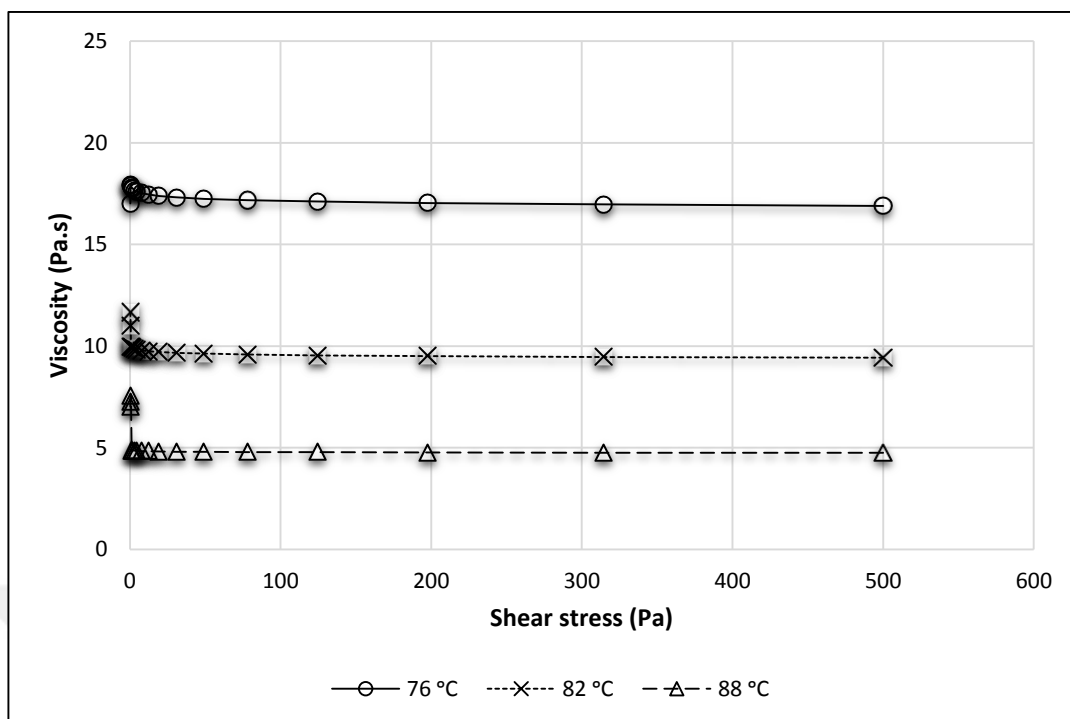


Figure 7.27 Steady Shear Flow measurements for 160/220 (Base)

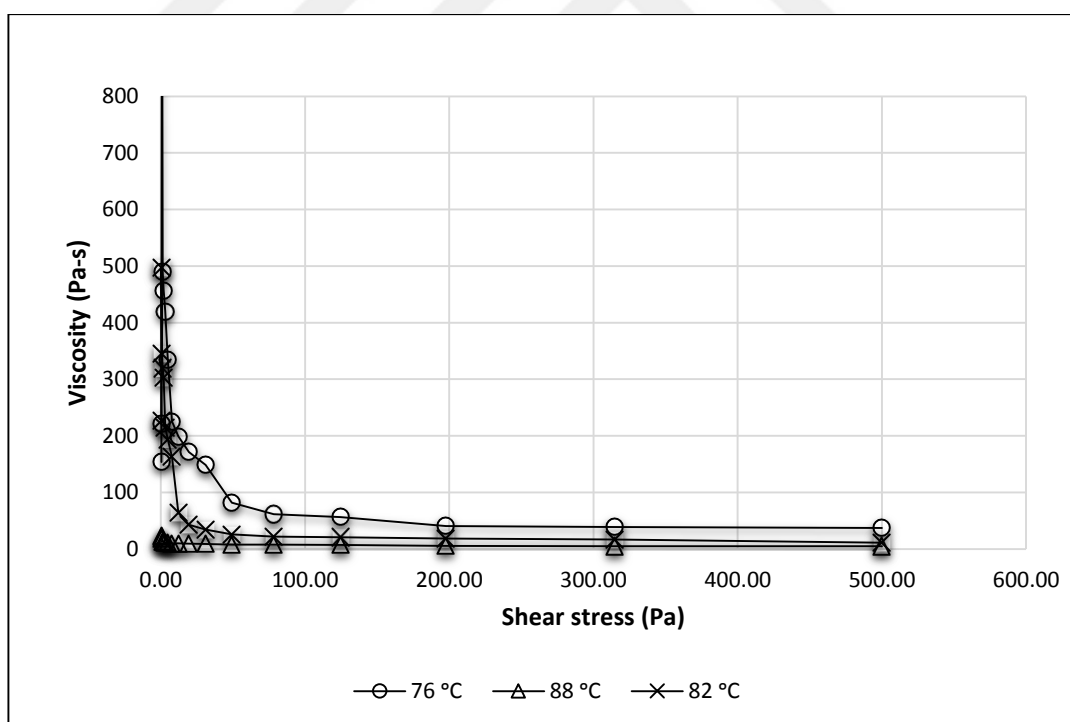


Figure 7.28 Steady Shear Flow measurements for 160/220 (SBS)

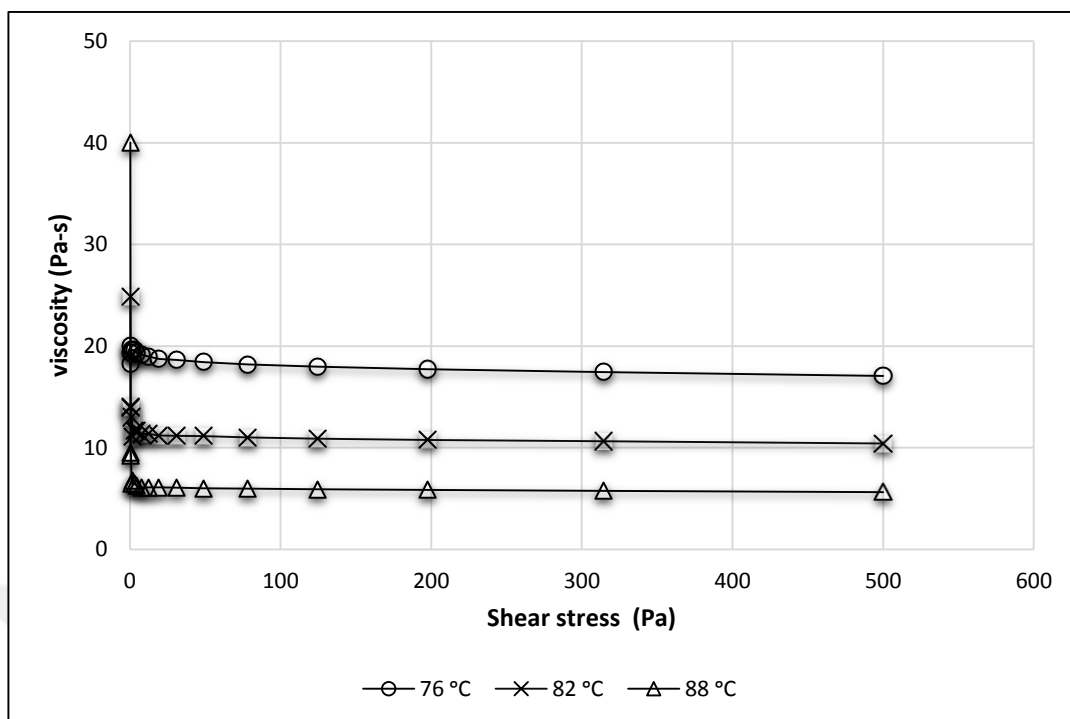


Figure 7.29 Steady Shear Flow measurements for 160/220 (Elvaloy)

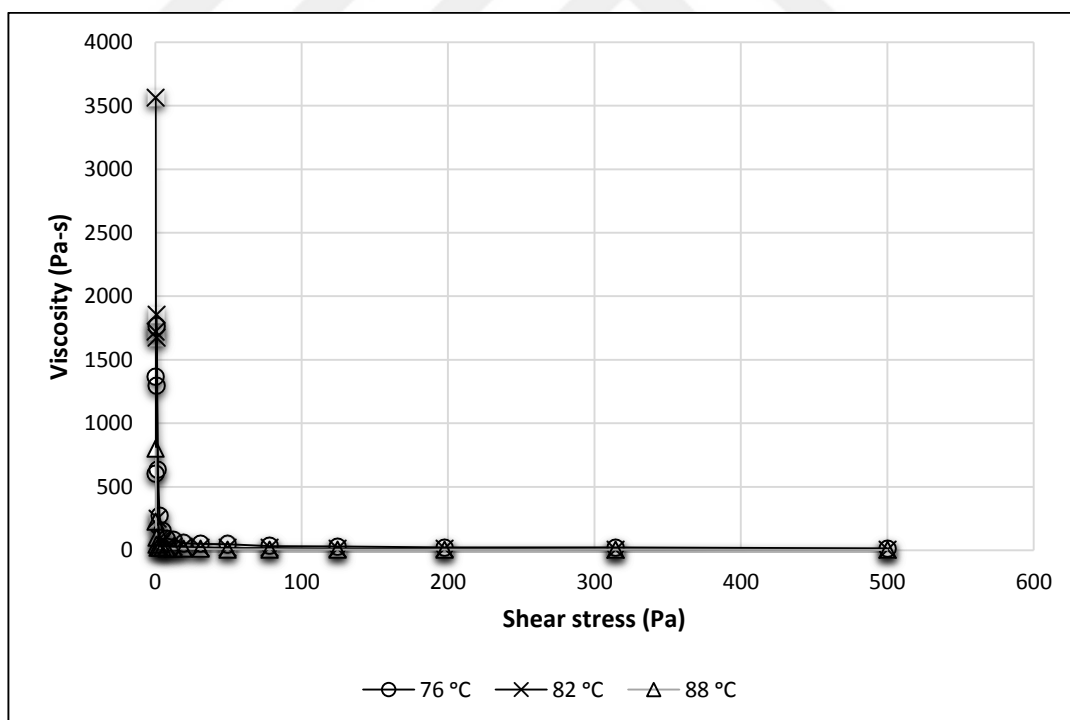


Figure 7.30 Steady Shear Flow measurements for 160/220 (Organic)

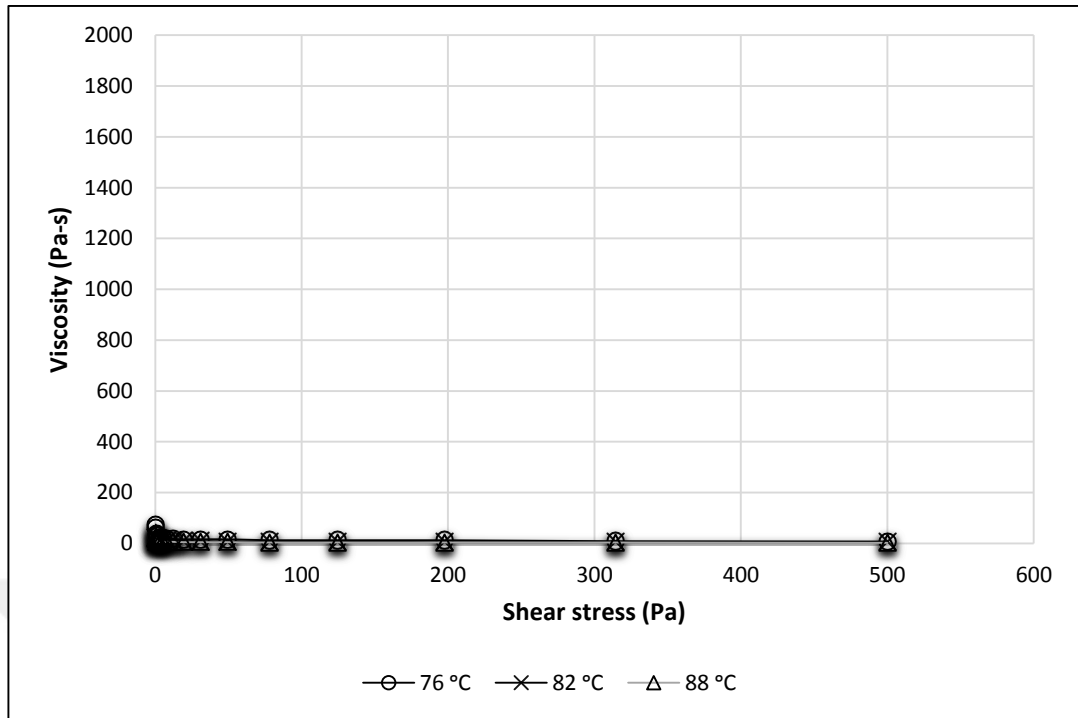


Figure 7.31 Steady Shear Flow measurements for 160/220 (Chemical)

In order to obtain the mixing and compaction temperatures, the viscosity values at steady-state conditions are plotted and extrapolated against the temperature as illustrated in Figure 7.32.

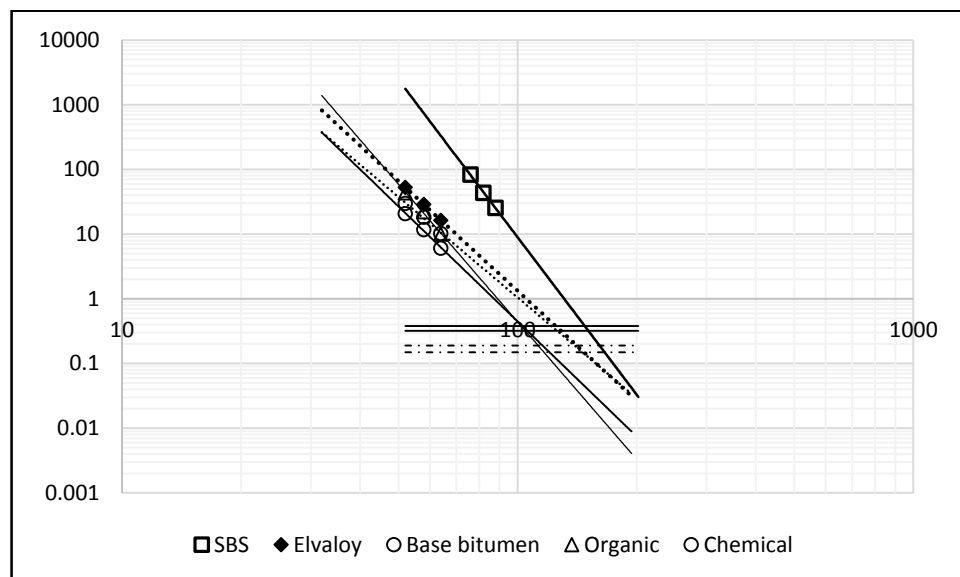


Figure 7.32 Mixing and compaction temperatures calculation for SSF

Table 7.4 SSF method results

Material	50/70		160/220	
	Mixing Temp. (°C)	Comp. Temp. (°C)	Mixing Temp. (°C)	Comp. Temp. (°C)
Base bitumen	152	140	140	125
PMB (SBS)	166	148	154	138
PMB (Elvaloy)	157	142	142	127
WMA (Organic)	133	124	120	115
WMA (Chemical)	136	124	129	118

The steady shear flow method can be applied for different penetration bitumen grades with both WMA and polymer additives. As expected, as the penetration value of the bitumen increases, that is, the bitumen becomes more fluid, the required bitumen and aggregate mixing and compaction temperatures decrease (Table 7.4).

When the mixing and compaction temperature values of polymer modified bitumen samples were compared with each other, the mixing and compaction temperature values of the SBS polymer were higher than the Elvaloy polymer, regardless of the penetration grade. However, as can be seen in Table 7.4, mixing and compaction temperatures of 50/70 and 160/220 bitumen samples containing Elvaloy showed less increase compared to the mixing and compression temperature levels of base bitumen.

On the other hand, for the base bitumen sample, the steady shear flow method yielded almost similar temperatures compared to the ASTM (equiviscous) method. While for WMA samples, the determined temperatures are considerably decreased. It has been noticed that the detected behavior was non-Newtonian and the viscosity value decreased with the increase of the shear stress. This can be attributed to the sensitivity of the Dynamic Shear Rheometer (DSR) machine which is used to perform this test and also to the low range of temperatures (76°C, 82°C, and 88°C) utilized in this method. The mixing and compaction temperature values of 50/70 and 160/220 penetration bitumen samples containing organic and chemical WMA additives produced close results.

7.1.5 Phase Angle Method Results

This test is performed by measuring the frequency sweep of the bitumen sample by applying a range of frequencies from 0.1 to 100 rad/sec. Phase angle master curve is developed by using Time-Temperature Superposition (TTS) procedure and utilizing 80 °C as a reference temperature as shown in Figures 7.33 to 7.42. Master curves are made by manually shifting modulus versus frequency plots (isotherms) at different temperatures along the logarithmic frequency axis to produce a smooth master curve.

