DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

EFFECTS OF WARM MIX ASPHALT ADDITIVES ON AGING CHARACTERISTICS OF BITUMINOUS MIXTURES

by
Peyman AGHAZADEH DOKANDARI

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EFFECTS OF WARM MIX ASPHALT ADDITIVES ON AGING CHARACTERISTICS OF BITUMINOUS MIXTURES

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We have read the thesis entitled "**EFFECTS OF WARM MIX ASPHALT ADDITIVES ON AGING CHARACTERISTICS OF BITUMINOUS MIXTURES**" completed by **PEYMAN AGHAZADEH DOKANDARI** under supervision of **Assoc. Prof. Dr. Ali TOPAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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EFFECTS OF WARM MIX ASPHALT ADDITIVES ON AGING CHARACTERISTICS OF BITUMINOUS MIXTURES

ABSTRACT

Since the utilization of Warm Mix Asphalt (WMA) technology is increasing rapidly around the world, it's commonly believed that there are some unknown characteristics of this technology which should be investigated more sensibly. As most of the field practices of this technology have been applied recently, there is nearly no chance to evaluate long-term characteristics of existing WMA pavements practically.

Within the scope of this study, short- and long-term aging conditions were applied to mixtures prepared with various contents of four different WMA additives as well as to control specimens with no additive content. WMA additives, which were distinctly assessed in this study, are Sasobit and Rediset WMX as non-foaming granular additives; moreover Advera and Natural Zeolite both in powder form as foaming additives, respectively. To estimate the proportion of hardening of WMA mixtures containing different types of additives, Indirect Tensile Strength (ITS) of both short- and long-term aged specimens were determined as well as of un-aged specimens. Based on relative aging indices (as the ratio of ITS results of aged specimens to ITS results of un-aged specimens), comparisons were made between four WMA additives to assess their effect on aging characteristics of mixtures. The defined Aging Index (AI) for each WMA additive can give us an evaluation capability to predict how a WMA pavement would be subjected to damages during service life of a pavement in comparison to a Hot Mix Asphalt (HMA) pavement.

The results showed that aging indices for WMA technologies are rather less than the index for HMA mixture. The defined aging index is a relative parameter; the less aging index of a mixture is the better that mixture is in terms of aging characteristics. Rediset® WMX represented the least aging index. Sasobit performed nearly similar to Rediset WMX. Foaming additives including Advera and natural zeolite represented relatively weak aging strengths.

Keywords : Warm mix asphalt; Sasobit; Rediset WMX; Advera WMA; natural zeolite; short term aging; long term aging; indirect tensile strength;

ILIK KARIŞIM ASFALT KATKILARIN BİTÜMLÜ KARIŞIMLARIN YAŞLANMASI ÜZERİNDEKİ ETKİLERİ

ÖZ

Günümüzde dünya genelinde Ilık Karışım Asfalt (IKA) teknolojisinin kullanımı hızla artmaktadır. Bu nedenle, IKA teknolojisinin belirlenmemiş bazı yönleri ve özelliklerinin ortaya çıkarılması gerekmektedir. Henüz bu alandaki uygulama ve araştırmalar yeni olduğundan, mevcut IKA katkılı kaplamaların pratikte uzun vadeli özelliklerini değerlendirmek henüz tam olarak mümkün olamamaktadır.

Bu çalışma kapsamında, laboratuvarda kısa ve uzun dönem yaşlanma koşullarına tabi tutularak değişik içeriklerde dört farklı IKA katkılı karışım hazırlanmıştır. Bununla birlikte, hiçbir katkı maddesi içeriğine sahip olmayan numuneler de kontrol amaçlı hazırlanmıştır. Bu tezde değerlendirilen katkılar, Sasobit (organik katkı) ve Rediset WMX (kimyasal katkı) gibi granüler katkılar ile bunların yanında toz halinde olan Advera WMA ve doğal zeolit gibi köpüklendirme yöntemi içerisinde değerlendirilen katkılardır. Sertleşme oranlarının değerlendirilebilmesi için yaşlandırılmamış, kısa dönem yaşlandırılımış ve uzun dönem yaşlandırılmış farklı katkılar içeren IKA numuneleri üzerinde indirekt çekme deneyi uygulanmıştır. Kısa ve uzun dönem yaşlandırılmış numunelerin indirekt çekme mukavemeti (ITS) değerleri ile yaşlandırılmamış kontrol numunelerinin ITS değerleri arasındaki oran yaşlanma indeksi olarak hesaplanmıştır. Elde edilen yaşlanma indekslerine göre, dört farklı IKA katkısının, karışımdaki yaşlanma özellikleri üzerine etkisi değerlendirilmiştir. Her bir IKA katkısı için hesaplanan yaşlanma indeksi, o katkının kaplamanın servis ömrü boyunca, yaşlanmaya bağlı bozulmalara karşı gösterdiği davranış özelliklerinin belirlenmesinde yardımcı olmaktadır.