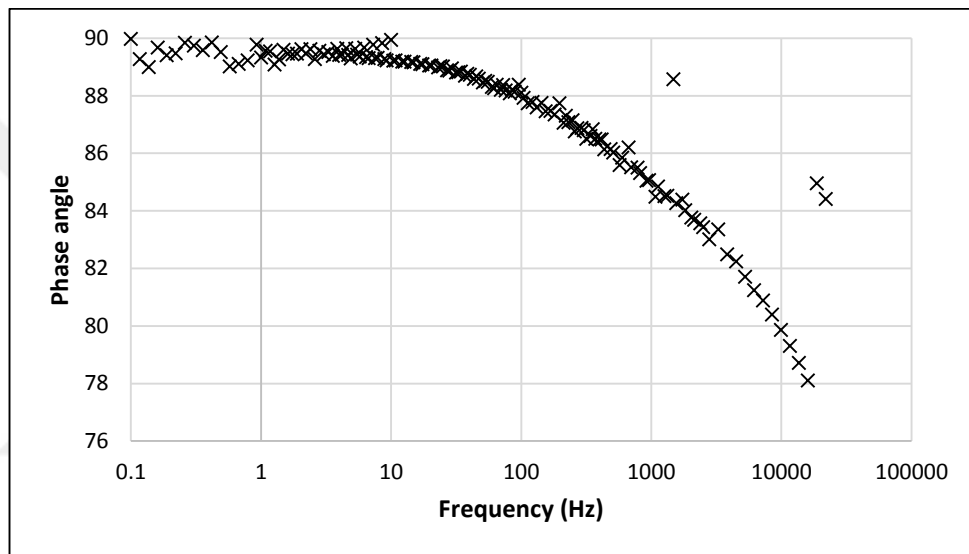


Figure 7.33 Master curve for 50/70 (Base)

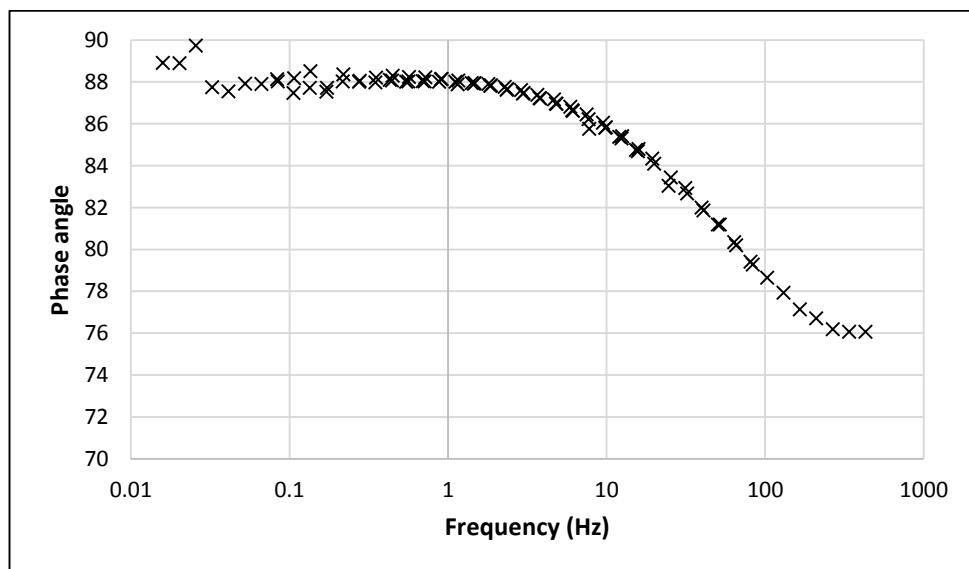


Figure 7.34 Master curve for 50/70 (SBS)

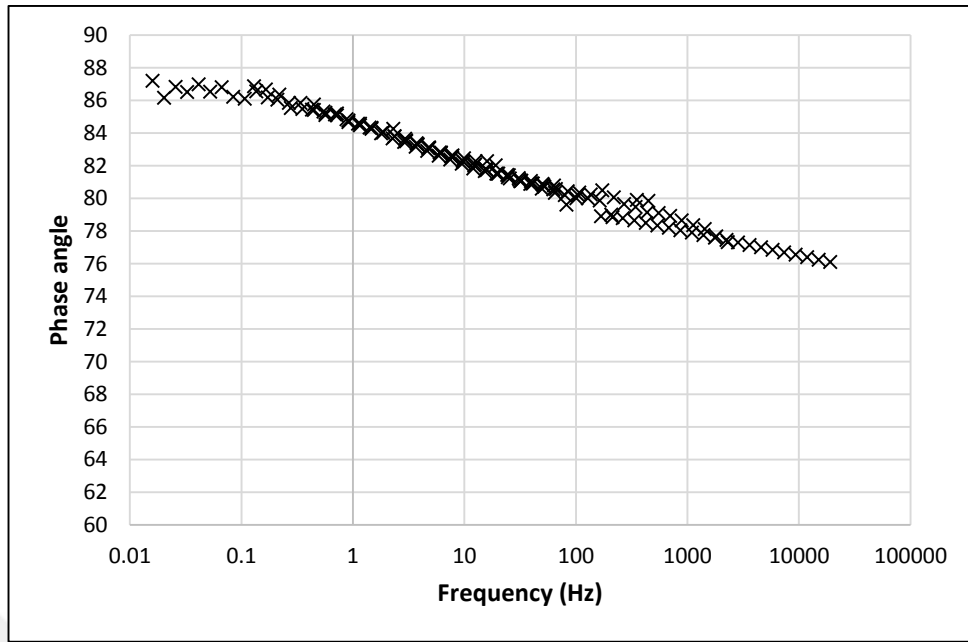


Figure 7.35 Master curve for 50/70 (Elvaloy)

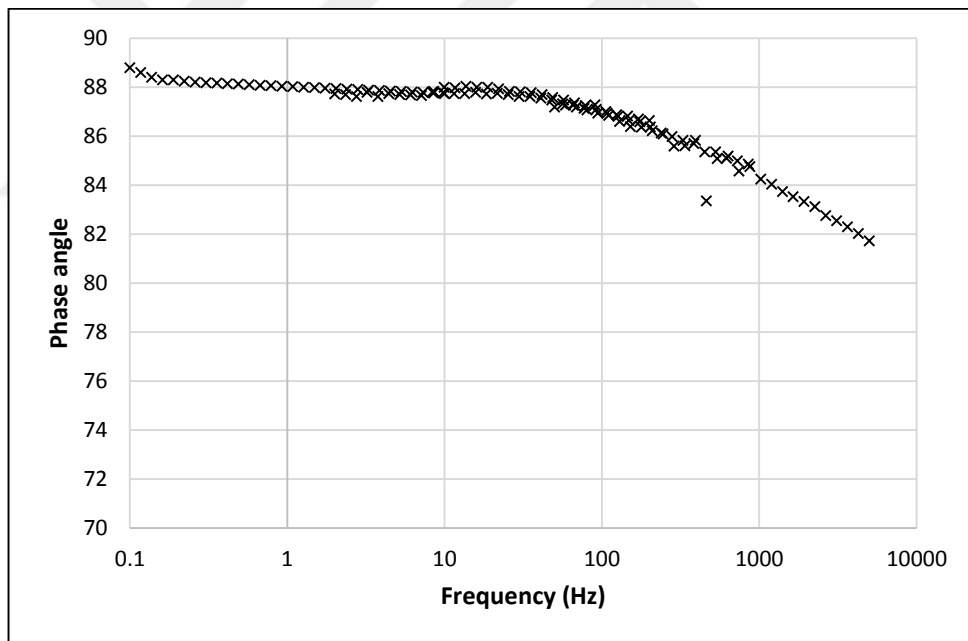


Figure 7.36 Master curve for 50/70 (Chemical)

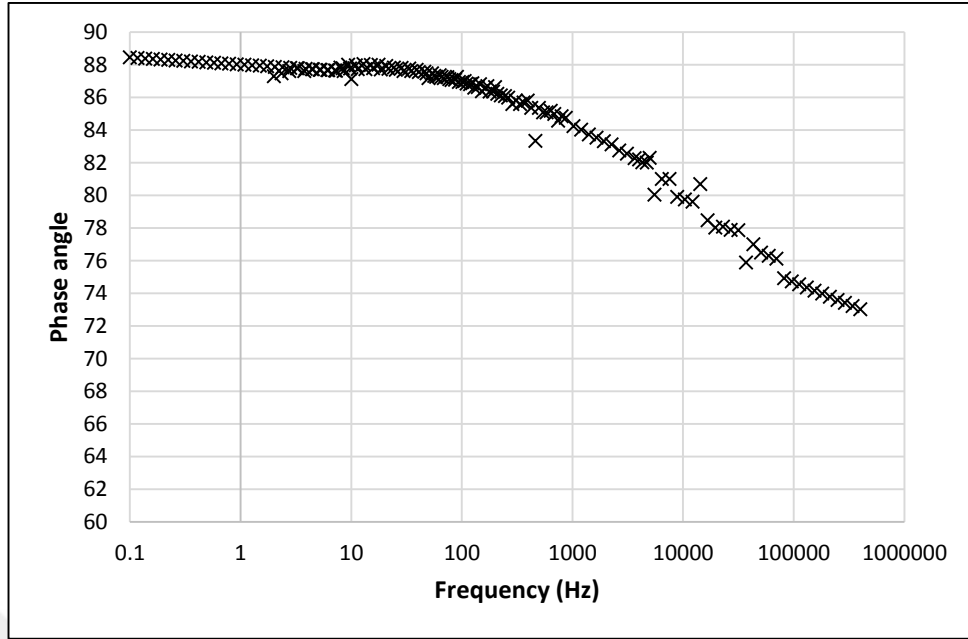


Figure 7.37 Master curve for 50/70 (Organic)

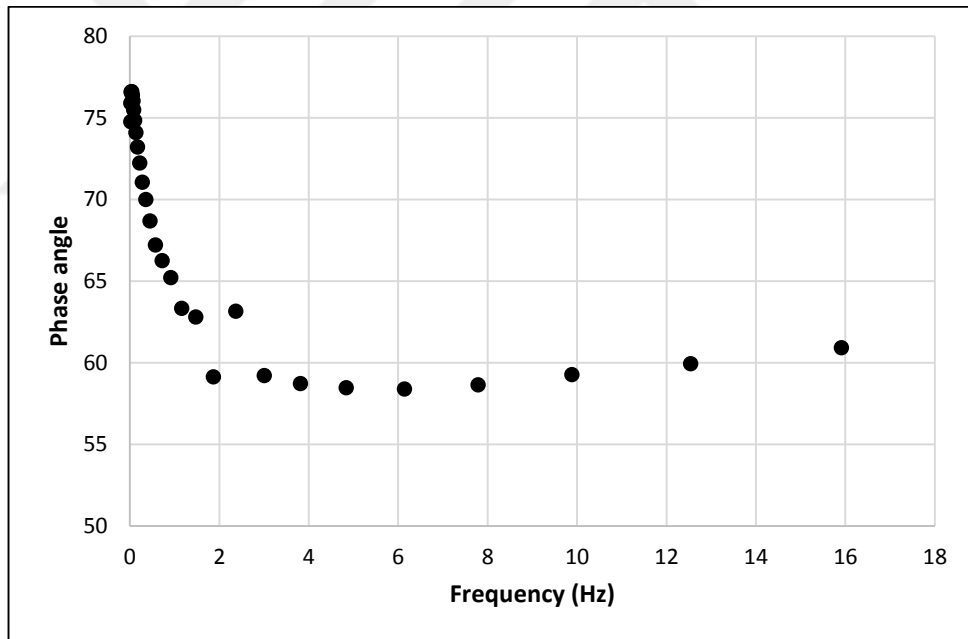


Figure 7.38 Master curve for 160/220 (Base)

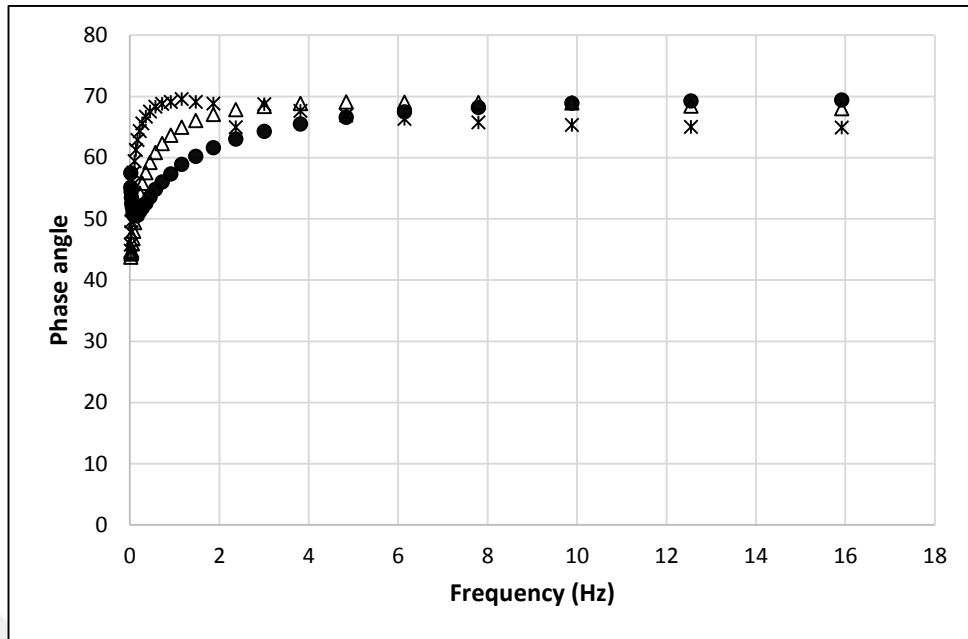


Figure 7.39 Master curve for 160/220 (SBS)

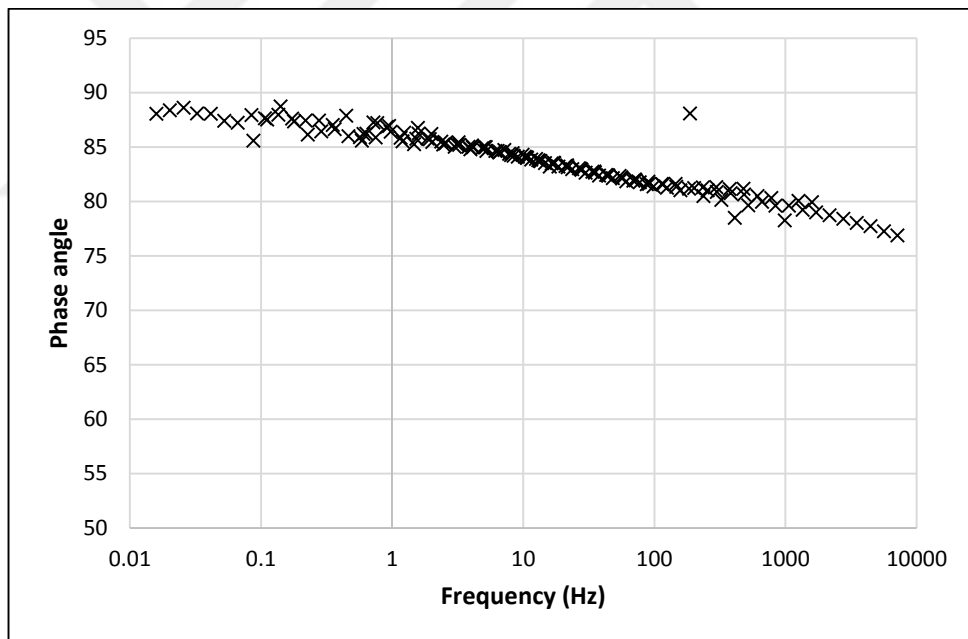


Figure 7.40 Master curve for 160/220 (Elvaloy)

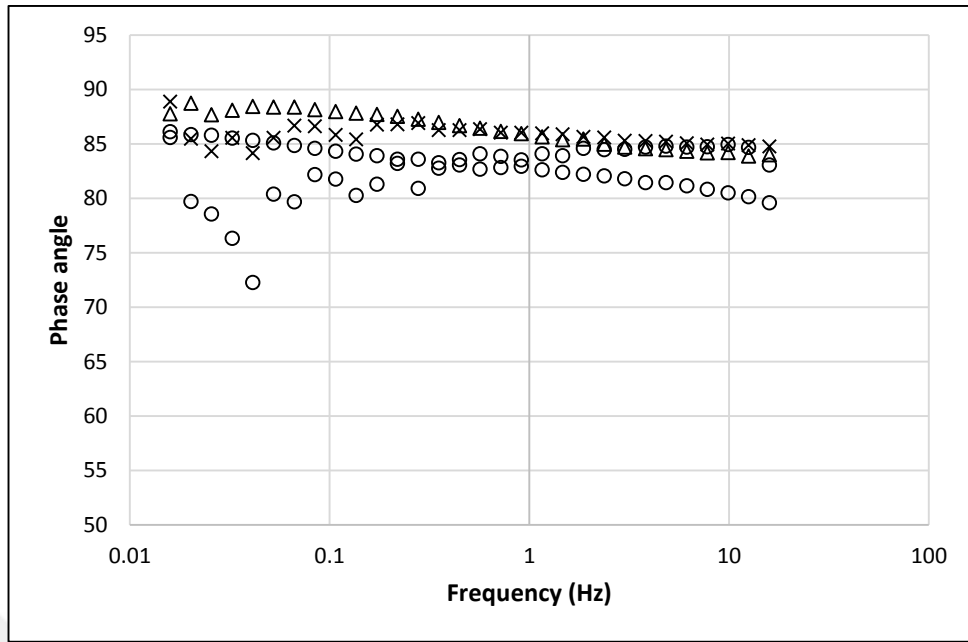


Figure 7.41 Master curve for 160/220 (Chemical)

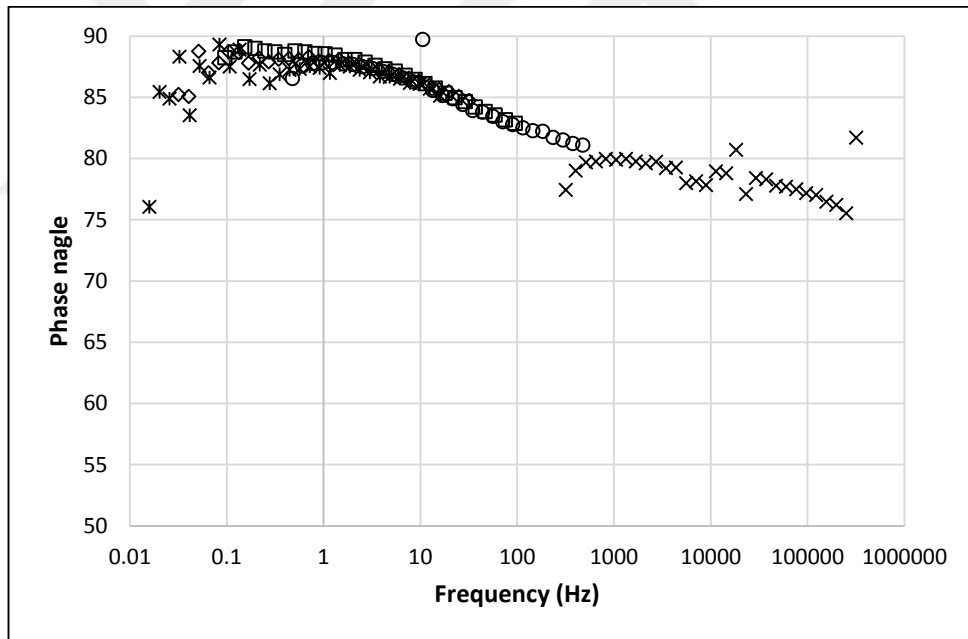


Figure 7.42 Master curve for 160/220 (Organic)

As mentioned earlier, the Phase Angle method is based on the non-Newtonian viscoelastic behavior of the modified bitumen. The method was applied to samples prepared by adding different additive types to both 50/70 and 160/220 grade bitumen samples.

Although the determination of the required mixing and compaction temperatures can be easily determined for samples prepared using 50/70 grade bitumen samples, while for bitumen samples produced with 160/220, the method has yielded very scattered results (Figures 7.38-7.42).

In this method, it is necessary to reach the phase angle value of 85-90 ° to determine the required mixing and compaction temperatures. In many of the samples produced with 160/220 penetration grade bitumen and additives, the phase angle value of 85-90° could not be achieved or produced dispersed and scattered results. Therefore, the results comments have been made for 50/70 penetration grade bitumen. Table 7.5. shows the results of the method.

Table 7.5 Phase angle method results

Material	50/70		160/220	
	Mixing Temp. (°C)	Comp. Temp. (°C)	Mixing Temp. (°C)	Comp. Temp. (°C)
Base bitumen	144	134	No result	No result
PMB (SBS)	163	150	No result	No result
PMB (Elvaloy)	161.6	148	No result	No result
WMA (Organic)	145	135	No result	No result
WMA (Chemical)	145	134.5	No result	No result

The mixing and compaction temperatures determined according to the phase angle method gave lower values for base bitumen than the mixing and compaction temperatures determined according to the ASTM (equiviscous) method. It was observed that the temperature increased as expected with the addition of polymer and the mixing and compaction temperature values of both SBS and Elvaloy samples were almost similar (Table 7.5).

However, it was found that the implementation of this method for organic and chemical WMA additive added to the bitumen of the 50/70 penetration grade (although the phase angle value of 85-90° was obtained in Figures 6.28 and 6.29) did not have a significant effect on mixing and compaction temperatures. As the penetration value of the bitumen increases, the material becomes softer and more fluid, in other words, it tends to behave as Newton fluid. The same is true for bitumen samples produced with

WMA additives. As mentioned earlier, this method is applied to samples that do not exhibit Newtonian behavior.

The purpose of WMA additives is to save energy by reducing the viscosity of the bitumen (making the bitumen more fluid), thereby achieving lower mixing and compaction temperatures. The results of the method did not show a decrease in the expected mixing and compaction temperatures when analyzed on the basis of 50/70 penetration bitumen samples containing organic and chemical WMA additives (since the samples showed Newton behavior). This is an expression that the phase angle method is not suitable for liquids with low viscosity and non-Newtonian fluids.

7.2 Marshall Mix Design and Optimum Bitumen Content Determination

In this study, the asphalt mixtures characteristics were determined for 50/70 penetration grade involving additives by the Marshall method over a range of the determined mixing and compaction temperatures (Appendix A). It is important to note that the highest and lowest determined mixing and compaction temperatures were taken into account for the determination of optimum bitumen content. This bitumen content will then be utilized for characterizing the mechanical properties of asphalt mixtures. For polymer modified samples (SBS and Elvaloy), the ASTM (equiviscous) method and Zero Shear Viscosity resulted in the highest and lowest temperatures, respectively. While for WMA, the ASTM (equiviscous) method and the Steady Shear Flow Method yielded the highest and lowest temperatures, respectively.

The optimum bitumen content was determined for wearing course as the content corresponding to 4% air voids as stated at the National Asphalt Pavement Association (NAPA). The results of the optimum content are summarized in Figure 7.43.

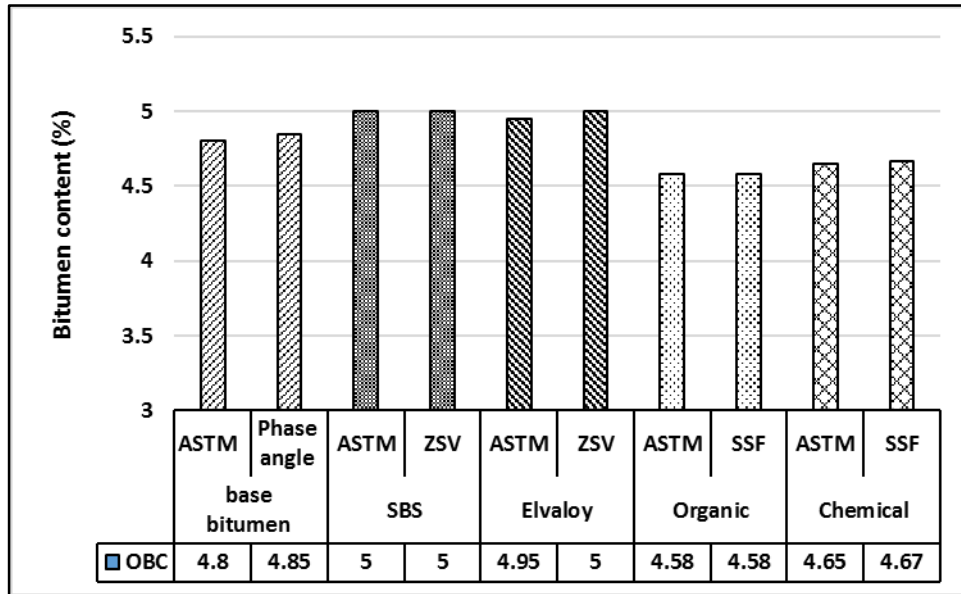


Figure 7.43 Optimum Bitumen Content based on different methods

As depicted in Figure 7.43, the optimum bitumen content for the unmodified HMA mixture was determined as 4.8%. The optimum bitumen content regarding SBS polymer modified specimens prepared with temperatures determined by the ASTM (equiviscous) and ZSV methods is found as 5%. In the case of Elvaloy polymer modified bitumen, the asphalt concrete specimens prepared with temperatures determined by ASTM (equiviscous) and ZSV methods (as lowest and highest temperatures) are calculated as 4.95% and 5%, respectively. The optimum bitumen content regarding specimens involving WMA additives is found as 4.65% and 4.6% related to ASTM (equiviscous) and SSF methods. Also, the optimum bitumen content of WMA asphalt specimens involving Chemical additives is determined as 4.58% for both ASTM (equiviscous) and SSF methods.

The optimum bitumen content results have shown that the polymer modified bitumen samples yielded the highest content while the asphalt samples involving WMA additives exhibited the lowest content. Among each additive, it is evident from these results that the variation in mixing and compaction temperatures (considered as highest and lowest temperatures level) do not influence the determined optimum bitumen content.

Based on the gained results regarding the relationship between the optimum bitumen content and mixing and compaction temperatures, the determined optimum bitumen contents are utilized for each method to prepare asphalt concrete samples. Stability, Flow, Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) are then measured and evaluated.

Figure 7.44 presents the Marshall stability values for each method and additives. As depicted in Figure 7.44, among each sample prepared with the same additives, the reduction in mixing and compaction temperatures determined by different methods decreased the stability value of the asphalt mixtures. Besides, when comparing the samples prepared with SBS and Elvaloy polymer modified bitumen, all the methods yielded similar stability results except for specimen prepared with temperatures obtained through the ZSV method. Marshall stability values of samples involving Elvaloy polymer modified bitumen samples demonstrated higher values in comparison with SBS polymer modified bitumen samples when both are prepared through the ZSV method. The stability of the asphalt mixture sample is derived mostly from internal friction and cohesion. Cohesion is the binding force of bitumen while internal friction is the interlocking and frictional resistance of aggregates. The binding ability is dependent upon the bitumen fluidity which is controlled by the temperature (i.e. the mixing temperature). While frictional resistance is more influenced by the compaction effort which is sensitive to the utilized temperature (i.e. the compaction temperature). In other words, the reduction in the utilized temperatures during the construction decreases the workability of the mixture. Thus, the SBS modified samples constructed at the temperatures obtained from the ZSV method, which is greatly lower than the temperatures estimated by the ASTM (equiviscous) method, has demonstrated a substantial reduction in Marshall resistance. Figure 7.43 also presents the Marshall stability values of asphalt samples involving WMA additives. As expected stability of value regarding samples involving polymers is higher than the sample prepared with WMA additives.

Among the WMA samples involving organic additives, the sample prepared with SSF demonstrated low stability values. Similar results can also be noticed for chemical

WMA additive. These results again indicate that the decrease in construction temperature may lead to a relative reduction in the stability value.

As indicated earlier, Marshall stability is influenced by the utilized construction temperature and this impact is variable based on the reduction in these temperatures. For instant, the impact of the variation in mixing and compaction temperatures for SBS modified samples is high when the ASTM (equiviscous) and ZSV methods are considered. Such high variation resulted in a decline in the stability of the asphalt sample. While Elvaloy modified samples have shown less variation in the determined mixing and compaction temperatures for all methods compared to the SBS modified samples which yielded in less fluctuated stability results. The same statement can also be made for the WMA samples where the temperatures are less varied.

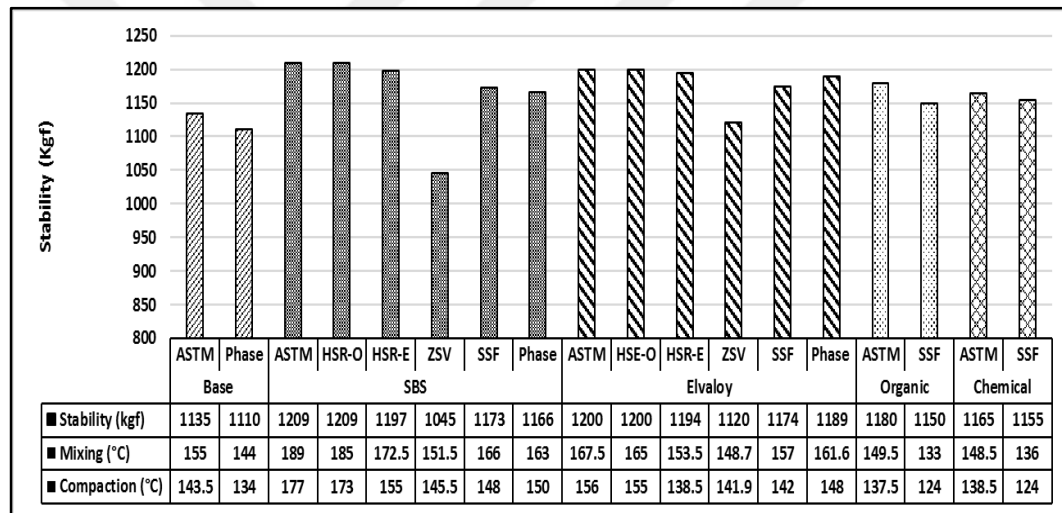


Figure 7.44 Stability Values regarding different methods

Other Marshall characteristics such as flow, Voids in Mineral Aggregate (VMA), and voids filled with asphalt (VFA) were determined as illustrated in Table 7.6. As can be seen, these values are less affected by the variation of mixing and compaction temperatures. In general, the flow and VMA values are decreased with increasing temperatures. While the temperature has not a similar impact on VFA values. It can be noticed that VFA increased as the temperature increased. Generally, the VFA value is dependent on the bitumen content. In other words, the more the bitumen content in the mixture the higher the VFA value which gives a better explanation about the increasing of VFA for polymer bitumen mixtures compared to the unmodified as well as to the

asphalt specimens involving organic and chemical additives. The reduction in VMA with the decrease in the temperature is indicating that the bitumen is not adequately coating the aggregate particles in the mixture. The flow value decreased with the increasing temperatures. However, according to Turkish specification, the recommended flow of wearing course Type 1 is between 2 and 4 mm. Therefore, the results are in compliance with the specification.

Table 7.6 Marshall characteristics

	Base bitumen	SBS Polymer		Elvaloy Polymer		Organic WMA Additive		Chemical WMA Additive		Specs. limits
	ASTM	ASTM	ZSV	ASTM	ZSV	ASTM	SSF	ASTM	SSF	
Flow	2.6	2.58	2.45	2.6	2.44	2.3	2.2	2.24	2.15	2-4
VFA	71	73	74	72	73.4	70	69	68	68	65-75
VMA	14	14.3	14.15	14.25	14.14	14	14	14.3	14	14-16

7.3 Indirect Tensile Strength

The Indirect Tensile Strength (ITS) test results are plotted for each method using the determined optimum bitumen contents aiming to examine the effect of the mixing and compaction temperatures on the tensile strength properties for all mixtures as presented in Figure 7.45.

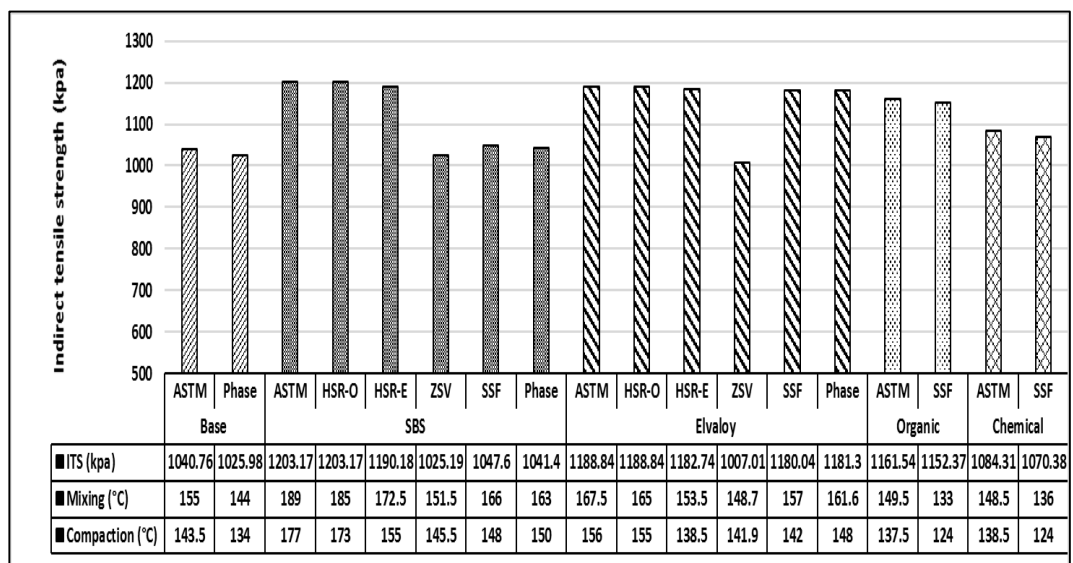


Figure 7.45 Indirect Tensile Strength (ITS) results

As seen in Figure 7.45, the ITS of both samples involving polymer and WMA additives are higher than the unmodified mixtures regardless of the mixing and compaction temperatures utilized. The increase in the indirect tensile strength of the mixtures can be attributed to the increased stiffness of the modified bituminous mixtures. Besides, when comparing the samples prepared with SBS and Elvaloy polymers, all the methods showed similar ITS results except for the temperatures obtained by the SSF and phase angle methods. The asphalt concrete samples modified with SBS polymer using the temperatures determined through the SSF and phase angle methods have demonstrated lower ITS value compare to the asphalt samples prepared with Elvaloy polymer. For both polymers modified asphalt samples, the utilization of the temperatures determined by the ZSV resulted in the lowest ITS value. At low temperatures, the viscosity of the bitumen material becomes higher and the material consistency tends to be thicker. Such a condition has a direct effect on the coating ability of the bitumen with the aggregate particles which also negatively influence the adhesion force. Both coating and adhesion are associated with the variation in the obtained mixing and compaction temperatures which are more evident in SBS-modified asphalt samples compare to other additives. Accordingly, the SBS-modified asphalt samples have fluctuated indirect tensile strength (ITS) results. Moreover, some researchers have clarified that the variation in compaction temperature has an essential impact on the performance of the asphalt sample and the reduction in the compaction temperature for asphalt samples have the same properties would generate a lower performance (Rahmat et al., 2019; Raposeiras et al., 2017).

On the other hand, for asphalt concrete samples involving organic WMA additives, the obtained ITS results were not much sensitive to the reduction in the construction temperatures. Similar results were also noticed for specimens prepared through chemical additives. It can be noticed that the mixing and compaction temperatures have a relative impact on the performance of the asphalt mixtures representing by the ITS value.

7.4 Selecting Appropriate Mixing and Compaction Temperatures of PMB and WMA

As mentioned earlier, the ASTM (equiviscous) method was developed to specify the required mixing and compaction temperatures of unmodified bitumen (base bitumen). Also, the proposed methods required either to use a different equipment or models. Thus, it is necessary to find an alternative approach that can overcome the shortcoming of the ASTM (equiviscous) method (for both polymers modified bitumen and the WMA samples) and the complexities from the proposed methods. So that, based on the earlier results, the mixing and compaction temperature results that have not affected the performance of the asphalt mixture are considered to be the optimum values. For polymer modified samples (SBS and Elvaloy), the temperatures estimated by the high shear rate methods have no clear impact on the performance. While for WMA, the steady shear flow method showed almost similar effect on the performance compared to the ASTM (equiviscous) method. Based on that, the average temperatures determined by these methods are used to make back calculation on the viscosity-temperature charts of the ASTM (equiviscous) method to find a new viscosity limits that can suits the polymer modified bitumen and the WMA as illustrated in Figure 7.46 to 7.49.