Elde edilen sonuçlara göre, IKA katkılar ile hazırlanan karışımların yaşlanma indeksleri, sıcak karışım asfaltlara göre daha düşüktür. Tanımlanan yaşlanma indeksine göreceli bir değer olup, bitümlü karışımlardaki yaşlanma indeksi ne kadar düşük ise, yaşlanmaya karşı dayanımın o kadar yüksek olduğunu ifade eder.

Kimyasal IKA katkısı olan Rediset WMX'in, diğer IKA katkılarla karşılaştırıldığında, en düşük yaşlanma indeksine sahip olduğu belirlenmiştir. Benzer açıdan, organik IKA katkısı olan Sasobit'in Rediset WMX ile yakın davranış gösterdiği tespit edilmiştir. Advera WMA ve doğal zeolit gibi köpüklendirme yöntemlerinin, yaşlanmaya karşı nisbeten daha az direnç gösterebildikleri belirlenmiştir.

Anahtar Sözcükler: Ilık karışım asfalt; Sasobit; Rediset WMX; Advera; doğal zeolit; kısa dönem yaşlanma; uzun dönem yaşlanma; indirekt çekme mukavemeti;

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CHAPTER ONE
INTRODUCTION

1.1 Brief History

Most of the field pavement practices around the world consist of the conventional Hot Mix Asphalt (HMA). For last decade, implementing of WMA technologies has gained popularity in Europe and some other countries as well as in the United States of America. The idea of adding an additive to bitumen in order to lower mixing temperature goes back to the fifties where sulfur modified mixes were prepared to reduce application temperature and bitumen content. Sulfur modified asphalts lost popularity as the emissions rate was so high and hazardous. On the other hand, there was another attempt to produce asphalt by foaming with water steam in 1956 in the US. Since that time, foaming technology has been used generally in asphalt mixtures. WAM-Foam (a foaming technology introduced by Shell Bitumen) has been used in Germany and in other sides of Europe. Beside these, for the last decades, wax additives have been used for achieving desired workability especially in Germany. The first WMA field practice was carried out in 1999 in the US. Since then, various new technologies (such as the technologies discussed in chapter four) have been introduced to the market.

1.2 Aims and Scope of the Research

This dissertation aims to assess the aging properties of bitumen involving WMA additives which are popular in Europe such as Sasobit® (organic additive), Rediset® WMX (chemical additive) and Advera® WMA (synthetic zeolite). Besides, to analyze and introduce a new kind of natural WMA additive, a project (TÜBİTAK MAG No.110M567) under the supervision of The Scientific and Technological Research Council of Turkey has been started since April 2011. This M.Sc. thesis is a part of the TÜBİTAK project aiming to search the above mentioned WMA technologies.

In this research, mixture aging indices related to WMA additives have been calculated using Indirect Tensile Strength (ITS) values. To obtain aging indices, WMA mixtures have been prepared using various percentages of four different additives. Mixtures have been subjected to aging procedure in accordance to AASHTO R30 standard. Aging indices were then calculated based on the ratio of ITS test results conducted on aged and un-aged specimens. The results have also been compared with the aging indices related to HMA specimens.

CHAPTER TWO
FAILURES AND AGING PROPERTIES OF ASPHALT PAVEMENTS

Independent of how well an asphalt concrete would be prepared and applied, distresses may appear during the service life of a pavement. Traffic loads, environmental conditions and many other reasons may cause distresses in asphalt concrete. Aging characteristics of an asphalt pavement play vital role in occurring of the failures. An asphalt pavement which is more resistant to aging is less likely to many failures.