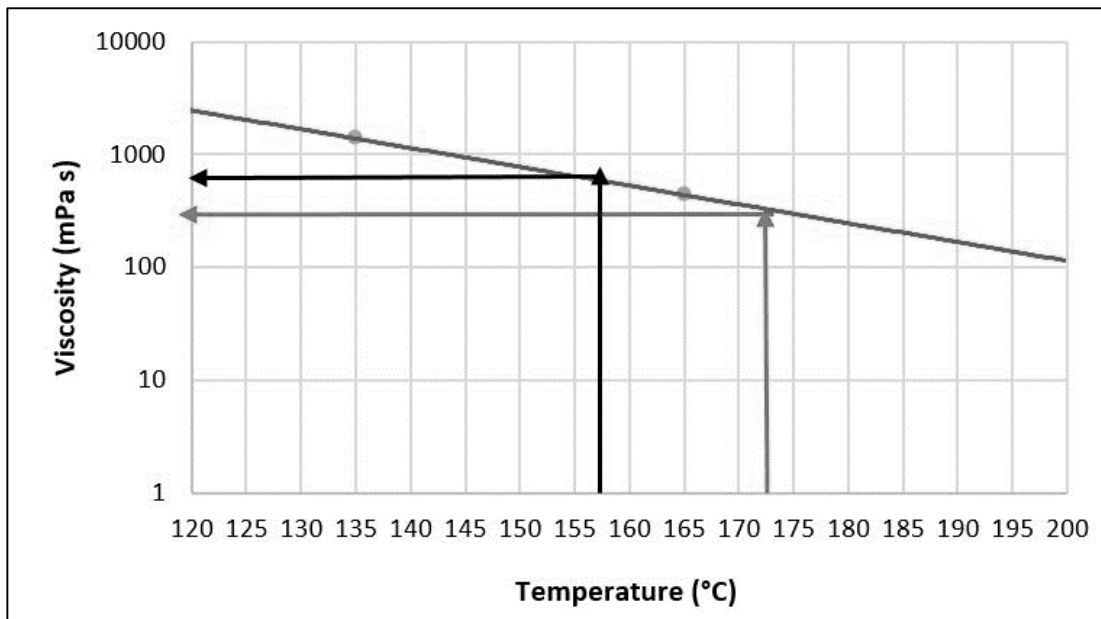


Figure 7.46 Back calculation on the viscosity-temperature charts for PMB (SBS)

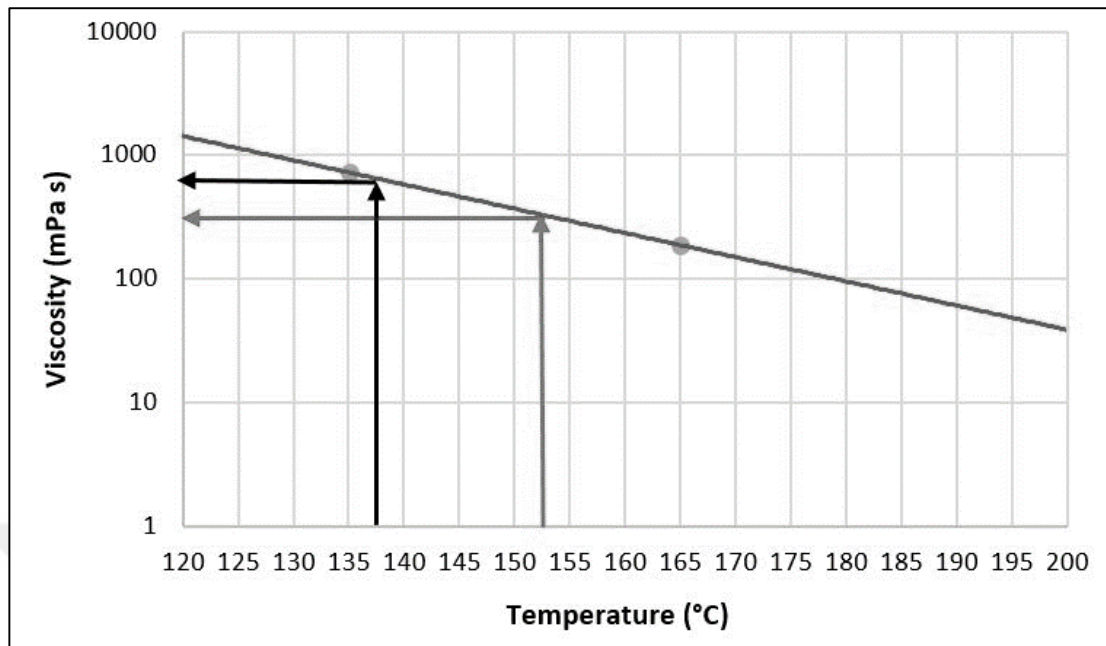


Figure 7.47 Back calculation on the viscosity-temperature charts for PMB (Elvaloy)

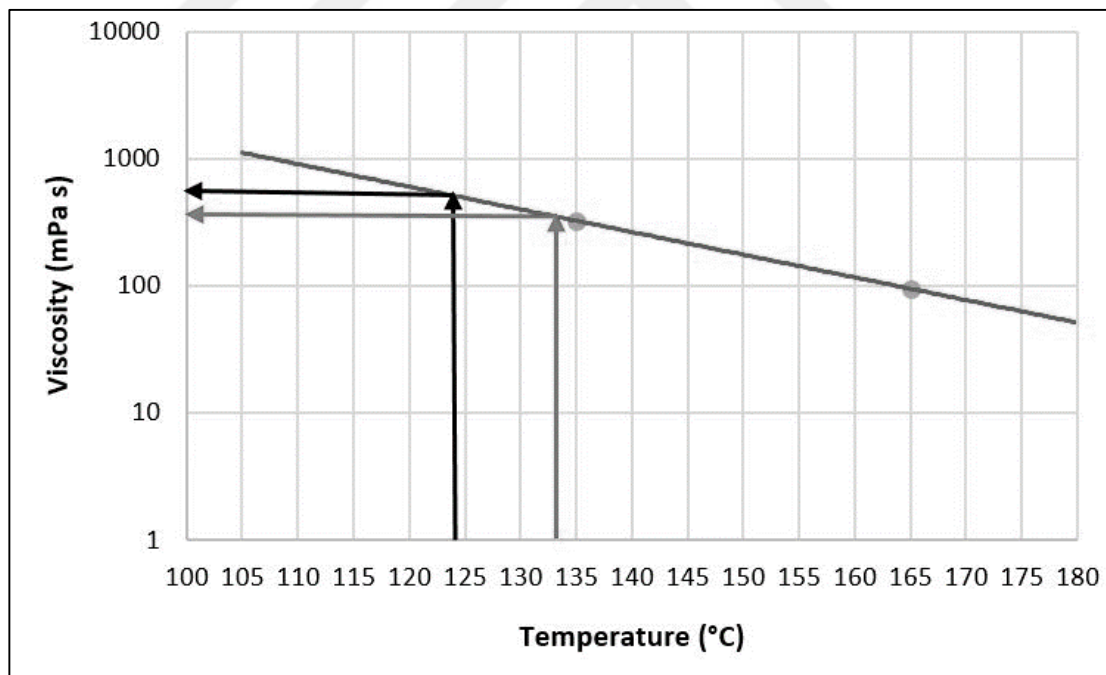


Figure 7.48 Back calculation on the viscosity-temperature charts for WMA (Organic)

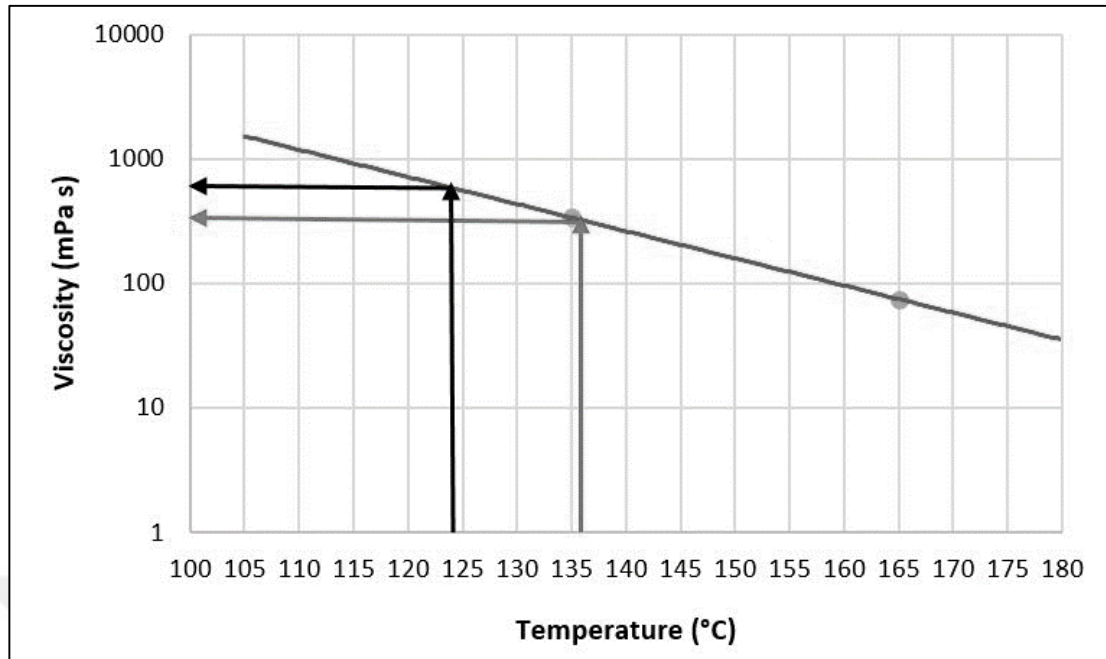


Figure 7.49 Back calculation on the viscosity-temperature charts for WMA (Chemical)

Based on Figures 7.46 to 7.49, the new mixing and compaction of polymer modified bitumen and WMA samples limits that can be used to modify the ASTM (equiviscous) method are presented in Table 7.7.

Table 7.7 New suggested limit to determine mixing and compaction temperatures for PMB and WMA

PMB		WMA	
Mixing (Pa. s)	Compaction (Pa. s)	Mixing (Pa. s)	Compaction (Pa. s)
0.325±0.03	0.651±0.025	0.34±0.015	0.552±0.04

CHAPTER EIGHT

EVALUATION OF ECONOMIC AND ENVIRONMENTAL IMPACTS

Flexible pavements, which are also generally known as hot mix asphalt (HMA), are the most common type of pavements over the world. This is due to their low initial construction cost, surface smoothness, load distribution characteristics, etc. HMA is usually constructed of bitumen and aggregates which should be heated at elevated temperatures before the production of the mix at the asphalt mixing plant, the required mixing temperature is generally determined through a standard method (ASTM D2493). The standard method was developed based on unmodified bitumen behavior. Thus, the application of this method on other bitumen types such as polymer modified bitumen and warm mix asphalt is not proper since the behavior of such materials is not taking into consideration (Androjić & Alduk, 2016). Consequently, the determined temperatures for such materials are excessively high and the implementation of those temperatures will create a higher energy consumption which will harm the environment as well as increase the total cost of the asphalt production.

The energy consumption during the HMA manufacturing process affected by a couple of constraints such as the moisture level in the mineral, the interruptions during the manufacturing process, and the production temperature of the asphalt mixture. Ang et al. observed that a 3% decrease in the mixture's moisture level resulted in a 55% to 60% energy savings (Ang et al., 1993). In another study carried out by Young, he considered the influence of the discontinuity in the production of asphalt mixture, and he exhibited that any interruptions may create a fuel expenditure between 20% to 35% (Young, 2008). In addition, the temperature during the manufacturing of HMA is an important factor in energy consumption. Jenny showed that the reduction in the production temperature from 180 °C to 115 °C during the manufacture of an asphalt mixture develops a reduction in fuel consumption for 1.5 kg/t of produced asphalt mixture (Jenny, 2009). Therefore, in the perspective of energy consumption, the usage of bituminous material that requires lower production temperature such as the warm mix asphalt (WMA) technology is a good alternative for the HMA since it requires lower production temperature (Cervarich, 2003; Davidson, 2008). However, in order

to satisfy the development in the traffic demand, the utilization of different polymer types into the bitumen is considered as a practical solution. Nevertheless, using polymer modified bitumen (PMB) necessitates higher production temperatures, which may generate harmful atmospheric emissions than the base (unmodified) bitumen (Grabowski & Janowski, 2010; Romier et al., 2006; Sivilevicius, 2011).

On the other hand, energy consumption is considered as a crucial parameter in determining the type of a plant to be used. Generally speaking, the energy consumption of the batch-type is higher than the drum mix type, in which the mineral materials are dried, heated, and mixed in the same drum. Therefore, batch-type is currently more popular due to its versatility, handling, and better quality of production (Ang et al., 1993).

In this study, in order to evaluate the economic and environmental impacts of utilizing lower production temperatures, several proposed methods (except for phase angle method because no results were obtained for 160/220 bitumen) have been implemented on the bitumen samples modified with different polymers and WMA additives. The economic impacts of the determined production temperatures through different models were evaluated by the estimation of energy consumption in terms of electricity and natural gas costs for the asphalt batch type plant. Moreover, the expected environmental influences were considered by estimating of the carbon dioxide emissions

8.1 Estimation of Energy Consumption

There are various parameters taken into account during the production of asphalt in plants however within the scope of the study, comparisons have been made by considering the mixing (production) temperature values determined with different models. The impact of the variation of the determined mixing temperature for the bitumen samples produced with 50/70 and 160/220 penetration grade and different additives on the natural gas and electricity consumption during the asphalt production

is discussed. Since there is no standard related to this concept, evaluations will be made on the results based on the previous literature studies.

8.1.1 Electricity Consumption

For batch-type plants, the electricity consumption is calculated as of 3.24 kWh/ton at a temperature level of 160-165 °C with an annual production of 100,000 tons (Sonmez & Temren 2013). Braziunas and Sivilevicius investigated the dependency of electrical consumption on the utilized production temperature in batch type asphalt plants. They suggested that every 5°C temperature variation in the batch-type asphalt plant creates an 11% change in electricity consumption (Bražiūnas & Sivilevičius, 2014). In light of these findings, the current pricing is calculated for the production of 100.000 tons of asphalt for variable production temperatures (Table 8.1). As of January 2020, 1kWh electricity usage has been taken as 0.9523 Turkish Lira (TRY) in cost calculation for industrial usage (1 TRY currency equals to 0.143 USD in May 2020).

Table 8.1 Energy Consumption corresponding to different mixing (production) temperatures for batch-type plant usage

Temperature(°C)	Energy Consumption (kWh/ton)	Energy Consumption Cost (TRY /ton)	Annual Energy Consumption Cost (for 100.000 ton)- TRY
120-125	0.79	0.75	74.894.87
125-130	0.89	0.84	84.452.58
130-135	1.58	1.50	150.090.63
135-140	1.78	1.69	169.244.46
140-145	2.00	1.91	190.842.60
145-150	2.26	2.15	215.196.99
150-155	2.55	2.43	242.659.37
155-160	2.87	2.74	273.626.36
160-165	3.24	3.09	308.545.20
165-170	3.61	3.43	343.464.04
170-175	4.01	3.82	382.334.74
175-180	4.47	4.26	425.604.54
180-185	4.89	4.74	473.771.29
185-190	5.54	5.27	527.389.19

8.1.2 Natural Gas Consumption

Androjić and Alduk carried out a model-based study on the influence of various factors on the change of natural gas consumption in the batch-type asphalt plant (Androjić & Alduk, 2016). The study aimed to create models that correlate between the energy consumed at the batch-type asphalt plant with the production temperature, the moisture in the aggregate particles, and the hourly capacity. The average daily temperatures at the asphalt plant ranged from 158 to 184 °C during the test. The production temperature is correlated with energy consumption in terms of natural gas. Based on the analysis results, a regression function between the consumption of natural gas and the production temperature of the produced asphalt has been developed. As a result of this study, the natural gas consumption per ton depending on the mixing (production) temperature in the batch-type plant can be estimated by using the following equation (Equation 8.1).

$$\text{Natural gas consumption } \left(\frac{\text{m}^3}{\text{ton}}\right) = 0.0935 \times \text{Mixing temperature (}^\circ\text{C)} - 7.6635 \quad (8.1)$$

8.2 CO₂ Emission

One of the major environmental concerns regarding the utilization of high temperatures during the asphaltic material construction is the emission of CO₂. Mallick and Bergendahl investigated the total CO₂ emission for the production of HMA (Mallick & Bergendahl, 2009). Their study aimed to develop a model to estimate the CO₂ emission generated by the mixing (production) temperature of bitumen samples. For this purpose, the CO₂ emission of bitumen samples involving WMA additives was laboratory-measured using the Draeger equipment. The data of the experimental results were collected at several temperatures over a range of bitumen contents. A linear analysis was conducted using different dependent variables such as mixing temperature, bitumen content, and WMA additives percentage. Among the dependent variables, the mixing temperatures showed a very significant relationship with CO₂ emissions. Consequently, the relationship between the mixing temperature and the CO₂ emission is predicted as in equation 8.2.

$$C_{\text{CO}_2} = 2.175 e^{0.039 T} \quad (8.2)$$

where C_{CO_2} is the CO_2 concentration in ppm expected in the 2000 ml flask headspace in equilibrium with 200 g of asphalt mixture and T is the mixing temperature in degree Celsius.

8.3 Energy Consumption Results

Depending on the previous studies, electricity and natural gas consumption were priced for 100.000 tons of annual asphalt in the batch-type asphalt plant as a result of the model studies conducted on the modified and unmodified bitumen samples with 50/70 and 160/220 penetration grades. Detailed analyses are given in Tables 6 and 7.

Tables 8.2 and 8.3 demonstrate the variation in production temperature for each bituminous sample, with total consumption for 100.000 tons of asphalt. The analysis results demonstrated that the decrease in the mixing temperature resulted in a reduction in asphalt production. This is because the independent variable during the analysis is the mixing temperature.

Table 8.2 Electricity and natural gas consumption per 100.000 tons of annual for 50/70 asphalt manufacturing

Method	Mixing Temperature (°C)	Natural Gas Consumption (TRY)	Electricity Consumption (TRY)	Total cost (TRY)	Change according to ASTM (%)
Base bitumen					
ASTM	155	1.07E+06	2.74E+05	1.34E+06	-
5 % SBS					
ASTM	189	1.57E+06	5.27E+05	2.09E+06	
HSR-O	184	1.49E+06	4.74E+05	1.97E+06	-6
HSR-E	172.5	1.32E+06	3.82E+05	1.71E+06	-18
ZSV	151.5	1.02E+06	2.43E+05	1.26E+06	-40
SSF	166	1.23E+06	3.43E+05	1.57E+06	-25
Elvaloy Polymer					
ASTM	167.5	1.25E+06	3.43E+05	1.60E+06	-
HSR-O	164.5	1.21E+06	3.09E+05	1.52E+06	-5
HSR-E	153.5	1.05E+06	2.43E+05	1.29E+06	-19
ZSV	148.7	9.77E+05	2.15E+05	1.19E+06	-25
SSF	157	1.10E+06	2.74E+05	1.37E+06	-14
Organic WMA Additive					
ASTM	149.5	9.88E+05	2.15E+05	1.20E+06	-
SSF	133	7.47E+05	1.50E+05	8.97E+05	-25

Table 8.2 continues

	Chemical WMA Additive				
ASTM	148.5	9.74E+05	2.15E+05	1.19E+06	-
SSF	136	7.91E+05	1.69E+05	9.60E+05	-19

Table 8.3 Electricity and natural gas consumption per 100.000 tons of annual for 160/220 asphalt manufacturing

Method	Production Temperature (°C)	Natural Gas Consumption (TRY)	Electricity Consumption (TRY)	Total cost (TRY)	Change according to ASTM (%)
Base bitumen					
ASTM	143.5	9.01E+05	1.91E+05	1.09E+06	-
5 % SBS					
ASTM	180.5	1.44E+06	4.74E+05	1.92E+06	
HSR-O	177	1.39E+06	4.26E+05	1.82E+06	-5
HSR-E	165	1.22E+06	3.09E+05	1.52E+06	-20
ZSV	148.6	9.75E+05	2.15E+05	1.19E+06	-38
SSF	154	1.05E+06	2.43E+05	1.30E+06	-32
Elvaloy Polymer					
ASTM	161	1.16E+06	3.09E+05	1.47E+06	-
HSR-O	150.5	1.00E+06	2.43E+05	1.25E+06	-15
HSR-E	138	8.20E+05	1.69E+05	9.89E+05	-32
ZSV	125	6.30E+05	8.45E+04	7.14E+05	-51
SSF	142	8.79E+05	1.91E+05	1.07E+06	-27
Organic WMA Additive					
ASTM	136	7.91E+05	1.69E+05	9.60E+05	-
SSF	120	5.57E+05	7.49E+04	6.32E+05	-34
Chemical WMA Additive					
ASTM	137.5	8.13E+05	1.69E+05	9.82E+05	-
SSF	129	6.88E+05	8.45E+04	7.73E+05	-21

As seen in Tables 6 and 7, the production temperature plays a significant role in the total cost of the asphalt mixtures., The temperatures obtained by the ZSV method resulted in the lowest energy cost compared to the ASTM (equiviscous) method for both 50/70 and 160/220 bitumen involving polymer, while the temperatures determined by HSR-O showed less impact on the total energy cost. For bitumen samples produced with WMA additives, it can be noticed that the temperatures

obtained by the SSF method have decreased the estimated energy cost, compared to the ASTM (equiviscous). Also, among the WMA additives, bitumen samples involving the organic type of additive resulted in the lowest estimated energy cost compared to the chemical. This result is attributed to the lowest obtained temperature requirement for the production of the bitumen samples involving chemical WMA additives.

8.4 CO₂ Emission Results

The emission concentration was estimated based on the model suggested by Mallick and Bergendahl (2009). The possible reduction percentages compared to the ASTM (equiviscous) method are calculated for both 50/70 and 160/220 penetration grades bitumen involving different additives (Figures 8.1 and 8.2).

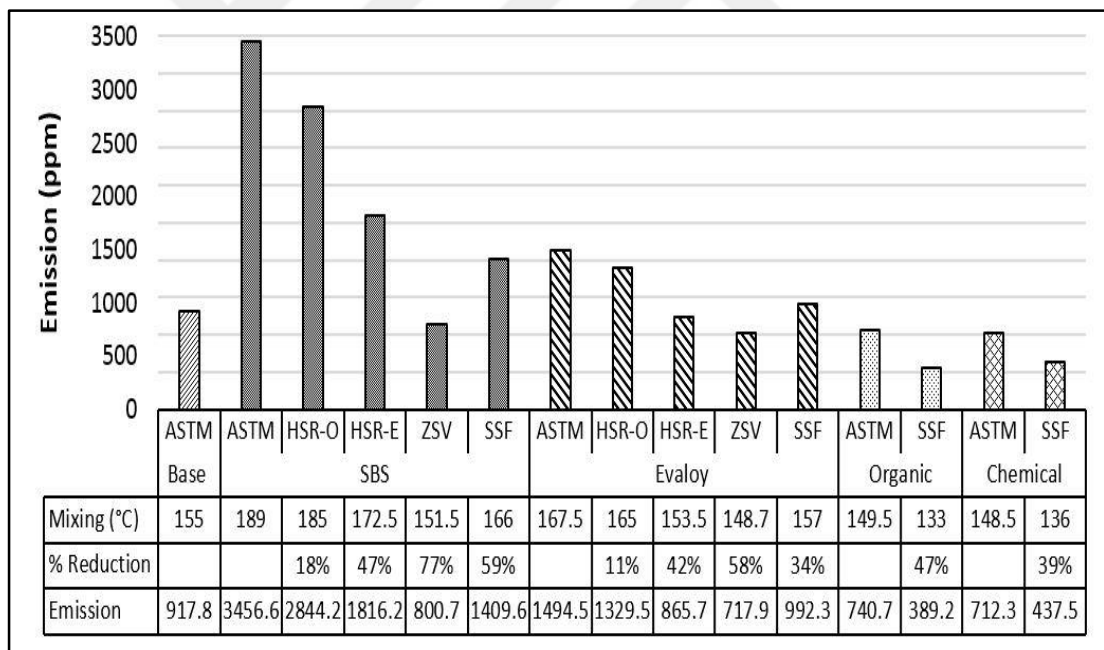


Figure. 8.1 CO₂ emission results for 50/70 bitumen samples involving different additive

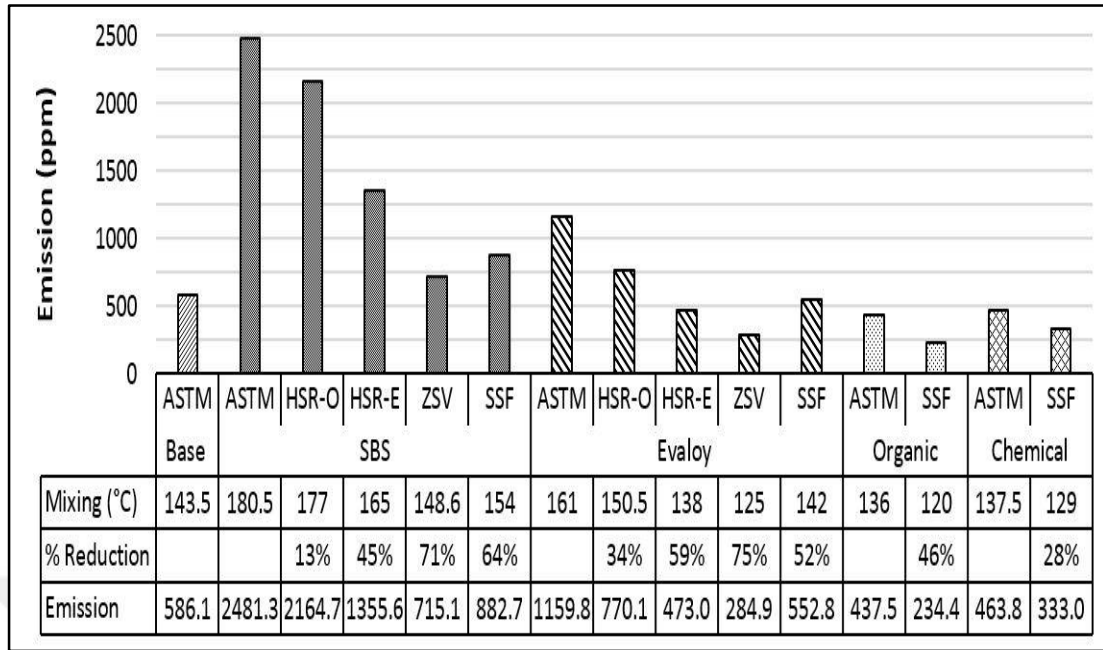


Figure 8.2 CO₂ emission results for 160/220 bitumen samples involving different additive

As seen in Figures 2 and 3, the more the decrease in the production temperatures, the more the reduction in carbon emission. The highest carbon emission reductions were observed by the application of the ZSV method for both 50/70 and 160/220 PMB samples because the lowest production temperatures were obtained by the ZSV method. For the samples containing WMA additives, the production temperatures calculated by the SSF method resulted in a substantial reduction in carbon emission compared to the ASTM (equiviscous) method. Moreover, similar to the estimation of energy cost, the utilization of organic WMA additive caused the lowest carbon emission since it has the lowest production temperature among all samples.

CHAPTER NINE

CONCLUSION AND RECOMMENDATION

The goal of the thesis is to identify and investigate an accurate procedure that can be utilized for determining the mixing and compaction temperatures for bitumen binders involving different kinds of polymer (elastomer type and reactive elastomeric terpolymer type) and warm mix asphalt additives (organic and chemical). For this purpose, two series of experiments were performed in this research. The 1st series involved measuring the suitability and applicability of each proposed method (high shear rate method (HSR), zero shear viscosity method (ZSV), steady shear flow method (SSF), and phase angle method) regarding the determination of mixing and compaction temperatures of both polymer PMB and WMA samples and then compared with the ASTM (equiviscous) method. The 2nd series was evaluating the impact of the determined mixing and compaction temperatures on the mechanical properties (such as stability, voids in mineral aggregate etc.) of the asphalt mixture through Marshall mix design and Indirect Tensile Strength test. The results of the experiments have led to the following conclusions:

1. Among all the additives (polymer and WMA additives), the proposed methods depicted lesser or slight less mixing and compaction temperatures as compared to the ASTM (equiviscous) method.
2. The high shear rate viscosity method in the original form (HSR-O) does not yield significant variation in mixing and compaction temperature for the both polymer modified bitumen samples in comparison with the ASTM (equiviscous) method. While this is not the case for high shear rate evolution method (HSR-E) which exhibited lesser mixing and compaction temperatures in comparison with the ASTM (equiviscous) method. The major advantage of high shear rate method is ease in application and does not require special equipment and models.
3. Mixing and compaction temperatures determined with the zero shear viscosity for the both PMB samples are substantially lower than the ASTM (equiviscous) method as well as lower than the other proposed methods. This method requires the utilization of a special model (Cross-Williamson model).

4. Both high shear rate method and zero shear viscosity method are based on the non-Newtonian behavior of the material such as samples involving different range of polymers. However, it is not suitable for Newtonian material such as base bitumen and bitumen including WMA additives.
5. The application of the steady shear flow method for PMB samples exhibits lower mixing and compaction temperature than the ASTM (equiviscous) method. Also, the implementation of this method gave lower mixing and compaction temperatures both WMA additives. While for base bitumen the determined temperatures are similar to the ASTM (equiviscous) method with no significant reduction.
6. For polymer modified bitumen samples, the mixing and compaction temperatures obtained by the phase angle method are also substantially lower than the ASTM (equiviscous) method. Besides utilization of this method does not lead to lower mixing and compaction temperatures for both base bitumen and WMA and the determined mixing and compaction temperatures are almost similar to the ASTM (equiviscous) method. The implementation of this method also requires to use the Dynamic Shear Rheometer equipment and the measured data should be drawn in a master curve.
7. The optimum bitumen content (OBC) for all mixtures are determined taking into the highest and the lowest developed temperatures into consideration. The asphalt samples involving polymers (SBS and Elvaloy) have resulted in the highest OBC compared to the other asphalt samples. The OBC results for asphalt samples prepared with WMA additives have shown lower bitumen content than other asphalt samples. The variation in mixing and compaction temperatures have shown no direct impact on the required bitumen content for all asphalt mixtures.
8. In the light of findings from stability values, it is possible to conclude that the stability of the asphalt samples involving polymers is higher than the other asphalt samples. Also, it has been noticed that the stability value has a close relation with the temperatures. In other words, the raise in the mixing and compaction temperatures increased the stability of the asphalt mixture. The stability of asphalt mixtures is dependent on the bonding ability of the bitumen. So, reducing the bitumen temperature (especially the mixing temperature) may reduce the bitumen

cohesion and affect stability. Also, the adhesion between the bitumen and the aggregate particles during the construction may considerably be affected when the temperatures are reduced and this may influence the asphalt mixture stability.

9. Other Marshall characteristics such as flow, Voids in Mineral Aggregate (VMA), and voids filled with asphalt (VFA) are less influenced by the mixing and compaction temperatures. In general, the VMA values are decreased with increasing temperatures and it can be noticed that VFA increased as the increase in temperature. The flow value also has not varied much with the change of the mixing and compaction temperatures utilized. All Marshall characteristics are within the specification limits.
10. Similar to the stability results, the ITS results are linearly related to the utilized mixing and compaction temperatures. The ITS results for modified asphalt samples are high compared to the other asphalt samples which can be referred to the higher cohesive ability of the modified mixtures as compared to the unmodified mixture.
11. Based on the obtained results, among all proposed methods, the HSR-O method may be considered as more practical and logical for polymer modified samples since the application of this approach generated lower temperatures and has shown less impact on the performance. For WMA samples, the implementation of the SSF method exhibited lower temperatures compared to the ASTM (equiviscous) method and also have depicted close results regarding the performance.
12. Moreover, the influences of the changes in production temperature have been evaluated in terms of the economic and environmental concerns. A linear relationship is noticed between the production temperature and energy consumption for the batch type asphalt plant.
13. The WMA samples have lower energy consumption compared to the other samples due to the lower mixing temperatures required during the construction. The utilization of the SSF seemed to be preferable since it yielded even lower temperatures than the ASTM (equiviscous) method and that significantly reduced the total cost of the required energy for production.
14. For PMB samples, the utilization of the temperatures obtained by ZSV is desirable with regard to the environmental perspectives because it depicted the lowest CO₂ emission compared to the ASTM (equiviscous) method.

The conclusion of this study covers the utilization of two types of polymer (elastomer and reactive elastomeric terpolymer type) as well as WMA additives (organic and chemical) considering the optimum suggested amounts. More research should be carried out by using different amounts and considering different kinds of polymers and WMA additives in order to perform more validation. Besides, the thesis involves the impact of the mixing temperature as the only independent parameter on the total cost of the asphalt mixture as well as on the generated environmental problems. More research should be carried out to include more parameters and different asphalt plants.



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APPENDICES

APPENDIX A

MARSHAL MIX DESIGN



Table A.1 Marshall mix design data for unmodified bitumen (ASTM)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	64.1	64.2	64.1	64.13	1172.7	684.2	1189.4	505.2	2.32					2.10	1045	0.985	1029
2	3.5	40.25	63.9	63.8	63.9	63.87	1171.4	685.1	1183.7	498.6	2.35					1.80	1034	0.99	1023
3	3.5	40.25	63.4	63.2	63.2	63.27	1180.9	688	1192.6	504.6	2.34					2.52	1101	1.005	1106
											2.34	2.57	9.04	16.01	43.54	2.14			1053
4	4	46	62.9	62.9	62.8	62.87	1175.2	686.2	1179.3	493.1	2.38					2.21	1192	1.015	1209
5	4	46	62.8	62.9	62.9	62.87	1183.1	691.2	1185.8	494.6	2.39					2.39	1079	1.015	1095
6	4	46	62.9	62.4	62.2	62.50	1185.4	693.4	1188.4	495	2.39					2.30	1181	1.025	1210
											2.39	2.55	6.32	14.52	56.49	2.30			1171
7	4.5	51.75	62	61.6	61.9	61.83	1190.3	695.3	1191.4	496.1	2.40					2.85	1192	1.043	1243
8	4.5	51.75	61.9	61.8	61.9	61.87	1170.9	687	1172	485	2.41					2.73	1309	1.04	1361
9	4.5	51.75	61.9	61.8	61.7	61.80	1180.3	695	1181.2	486.2	2.43					2.05	1201	1.043	1252
											2.41	2.53	4.73	14.08	66.41	2.54			1285
10	5	57.5	61.9	61.9	61.7	61.83	1187.1	701.1	1187.6	486.5	2.44					2.65	980	1.043	1022
11	5	57.5	61.6	61.7	61.6	61.63	1197.4	705.2	1197.5	492.3	2.43					2.59	936	1.049	981
12	5	57.5	61.7	61.5	61.7	61.63	1177.8	688.2	1178.1	489.9	2.40					2.72	853	1.049	894
											2.43	2.52	3.61	14.08	74.34	2.65			966

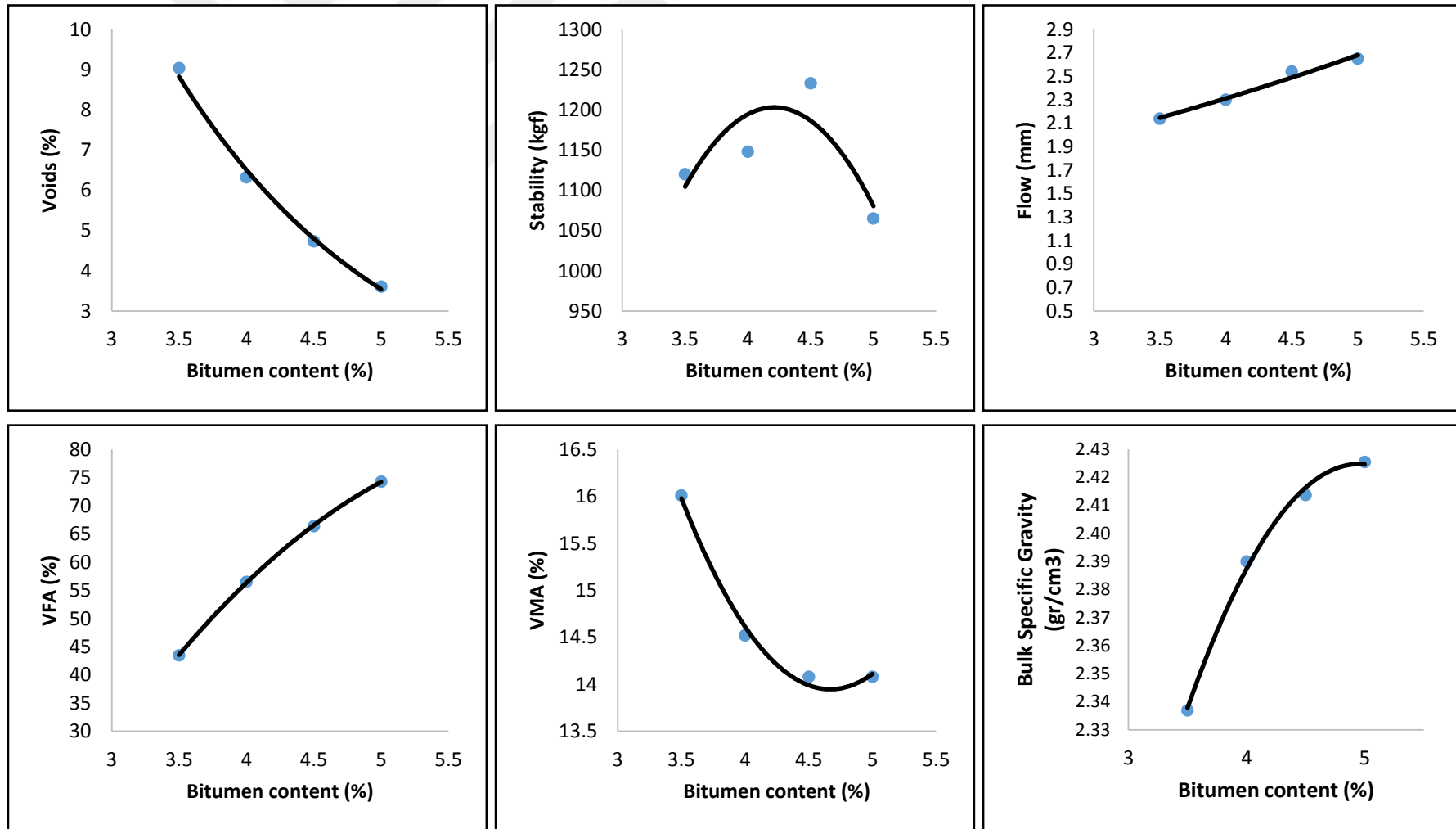


Figure A.1 Marshall mix design graphics for unmodified bitumen (ASTM)