2.1 Failures

Many types of failures have been defined for an asphalt pavement. These failures may be occurred due to many reasons. Failures can be categorized based on the reasons of happening. The main asphalt pavement failures can be described as follows:

2.1.1 Permanent Deformation

Permanent deformation best known as rutting is one of the major distresses of asphalt concretes. Rutting is simply surface depression in the wheel path. Rutting may be caused by several reasons such as unstable HMA, densification of HMA and settlement in subgrade (Fwa, 2006). Rutting may causes several inconveniences such as vehicle hydroplaning and pulling vehicles toward ruts. Figure 2.1 shows a typical rutting.

To prevent rutting, sufficient compaction of the layers should be applied exactly. Beside of this, pavement design especially in terms of drainage ability and layers thickness should be adequate. Mix design should also be the right design for the pavement case.

Figure 2.1 Rutting (Fwa, 2006)

Rutting typically occurs during the summer times under higher temperatures. This might be considered that rutting would be solely a bitumen problem, but it is more correct to indicate that rutting is the problem of the mixture and the structure (Asphalt Institute, 1995).

2.1.2 Fatigue Cracking

Fatigue cracks also known as alligator cracks because of their special shape are series of longitudinal and interconnected cracks mainly caused by repeated loads. These cracks normally initiate as short longitudinal cracks in the wheel path developing to an alligator pattern (Fwa, 2006).

Since the alligator cracks occur due to repeated traffic loads, there should be a distinctive care about traffic loads repetition during design process. On the other hand, when determining the mix design of the pavement, tensile stresses should be considered carefully. Figure 2.2 demonstrates an advanced stage of fatigue cracking.

Figure 2.2 Advanced stage of fatigue cracking (Fwa, 2006)

2.1.3 Thermal Cracking

Thermal cracking also called low temperature cracking or transverse cracking due to its transversal shape, is a type of pavement distress that occur as the temperature decreases in adverse environmental conditions. Since the asphalt concrete is strained from movement owing to the friction with underlying films, tensile stresses progress within the material. In case that these stresses exceed the tensile strength of the mixture, cracks start progressing in the transverse direction (Fwa, 2006). A typical thermal cracking has been shown in figure 2.3.

Figure 2.3 Thermal cracking (Fwa, 2006)

The width of the cracks may differ in different seasons. Depend on the width of the cracks; moisture infiltration may occur within the cracks. Thermal cracks also cause in inconvenience due to roughness while driving (Fwa, 2006).

2.1.4 Moisture Susceptibility

Moisture can be described as the first factor of distress in asphalt concrete. Asphalt concrete may be deemed at risk to water if the bitumen-to-aggregate adhesion deteriorates in the existence of water or water vapor (Hicks, 1991).

Moisture susceptibility is a complicated event. It is hard to say with confidence whether a specific feature will be the overriding issue in determining moisture susceptibility. Normally, moisture susceptibility is increased when moisture content raises in the mixture, This phenomenon reduces the bond between bitumen and aggregate surface or actually scours the bitumen (McGennis, Kennedy, & Machemehl, 1984). Moisture damage eventually results in loss of performance in asphalt concretes.

To prevent moisture induced damage, it is suggested to use good aggregates. In addition to this, aggregates and the bitumen should provide the bond needed. Many studies also present some additives which are helpful in terms of anti-stripping. Drainage conditions should be designed carefully as well. During application period mixing temperature must be concerned and there should be a distinctive care about adding completely dried aggregates. Initial objections on the WMA mixtures were that the aggregates are not heated enough to overcome moisture problems. Recent studies show that WMA pavements present enough strength against moisture induced damages as well as the HMA pavements (Kim, Zhang, & Ban, 2012).

2.2 Aging of Bitumen

The durability of asphalt concrete is a measure of its level of resistance to hardening (also called aging) over time. Generally, when bitumen ages, it becomes more brittle and harder. Beside this, the viscosity of aged bitumen is higher than virgin bitumen. Durability plays a considerable role on asphalt concrete mixture performance and considerably changes the other qualities (e.g. rutting and fatigue). Bitumen content and air voids are significant factors in control of durability. The main factors of aging can simply be described as follows (Pavement Interactive, 2012a; Allerga, Monismith, & Granthem, 1957):

- **Oxidation:** Is the reaction between bitumen and oxygen gas.

- **Volatilization:** Is the evaporation of the less heavy components of the bitumen over time. It is mostly due to temperature and happens mainly during mixing process.