Table A.2 Marshall mix design data for unmodified bitumen (Phase angle)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	62.9	62.6	62.4	62.6	1179.8	685.5	1191.5	506.0	2.332					2.39	1004	1.023	1027
2	3.5	40.25	62.9	62.9	62.9	62.9	1182.8	686.6	1196.4	509.8	2.320					2.03	978	1.015	993
3	3.5	40.25	62.8	62.9	62.7	62.8	1181.8	687.0	1194.0	507.0	2.331					2.01	996	1.018	1014
											2.328	2.569	9.41	16.35	42.5	2.14			1011
4	4	46	63.3	63.3	63.0	63.2	1180.3	685.5	1180.4	494.9	2.385					2.02	1046	1.008	1054
5	4	46	63.4	63.4	63.2	63.3	1181.8	688.2	1182.0	493.8	2.393					1.94	1125	1.005	1131
6	4	46	62.5	62.5	62.6	62.5	1171.8	680.1	1171.9	491.8	2.383					1.65	1156	1.025	1185
											2.387	2.551	6.44	14.63	56.0	1.87			1123
7	4.5	51.75	62.0	61.6	61.9	61.8	1180.2	693.2	1180.6	487.4	2.421					1.96	1123	1.043	1171
8	4.5	51.75	61.9	61.8	61.9	61.9	1189.9	695.6	1190.1	494.5	2.406					2.22	1151	1.040	1197
9	4.5	51.75	61.9	61.8	61.7	61.8	1185.4	694.1	1185.9	491.8	2.410					2.21	1142	1.043	1191
											2.413	2.534	4.77	14.12	66.2	2.13			1186
10	5	57.5	62.0	61.6	61.9	61.8	1199.5	706.8	1200.1	493.3	2.432					2.48	1005	1.049	1054
11	5	57.5	61.9	61.8	61.9	61.9	1185.1	697.5	1188.4	490.9	2.414					2.67	998	1.008	1006
12	5	57.5	61.9	61.8	61.7	61.8	1177.8	691.2	1178.1	486.9	2.419					2.65	994	1.025	1019
											2.422	2.516	3.77	14.22	73.5	2.60			1026

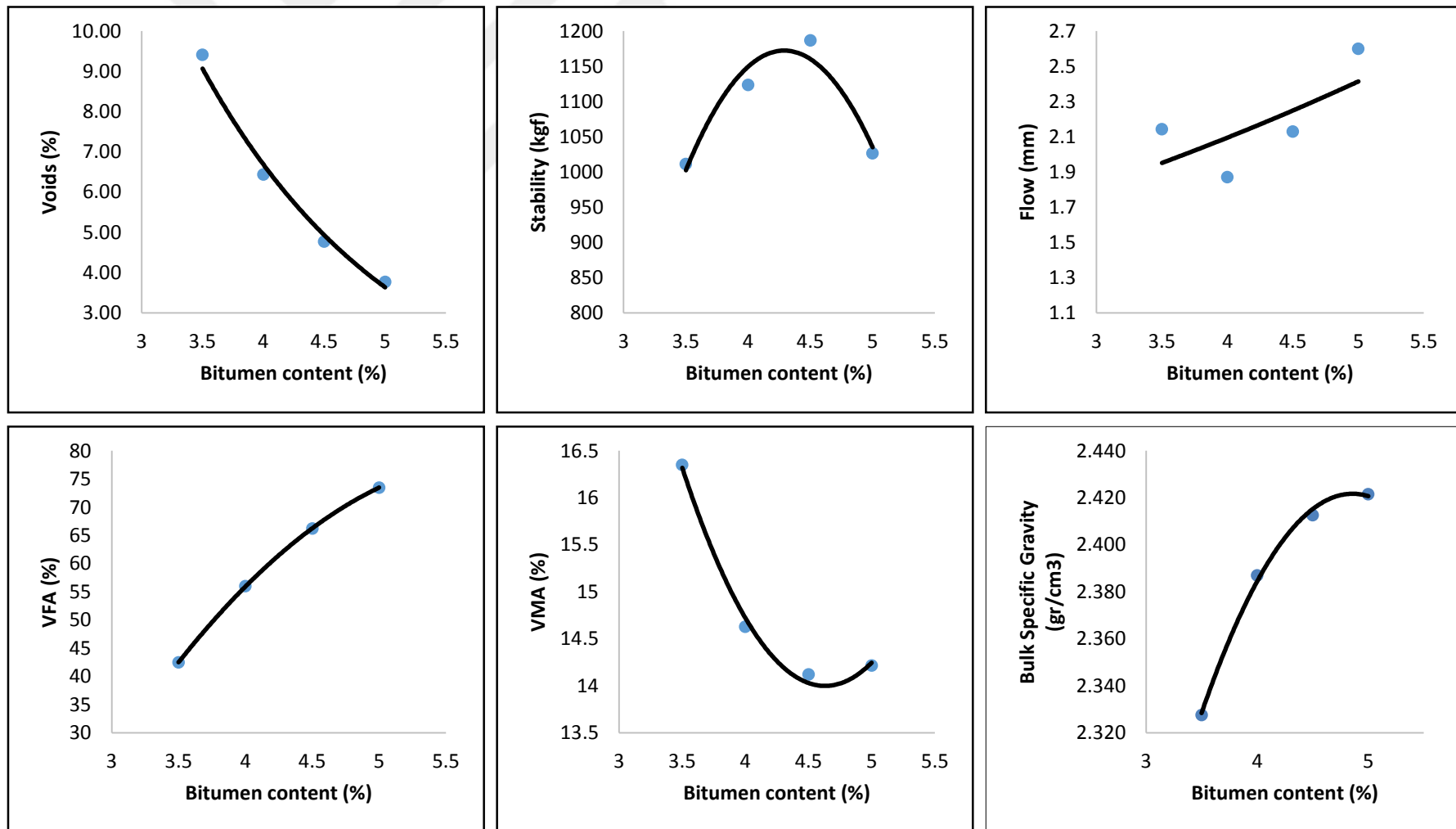


Figure A.2 Marshall mix design graphics for unmodified bitumen (phase angle)

Table A.3 Marshall mix design data for SBS PMB (ASTM)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	62.8	63.0	63.0	62.9	1165.4	676.8	1176.1	499.3	2.334					1.88	1052	1.015	1068
2	3.5	40.25	64.4	64.4	64.4	64.4	1173.1	685.2	1184.3	499.1	2.350					2.03	1158	0.978	1133
3	3.5	40.25	64.4	64.6	64.2	64.4	1174.3	680.0	1180.6	500.6	2.346					2.01	1166	0.978	1140
											2.343	2.571	8.84	15.78	44.0	1.97			1114
4	4	46	62.9	62.5	62.7	62.7	1178.2	683.7	1183.0	499.3	2.360					2.22	1120	1.020	1142
5	4	46	62.6	62.7	62.5	62.6	1184.6	692.6	1192.1	499.5	2.372					2.15	1164	1.023	1191
6	4	46	62.8	62.5	62.8	62.7	1175.6	685.5	1181.2	495.7	2.372					2.12	1066	1.020	1087
											2.368	2.553	7.25	15.32	52.6	2.16			1140
7	4.5	51.75	62.1	62.2	62.2	62.2	1180.0	684.7	1183.5	498.8	2.366					2.29	1220	1.033	1260
8	4.5	51.75	62.3	62.4	62.9	62.5	1179.0	690.6	1182.5	491.9	2.397					2.31	1266	1.025	1298
9	4.5	51.75	62.4	62.1	62.0	62.2	1176.1	686.6	1178.0	491.4	2.393					2.45	1244	1.033	1285
											2.385	2.535	5.92	15.10	60.8	2.35			1281
10	5	57.5	62.9	62.9	62.7	62.8	1186.0	698.9	1187.2	488.3	2.429					2.50	1150	1.018	1171
11	5	57.5	61.1	61.8	61.1	61.3	1185.1	698.0	1188.0	490.0	2.419					2.32	1208	1.059	1279
12	5	57.5	61.5	61.5	61.8	61.6	1183.1	697.5	1184.1	486.6	2.431					2.44	1123	1.049	1178
											2.426	2.518	3.66	14.05	74.0	2.42			1209

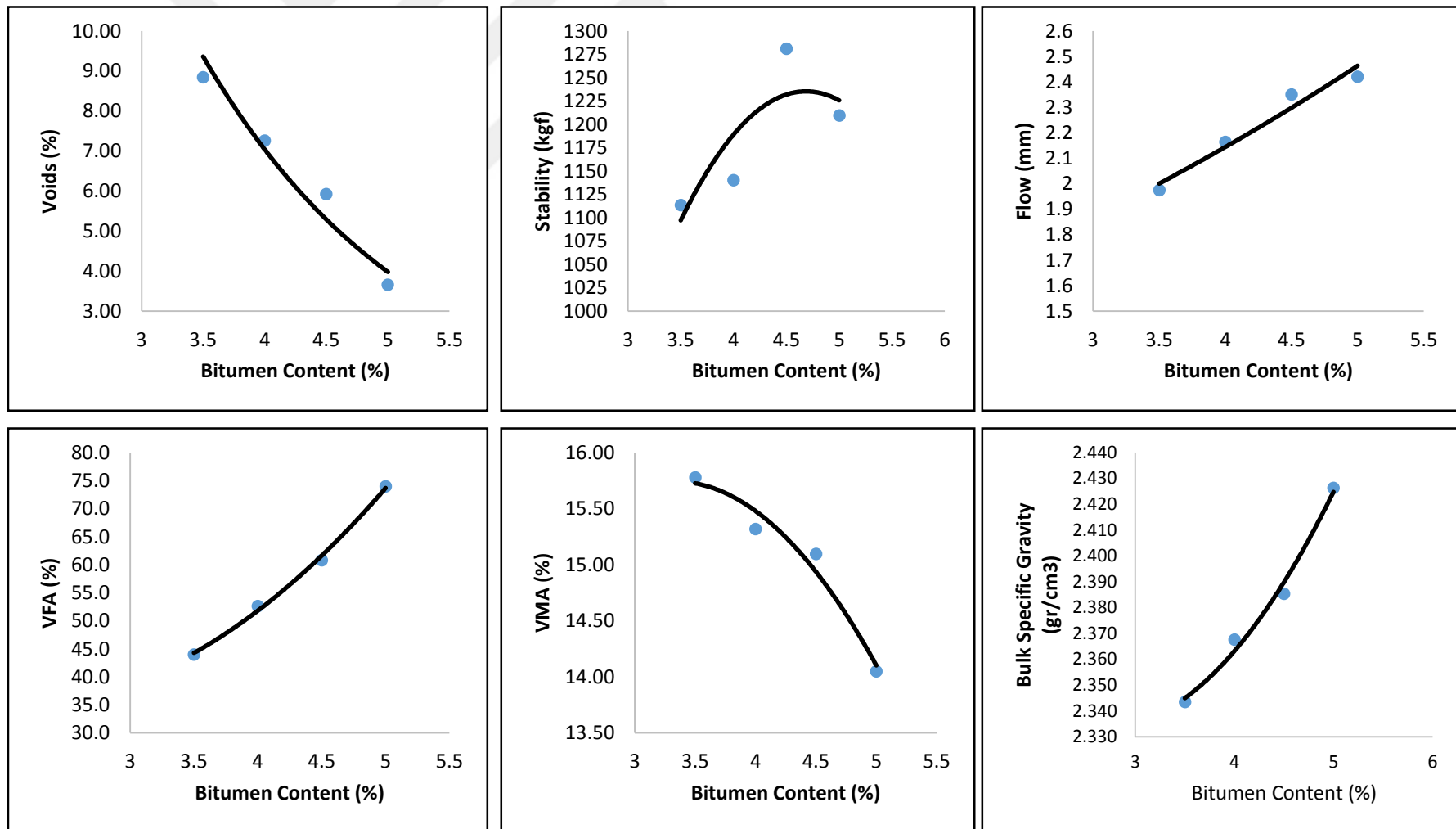


Figure A.3 Marshall mix design graphics for SBS PMB (ASTM)

Table A.4 Marshall mix design data for SBS PMB (ZSV)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	62.2	62.1	62.2	62.2	1176.8	670.5	1180.6	510.1	2.307					1.87	914	1.033	944
2	3.5	40.25	64.9	64.7	65.0	64.9	1173.1	685.2	1184.3	499.1	2.350					2.01	955	0.978	934
3	3.5	40.25	64.4	64.6	64.2	64.4	1174.3	680.0	1180.6	500.6	2.346					2.06	996	0.978	974
											2.334	2.571	9.19	16.10	42.9	1.98			951
4	4	46	64.9	64.7	65.0	64.9	1178.6	683.0	1184.3	501.3	2.351					2.62	1001	0.968	969
5	4	46	62.6	62.7	62.5	62.6	1180.6	688.0	1185.3	497.3	2.374					2.06	977	1.023	999
6	4	46	62.8	62.5	62.8	62.7	1179.4	684.0	1185.3	501.3	2.353					2.16	1020	1.020	1040
											2.359	2.553	7.58	15.62	51.5	2.28			1003
7	4.5	51.75	63.9	63.9	63.2	63.7	1181.0	685.7	1184.5	498.8	2.368					2.08	1064	0.995	1059
8	4.5	51.75	62.3	62.1	62.6	62.3	1180.0	690.6	1183.5	492.9	2.394					2.80	1015	1.030	1045
9	4.5	51.75	62.4	62.1	62.0	62.2	1176.1	686.6	1178.0	491.4	2.393					2.22	1023	1.033	1057
											2.385	2.535	5.93	15.11	60.7	2.37			1054
10	5	57.5	62.6	62.7	62.4	62.6	1185.8	697.1	1186.6	489.5	2.422					2.55	1011	1.023	1034
11	5	57.5	62.8	63.0	63.0	62.9	1187.1	698.8	1188.1	489.3	2.426					2.16	1022	1.015	1037
12	5	57.5	61.5	61.5	61.8	61.6	1183.1	695.5	1184.1	488.6	2.421					2.96	1014	1.049	1064
											2.423	2.518	3.77	14.15	73.4	2.56			1045

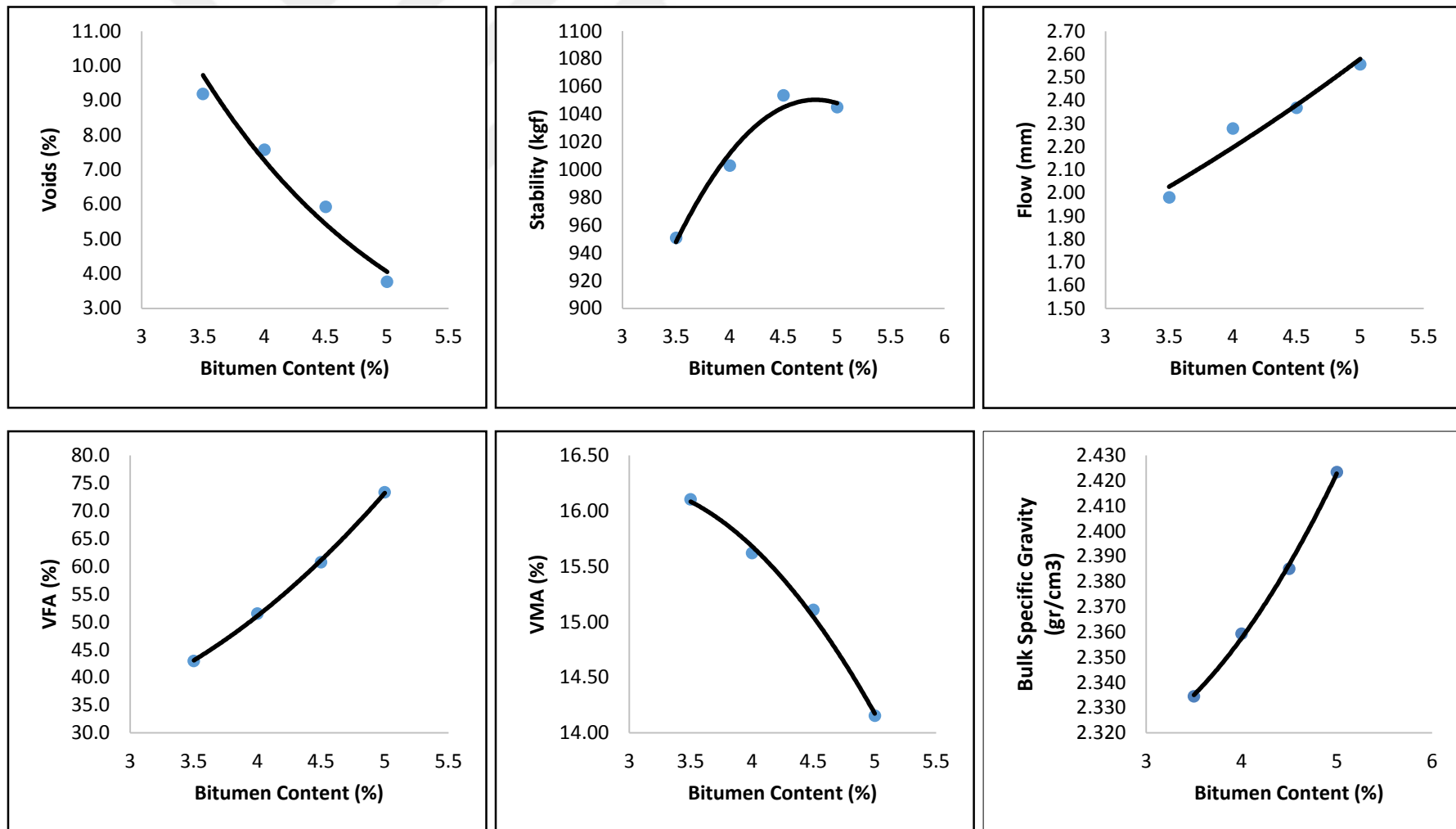


Figure A.4 Marshall mix design graphics for SBS PMB (ZSV)