- **Polymerization:** is the process of combining monomers together in a chemical reaction to form polymer chains. These chains are considered to cause a progressive hardening.

- **Thixotropy:** is the property of the bitumen when it sets where not physically disturbed or set in motion. In bitumen, thixotropy is assumed to be a consequence of hydrophilic suspended particles that form a lattice structure. This triggers an increase in viscosity and therefore, hardening (Exxon Company, 1997). This phenomenon can somewhat be reversible by heat and agitation. Roads with less traffic loads are largely at risk of thixotropy.

- **Syneresis:** can be defined as the separation of less viscous liquids from the more viscous liquids throughout the bitumen. This may cause hardening in the asphalt mixture. Due to either physical or chemical changes, shrinkage or rearrangement of the bitumen occurs in this case. Syneresis is considered to be a kind of bleeding distress (Exxon Company, 1997).

- **Separation:** is the absorption of the oily components, resins or asphaltenes from the bitumen by some aggregates with high level of porosity. This causes the bitumen hardening due to less oily components.

Aging is mainly contains of two components. First component is mainly associated with loss of volatilization in asphalt during the construction and mixing phase also called short-term aging, and the second component which is associated with gradual oxidation of the in-place material in the field called long-term aging (Bell, 1989).

2.3 Aging Simulation of Bitumen

Promising methods for laboratory simulating of asphalt concretes should consider short-term aging simulation conditions as well as the long-term aging conditions. Most simulation methods such as Thin Film Oven Test (TFOT), Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV) test try to subject bitumen itself to aging conditions whereas some methods subject mixture to aging conditions as AASHTO R 30 (Standard Practice for Mixture Conditioning of Hot Mix Asphalt) Method. Brief principles and test procedures for these methods are as follows:

2.3.1 Thin Film Oven Test (TFOT)

Welborn (1984), mentions Dow (1903), representing the use of an early extended heating test. Years later, Lewis and Welbom (1940), introduced the TFOT for making comparison between asphalts in terms of aging characteristics. Further work was described by Lewis and Halstead (1946). This test is a simulation of short-term aging process.

In initial practices of this test, a 50 ml of asphalt sample was heated in a 3 mm film inside a 140 mm diameter flat container for 5 hrs. at 163°C. AASHTO (American Association of State Highway and Transportation Officials, 2009a) and ASTM (American Society for Testing and Materials., 2009) then adopted this test as an aging simulation. Residue of the aged bitumen then is tested for penetration, softening point and ductility (Bell, 1989). Loss in mass is also calculated after test by weighing sample residue.

2.3.2 Rolling Thin Film Oven Test (RTFOT)

The California division of highways developed this test as an improvement to the TFOT in order to age bitumen in thinner films than the 3mm which is used in TFOT (Bell, 1989). Like TFOT, the RTFOT aging method is also used for simulating aging during mixing and placement (Short-term aging).

Hveem, Zube, and Skog (1963) adjusted the procedure for this test. 35 grams of un-aged bitumen is located in a cylindrical specific glassy bottle, which is then placed in a carousel inside the RTFOT device. This helps bitumen thickness to decrease to 1.25 mm in comparison with TFOT. The oven is heated to 163°C and the carrousel continues rotating for 85 minutes at 15 rpm rate. The carousel rotation continuously exposures new bitumen to the heat and air blown by a compressor (Bell, 1989). This test is adopted by both AASHTO and ASTM.

Samples residues are then tested for conventional bitumen tests such as penetration, viscosity, softening point and ductility to evaluate the effect of aging characteristics and to gain aging indices. Mass loss should also be calculated after extruding bottles from RTFOT oven. For further investigation, sample residues can be tested for Pressure Aging Vessel (PAV) to investigate long-term aging characteristics of the sample.

2.3.3 Pressure Aging Vessel (PAV) Test

This test is used for long-term aging simulation. Bitumen sample is then ready for Physical characteristics test. Heat and pressure are the conditions applied to bitumen sample to simulate aging during service life of the pavement. Bitumen sample residue of RTFOT which has been subjected to short-term aging is taken by PAV. Test procedure contains placing sample inside a steel pan and heated inside pressurized (305 psi) vessel to apply aging. This test has been adopted by AASHTO and the details can be found in AASHTO R 28.