Table A.5 Marshall mix design data for Elvaloy PMB (ASTM)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	62.5	62.6	62.7	62.6	1175.8	689.6	1197.3	507.7	2.316					2.67	1031	1.023	1055
2	3.5	40.25	62.7	62.4	62.5	62.5	1180.9	691.5	1201.9	510.4	2.314					2.30	980	1.025	1005
3	3.5	40.25	63.1	63.2	63.4	63.2	1169.3	684.4	1186.9	502.5	2.327					2.58	883	1.008	890
											2.319	2.571	9.80	16.66	41.2	2.52			983
4	4	46	63.2	62.9	63.1	63.1	1193.4	690.5	1206.3	515.8	2.314					2.36	1055	1.010	1066
5	4	46	62.9	62.9	62.8	62.9	1175.2	685.4	1184.9	499.5	2.353					2.61	1026	1.015	1041
6	4	46	62.5	62.5	62.4	62.5	1180.3	689.2	1192.0	502.8	2.347					2.39	1098	1.025	1125
											2.338	2.553	8.42	16.38	48.6	2.45			1077
7	4.5	51.75	63.1	62.9	62.8	62.9	1172.6	685.6	1176.4	490.8	2.389					2.62	1181	1.015	1199
8	4.5	51.75	62.5	62.5	62.5	62.5	1189.4	695.2	1191.1	495.9	2.398					2.57	1142	1.025	1171
9	4.5	51.75	63.2	63.1	63.2	63.2	1178.2	688.5	1180.9	492.4	2.393					2.09	1198	1.008	1208
											2.393	2.536	5.61	14.81	62.1	2.43			1192
10	5	57.5	62.5	62.5	62.5	62.5	1199.5	701.2	1200.7	499.5	2.401					2.44	1176	1.025	1205
11	5	57.5	63.1	63.2	63.3	63.2	1183.5	698.2	1184.3	486.1	2.435					2.62	1186	1.008	1195
12	5	57.5	62.9	62.8	61.8	62.5	1176.6	695.5	1177.3	481.8	2.442					3.07	1174	1.025	1203
											2.426	2.519	3.67	14.06	73.9	2.71			1201

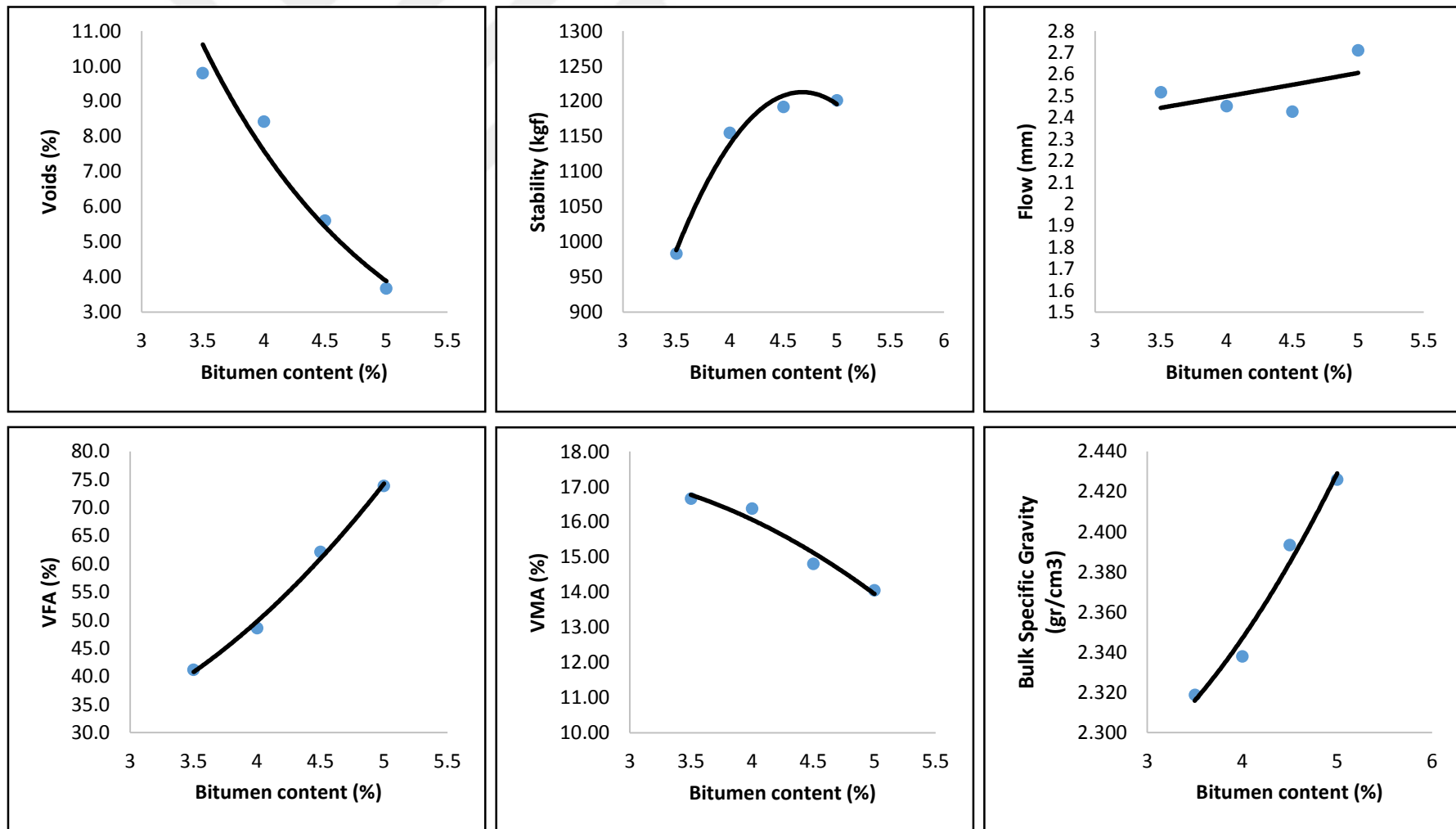


Figure A.5 Marshall mix design graphics for Elvaloy PMB (ASTM)

Table A.6 Marshall mix design data for Elvaloy PMB (ZSV)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	62.6	62.5	62.5	62.5	1173.6	678.2	1185.6	507.4	2.313					2.45	966	1.025	990
2	3.5	40.25	63.2	63.2	63.4	63.3	1178.9	688.3	1196.0	507.7	2.322					1.54	855	1.005	859
3	3.5	40.25	62.9	62.8	61.8	62.5	1180.2	689.6	1189.9	500.3	2.359					2.13	994	1.025	1019
											2.331	2.571	9.32	16.22	42.5	2.04			956
4	4	46	63.1	62.8	63.1	63.0	1184.5	691.2	1193.0	501.8	2.361					2.10	1077	1.013	1091
5	4	46	62.5	62.5	62.5	62.5	1191.6	697.0	1199.1	502.1	2.373					2.07	1125	1.025	1153
6	4	46	63.5	63.3	63.4	63.4	1188.4	692.4	1197.6	505.2	2.352					2.80	1059	1.003	1062
											2.362	2.553	7.48	15.52	51.8	2.32			1102
7	4.5	51.75	63.2	63.1	63.1	63.1	1183.0	690.5	1184.9	494.4	2.393					2.99	1158	1.010	1170
8	4.5	51.75	62.9	62.9	63.0	62.9	1192.7	696.7	1194.4	497.7	2.396					2.63	1133	1.015	1150
9	4.5	51.75	63.2	63.1	63.2	63.2	1188.3	695.0	1190.4	495.4	2.399					2.81	1162	1.008	1171
											2.396	2.536	5.51	14.72	62.6	2.81			1164
10	5	57.5	62.5	62.6	62.7	62.6	1191.3	702.4	1192.2	489.8	2.432					2.63	1103	1.023	1128
11	5	57.5	63.2	63.2	63.3	63.2	1176.5	693.1	1177.3	484.2	2.430					2.43	1106	1.008	1115
12	5	57.5	63.0	63.1	63.0	63.0	1169.6	685.4	1170.9	485.5	2.409					2.27	1112	1.013	1126
											2.424	2.519	3.77	14.14	73.4	2.44			1123

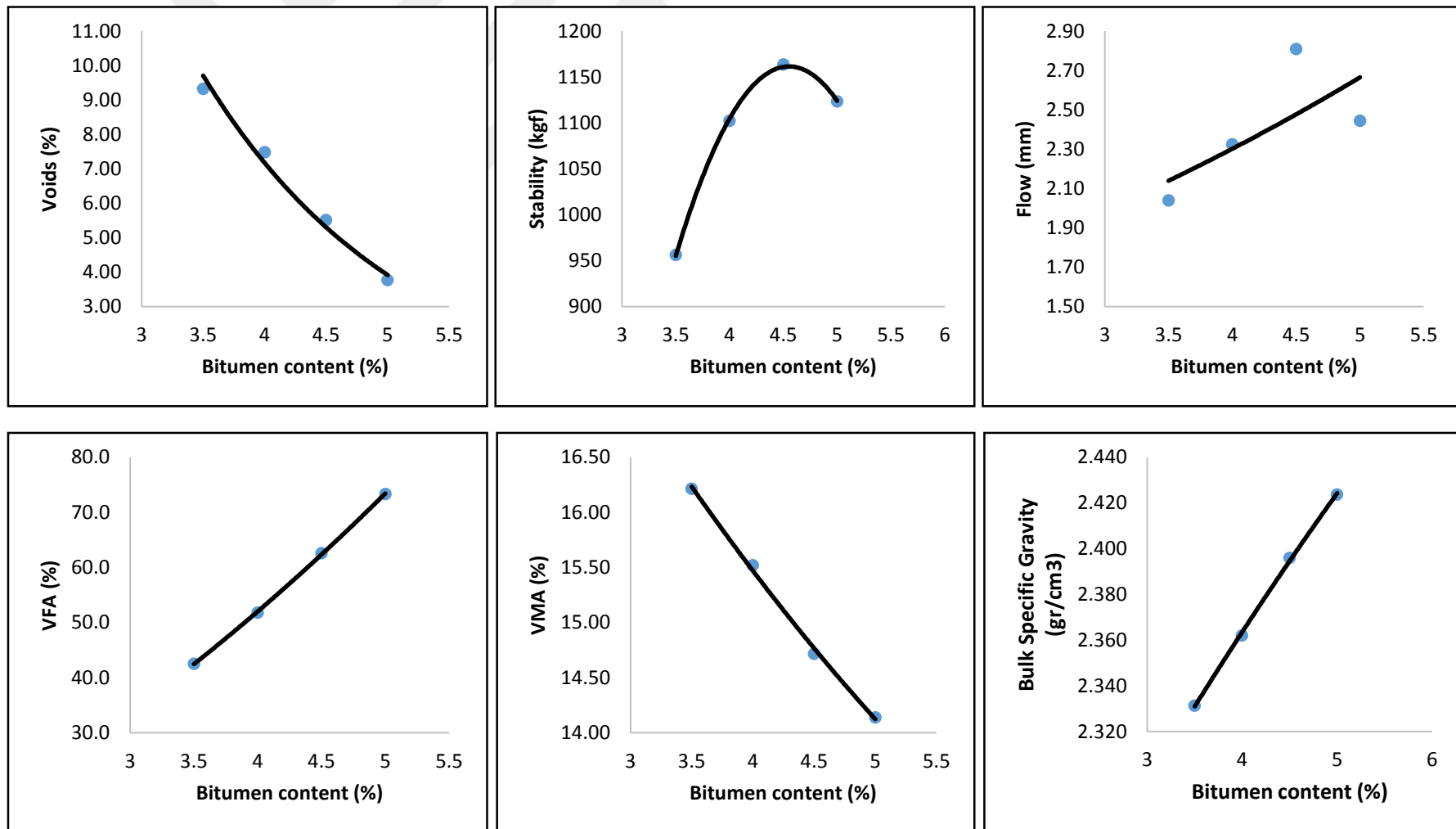


Figure A.6 Marshall mix design graphics for Elvaloy PMB (ZSV)

Table A.7 Marshall mix design data for WMA Organic (Sasobit) (ASTM)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm3)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	63.7	63.5	63.5	63.6	1161.5	677.2	1177.4	500.2	2.322					1.98	988	0.998	986
2	3.5	40.25	62.5	62.7	63.9	63.0	1169.5	678.4	1179.5	501.1	2.334					1.88	1034	1.013	1047
3	3.5	40.25	62.4	62.6	62.5	62.5	1170.5	681.6	1180.2	498.6	2.348					2.01	1101	1.025	1129
											2.335	2.568	9.10	16.10	43.5	1.96			1054
4	4	46	62.5	62.7	62.8	62.7	1176.7	686.3	1183.0	496.7	2.369					1.68	1123	1.020	1145
5	4	46	62.6	62.7	62.7	62.7	1177.9	687.4	1184.6	497.2	2.369					2.39	1064	1.020	1085
6	4	46	62.4	62.4	62.3	62.4	1173.6	685.4	1181.4	496.0	2.366					2.30	1096	1.028	1127
											2.368	2.550	7.14	15.30	53.4	2.12			1119
7	4.5	51.75	62.6	62.3	62.4	62.4	1179.6	695.0	1181.2	486.2	2.426					2.57	1146	1.028	1178
8	4.5	51.75	61.7	61.8	61.6	61.7	1178.1	693.1	1179.5	486.4	2.422					2.09	1231	1.046	1288
9	4.5	51.75	61.9	61.8	61.9	61.9	1176.4	691.0	1179.1	488.1	2.410					2.07	1106	1.040	1150
											2.419	2.532	4.46	13.88	67.9	2.24			1205
10	5	57.5	62.9	62.6	62.4	62.6	1181.2	701.2	1181.6	480.4	2.459					2.70	1028	1.023	1052
11	5	57.5	62.9	62.9	62.9	62.9	1181.3	704.8	1183.1	478.3	2.470					2.13	1155	1.015	1172
12	5	57.5	62.8	62.9	62.7	62.8	1181.4	692.7	1182.3	489.6	2.413					2.35	1234	1.018	1256
											2.447	2.515	2.70	13.31	79.7	2.39			1160

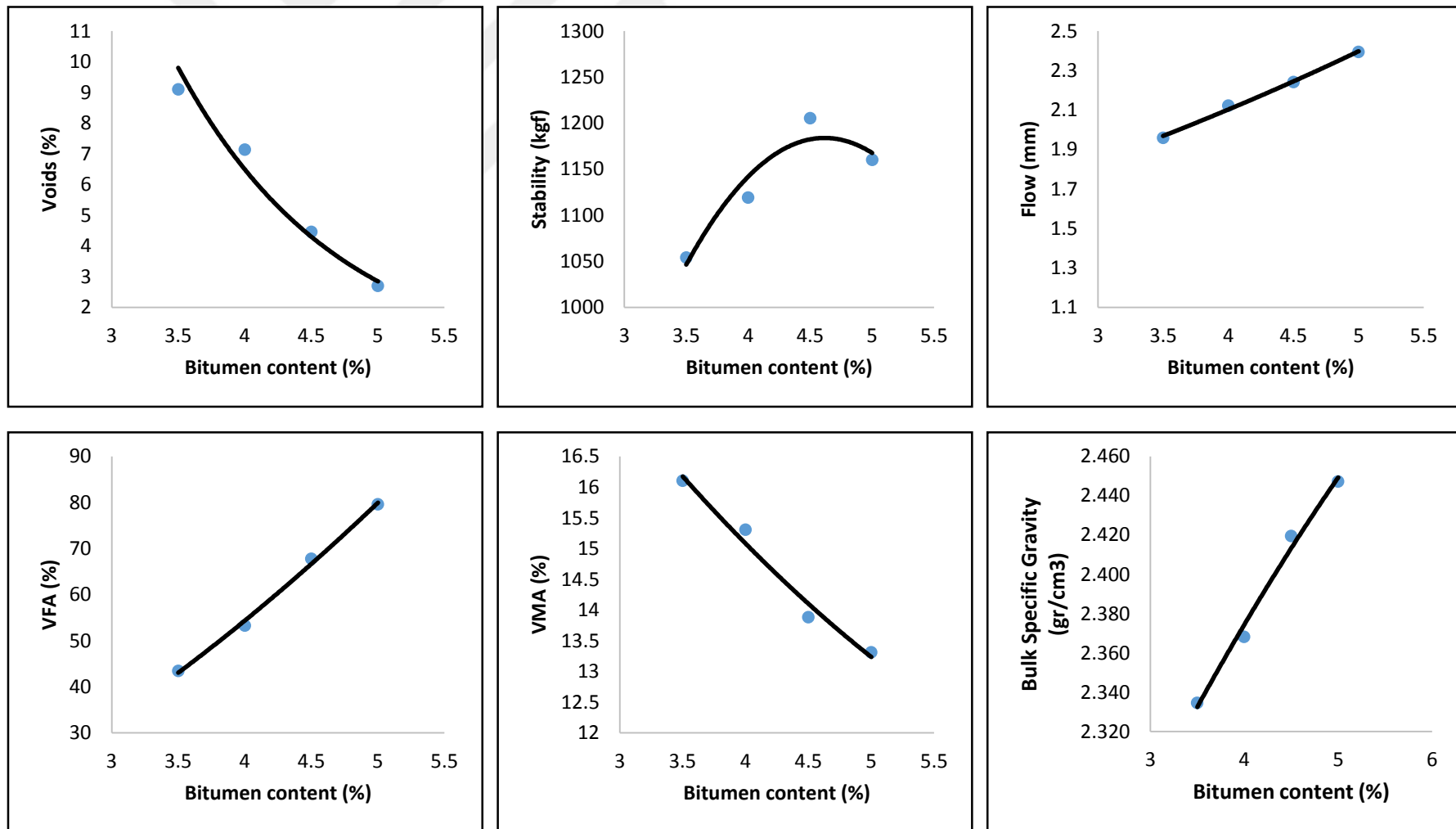


Figure A.7 Marshall mix design graphics for WMA Organic (Sasobit) (ASTM)