2.4 Aging of Bituminous Mixture (AASHTO R 30)

AASHTO has associated a standard for simulation aging on asphalt mixtures. As stated before, other simulation methods take bitumen samples to perform aging conditions on them. This standard takes bitumen – aggregate mixtures for further short- and long-term aging processes. Performance tests which take compacted Marshall or Gyratory compactor specimens can be applied after aging process.

Within the scope of this study, AASHTO R 30 conditioning method has been used to simulate short- and long-term aging in asphalt mixtures. Although this standard has been adopted for HMA mixtures, the same principles have been adopted for WMA mixtures as well due to lack of a standard for mixture conditioning of WMA mixtures. As the mixing and compacting temperatures are lower in WMA mixtures in comparison with HMA mixtures, it can be expected even low aging effects in field practices.

Brief instruction for this standard (for samples intended to be compacted with Marshall compactor) is as follows:

- For short-term aging simulation, asphalt mixtures is placed in a pan (in loose mix state) and spread to an even thickness ranging between 25 to 50 mm, and then the pan is placed inside a forced-draft oven set for 135°C for 4 h ± 5 minutes. The mix should be stirred every hour for providing a uniform conditioning. Mixture is then ready for compaction and curing process.

- For long-term aging simulation, short-term aging process should be done before. After compaction step, specimens should be cooled in an oven set for 60°C. Cooling may approximately take 2 h for appropriate sized specimens. Then the specimens are cooled in room temperature for 16 h. after extruding from mold, specimens are placed in an oven set for 85 ± 1°C for 120 ± 0.5 h. after this period, the oven should be turned off and the specimens are allowed to cool in room temperature inside the opened door oven. Cooling may take approximately 16 h.

2.5 Evaluation of Aging Behavior of Bitumen and Bituminous Mixture

There are significant differences between the behaviors of a virgin bitumen and an aged one. This is also true for a new asphalt pavement and a pavement aged during service life. Distresses in an asphalt pavement gain rate as the asphalt ages. The more the asphalt concrete ages the higher it is likely for pavement distresses. To evaluate aging characteristics of bitumen or an asphalt concrete, conventional performance tests can be used. Although many of these tests results may show differences due to aging, some tests can give us more proper evaluation as these tests results are affected by aging more. Normally, aged bitumen can be tested for a set of tests including Penetration, Softening Point, Rotational Viscosity (RV), Ductility, Bending Beam Rheometer (BBR) and Direct Tension Test (DTT) (Pavement Interactive, 2012b). Each test is used to evaluate a specific characteristic of the bitumen after being aged. Rather than bitumen conventional test, BBR and DTT for instance, are used to investigate low temperature cracking behavior of the bitumen.

As indicated in the first chapter, this study is a part of the TÜBİTAK MAG project No.110M567. The following sections contain brief explanations of three tests and their importance which are used within the scope of the mentioned research project. These tests are more applied on aged samples in order to investigate aging characterization of bitumen and bituminous mixtures.

2.5.1 Rotational Viscosity

Brookfield rotational viscometer is the most common device that is used to determine bitumen viscosity. The temperature range for this test is between 135°C and 165°C which is acceptable temperature range for mixing and compaction of the asphalt-aggregate mixtures (National Cooperative Highway Research Program., 2010). The Rotational Viscosity test helps to certify if the bitumen viscosity is sufficient for pumping and mixing or not (Roberts, Brown, & Kennedy, 1996). The graphics for viscosities vs. temperature are then plotted. acceptable temperature for mixing is range matching 0.17±0.02 Pa.s and acceptable temperature for compaction is range matching 0.28±0.03 Pa.s (NCHRP, 1996).

As the bitumen ages, it becomes stiffer, therefore the viscosity of an aged bitumen is rather more than the viscosity of a virgin bitumen in a specific temperature. ASTM (1973), presented the aging index as the ratio of the viscosity of the bitumen after aging to the viscosity of the bitumen before aging process. Although this index doesn't consider the conditions of mixing but it gives us a good evaluating index.