Table A.8 Marshall mix design data for WMA Organic (Sasobit) (SSF)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	64.2	64.4	64.1	64.2	1179.5	688.2	1195.0	506.8	2.327					1.63	962	0.983	946
2	3.5	40.25	63.5	63.4	63.7	63.5	1170.4	680.6	1188.2	507.6	2.306					1.96	995	1.000	995
3	3.5	40.25	62.3	62.5	62.6	62.5	1171.1	675.2	1186.3	511.1	2.291					1.93	999	1.025	1024
											2.308	2.568	10.13	17.05	40.6	1.84			988
4	4	46	63.2	63.3	63.2	63.2	1177.7	686.5	1186.4	499.9	2.356					1.50	1055	1.008	1063
5	4	46	63.2	63.5	63.1	63.3	1175.6	688.3	1183.2	494.9	2.375					2.01	1049	1.023	1073
6	4	46	62.8	62.9	62.7	62.8	1173.7	686.4	1185.8	499.4	2.350					2.15	1055	1.018	1074
											2.361	2.550	7.43	15.57	52.3	1.89			1070
7	4.5	51.75	63.2	63.8	63.7	63.6	1178.8	693.6	1181.2	487.6	2.418					2.09	1202	1.005	1208
8	4.5	51.75	62.7	62.7	62.5	62.6	1178.9	692.9	1179.3	486.4	2.424					2.22	1222	1.030	1259
9	4.5	51.75	62.9	62.8	62.7	62.8	1179.1	691.0	1179.9	488.9	2.412					2.35	1211	1.018	1233
											2.418	2.532	4.53	13.94	67.5	2.22			1233
10	5	57.5	61.5	61.3	61.3	61.4	1179.3	699.0	1179.8	480.8	2.453					2.33	1105	1.056	1167
11	5	57.5	62.2	62.2	62.2	62.2	1176.7	695.0	1177.1	482.1	2.441					2.70	940	1.033	971
12	5	57.5	62.3	62.5	62.7	62.5	1180.2	699.4	1180.7	481.3	2.452					2.40	912	1.025	935
											2.449	2.515	2.64	13.26	80.1	2.48			1024

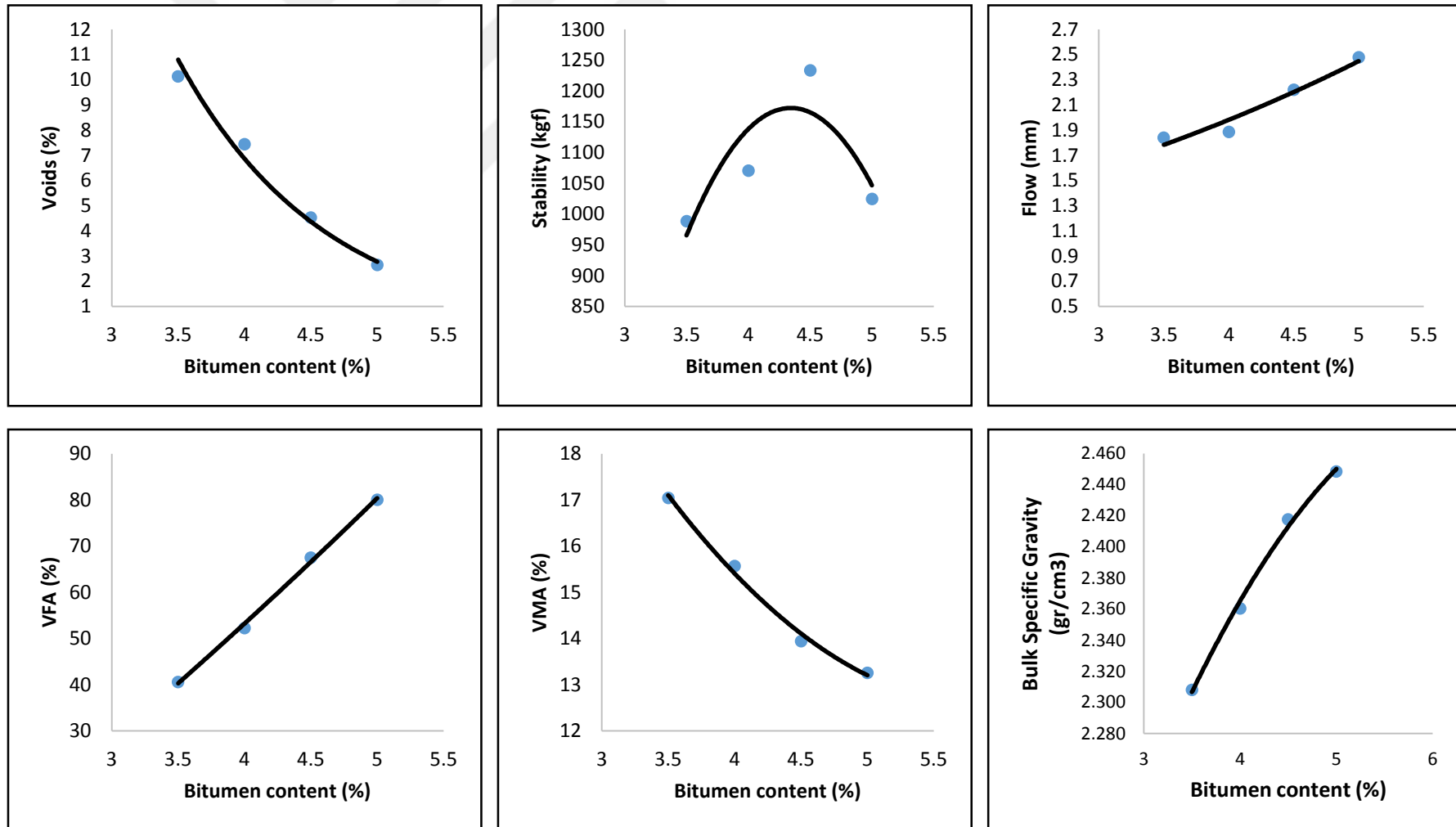


Figure A.8 Marshall mix design graphics for WMA Organic (Sasobit) (SSF)

Table A.9 Marshall mix design data for WMA Chemical (Rediset) (ASTM)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	63.3	63.3	63.0	63.2	1175.2	685.8	1190.3	504.5	2.329					1.49	1022	1.008	1030
2	3.5	40.25	63.4	63.4	63.2	63.3	1173.3	683.9	1188.6	504.7	2.325					1.88	992	1.005	997
3	3.5	40.25	62.5	62.5	62.6	62.5	1172.5	680.5	1188.4	507.9	2.309					2.01	988	1.025	1013
											2.321	2.569	9.64	16.59	41.9	1.79			1013
4	4	46	63.2	63.6	63.4	63.4	1175.6	681.8	1185.7	503.9	2.333					1.63	1154	1.003	1157
5	4	46	62.9	62.8	62.9	62.9	1175.6	681.8	1185.7	503.9	2.333					2.39	1195	1.013	1211
6	4	46	63.1	63.3	63.2	63.2	1175.6	681.8	1185.7	503.9	2.333					2.30	1229	1.008	1239
											2.333	2.551	8.53	16.56	48.5	2.10			1202
7	4.5	51.75	62.0	62.0	62.0	62.0	1186.6	696.1	1188.3	492.2	2.411					1.95	1056	1.038	1096
8	4.5	51.75	63.0	63.0	63.0	63.0	1193.4	705.2	1195.3	490.1	2.435					2.11	1088	1.013	1102
9	4.5	51.75	62.3	62.6	62.5	62.5	1176.4	691.0	1177.0	486.0	2.421					2.07	1106	1.025	1134
											2.422	2.533	4.37	13.78	68.3	2.04			1111
10	5	57.5	61.6	61.6	61.6	61.6	1195.5	704.0	1196.0	492.0	2.430					2.21	1055	1.049	1107
11	5	57.5	63.0	63.3	63.2	63.2	1195.0	706.3	1195.8	489.5	2.441					2.81	1102	1.008	1111
12	5	57.5	62.5	62.5	62.5	62.5	1181.4	701.2	1182.3	481.1	2.456					2.35	1119	1.025	1147
											2.442	2.516	2.91	13.48	78.4	2.46			1121

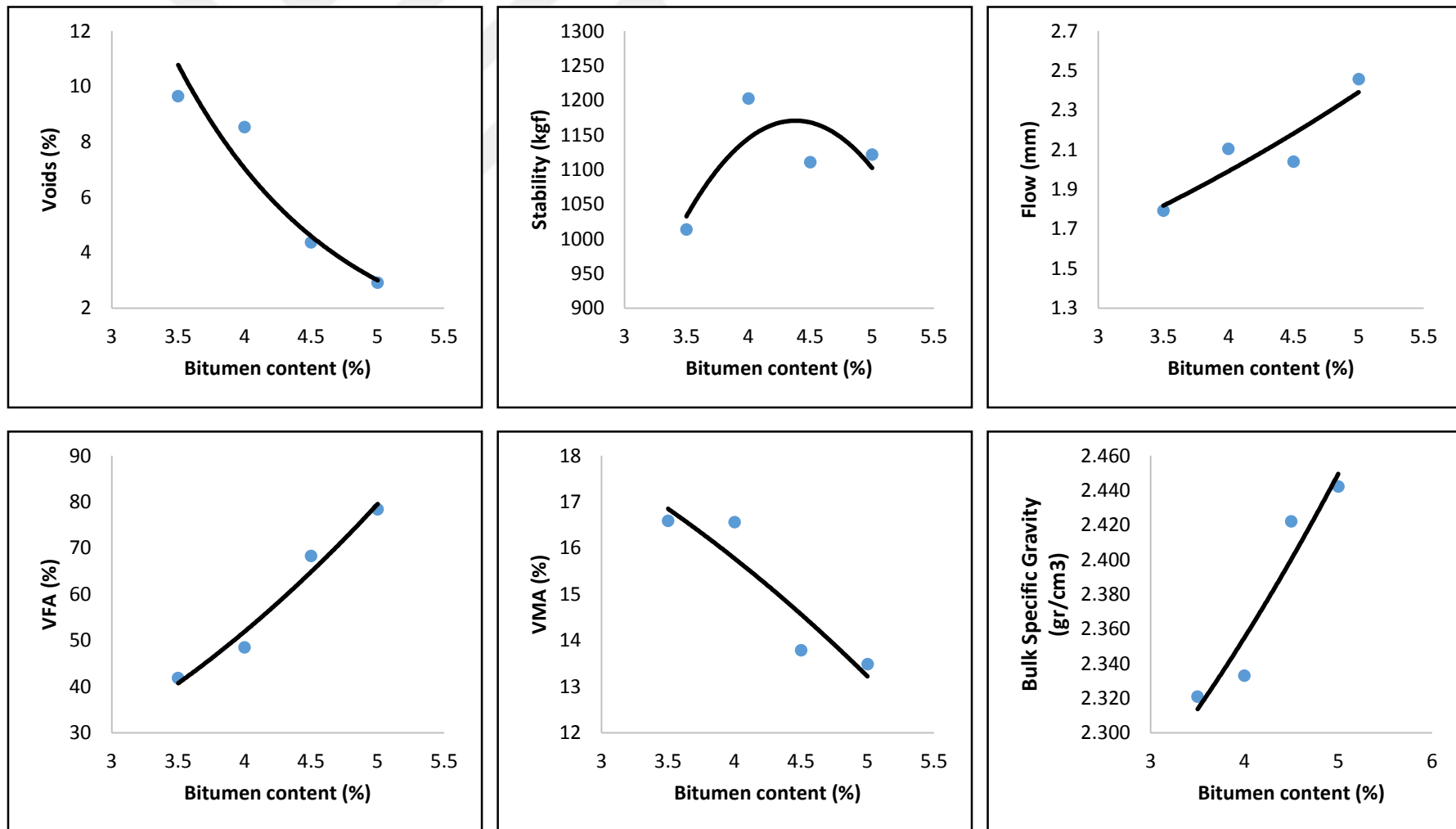


Figure A.9 Marshall mix design graphics for WMA Chemical (Rediset) (ASTM)

Table A.10 Marshall mix design data for WMA Chemical (Rediset) (SSF)

Specimen No.	Bitumen		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity (gr/cm ³)	Max. teo. specific gravity	Voids (%)	V.M.A (%)	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	%	gr.	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	40.25	63.5	63.5	63.5	63.5	1184.6	694.4	1199.7	505.3	2.344					2.01	1035	1.008	1043
2	3.5	40.25	63.4	63.4	63.2	63.3	1174.4	687.8	1181.9	494.1	2.377					1.60	985	1.005	990
3	3.5	40.25	62.5	62.5	62.6	62.5	1184.6	694.4	1199.7	505.3	2.344					1.70	1006	1.025	1031
											2.355	2.569	8.31	15.36	45.9	1.77			1021
4	4	46	63.4	63.2	63.6	63.4	1184.7	690.3	1192.8	502.5	2.358					2.10	985	1.003	988
5	4	46	62.9	62.8	62.9	62.9	1180.2	690.5	1185.6	495.1	2.384					1.95	1045	1.013	1059
6	4	46	63.1	63.3	63.2	63.2	1175.5	688.6	1179.8	491.2	2.393					2.20	1029	1.008	1037
											2.378	2.551	6.76	14.94	54.8	2.08			1028
7	4.5	51.75	61.9	61.8	61.6	61.8	1187.2	696.2	1188.8	492.6	2.410					2.16	975	1.038	1012
8	4.5	51.75	63.5	63.6	63.3	63.5	1190.1	697.6	1191.5	493.9	2.410					2.20	995	1.013	1008
9	4.5	51.75	62.3	62.6	62.5	62.5	1178.9	691.0	1180.1	489.1	2.410					2.15	1028	1.025	1054
											2.410	2.533	4.85	14.22	65.9	2.17			1025
10	5	57.5	61.8	61.9	61.6	61.8	1192.3	702.5	1193.2	490.7	2.430					2.22	1005	1.049	1054
11	5	57.5	62.6	62.7	62.6	62.6	1195.2	706.2	1196.5	490.3	2.438					2.31	821	1.008	828
12	5	57.5	62.5	62.5	62.5	62.5	1181.4	701.2	1182.3	481.1	2.456					2.14	997	1.025	1022
											2.441	2.516	2.96	13.53	78.1	2.22			968

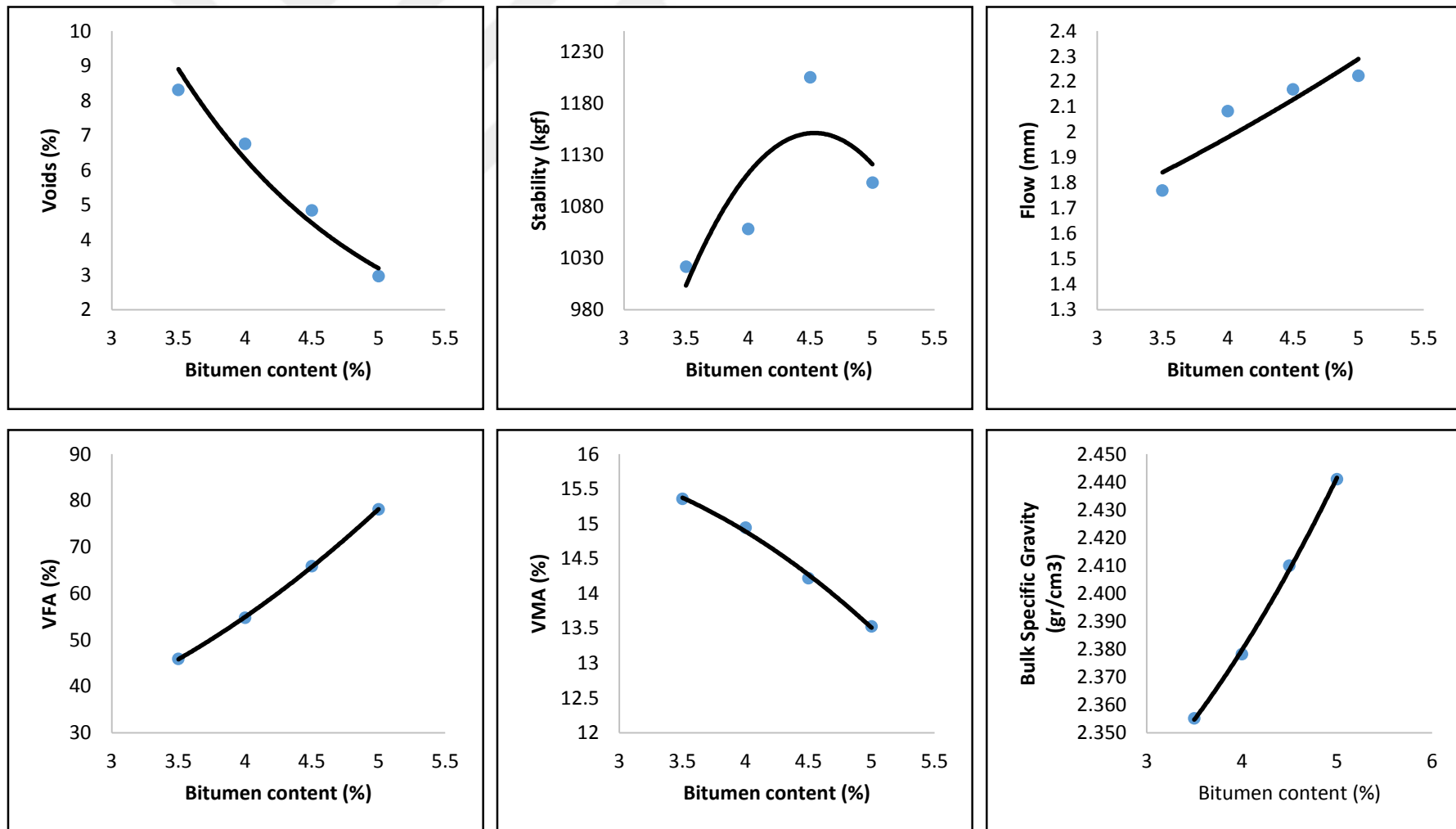


Figure A.10 Marshall mix design graphics for WMA Chemical (Rediset) (SSF)