2.5.2 Dynamic Shear Rheometer (DSR)

Asphalt is a viscoelastic material. It means that asphalt can behave like an elastic solid in certain conditions and like a viscos liquid in some other conditions. In terms of rheology, DSR is a device which is capable of characterizing rheological behavior of bitumen samples in different temperatures. This characterization is used in the Performance Grading (PG) bitumens. The device can measure a bitumen sample's complex shear modulus (G*) and phase angle (δ). Complex shear modulus (G*) is the resistance of the sample to resulting shear strain when subjecting to repeatedly shear stress. Since the phase angle (δ) is the interval between the strain caused by shear stress and the shear stress itself. The phase angle (δ) value for purely elastic materials is 0° since this value is 90° for purely viscous materials. This means that the higher the phase angle (δ), the more viscous the material (Pavement Interactive, 2012c).

DSR uses a thin bitumen sample, sandwiching it between two circular steel plates. To create shearing, the upper plate oscillates across the sample which is placed on the fixed upper plate.

DSR test can be conducted on un-aged and aged (by TFOT, RTFOT & PAV) samples. Aged samples show different rheological behavior in comparison with un-aged samples since they have become stiffer during aging time. The complex shear modulus (G*) and the phase angle (δ) values for an aged sample, help us understand how an asphalt concrete may behave after being aged during service life of the pavement. This helps us in predicting rutting and fatigue cracking of asphalt concretes.

Within the scope of the TÜBİTAK MAG No.110M567, rheological characteristics of WMA bitumen samples with various amounts of four different additives (Sasobit®, Rediset® WMX, Advera® WMA and Natural Zeolite) have been investigated using DSR test device. This dissertation doesn’t contain the DSR test results as it has been considered to assess aging characteristics of the WMA mixtures.

2.5.3 Indirect Tensile Test (IDT)

IDT can be used to define the creep compliances and the ITS of asphalt mixtures at low and normal temperatures. The ITS results can give us worthy evaluation keys in low temperature and fatigue cracking of asphalt pavements. Some studies introduce ITS result as a good indicator in predicting laboratory rutting potential of asphalt mixtures (Anderson, Christensen, & Bonaquist, 2003). This test is widely used in investigation of moisture induced damages of bituminous mixtures. AASHTO has associated a standard for assessment of moisture susceptibility of asphalt mixtures using ITS test results (AASHTO, 2007).

When evaluating the aging characteristics, as the bitumen ages, it becomes more brittle and stiffer, thus the ITS results of an aged mixture are rather more than the results of an un-aged mixture. This can provide us aging indices to investigate aging characterization of asphalt mixtures. Burak Sengoz (2003) has implemented ITS results of mixtures with various air voids, to assess aging and moisture susceptibility characteristics of HMA mixtures. Another study on short- and long-term aging behavior of rubber modified asphalts conducted by Liang and Lee (1996) has also proved the fact that the short-term and long-term aging increased the measured tensile strengths. Sengoz and Topal (2008) investigated the effect of SBS polymer modified bitumen on the ageing properties of asphalt mixtures using ITS test results. They calculated aging indices as the ratio of short- and long-term aged specimen's ITS values to the values of un-aged control specimens prepared with the same additive content. Hurley and Prowell (2005) used ITS results to check the rutting potential after application and the short- and long-term aging characterization of WMA mixes containing Sasobit®.

Test method details is described in the standard developed by ASTM (2012). Second section of Chapter five includes a brief procedure of this test.

CHAPTER THREE
WARM MIX ASPHALT TECHNOLOGY

This chapter includes a brief literature review on WMA technology. In the first part we read about some advantages of WMA mixes in comparison with conventional HMA mixes. Second part discusses about the classification of this technology and products. More details about the additives used in this study are presented in chapter five's materials section.

3.1 Advantages of the WMA

Studies conducted on WMA technology, mostly have a common sight about the advantages of the WMA mixes. These advantages are all originated from the major feature of WMA additives which is reducing the viscosity of the bitumen. This reduction results in increasing workability and ease of use, ecological benefits due to less emissions and reduction in costs due to less energy use.

3.1.1 Ease of Application

As stated before, the prominent feature of the WMA additives is their contribution in viscosity reduction. (Hurley & Prowell, 2006) The reduced viscosity helps the aggregates to be coated more easily and this simply cause improving the workability (Bennert, Reinke, Mogawer, & Mooney, 2010). During the mixing process it should be considered that the lower the viscosity, the easier the mixing (J.M. Croteau & B. Tessier, 2008). Compaction also needs less effort compared to HMA mixes due to lower bitumen viscosity (Kristjansdottr, Muench, Michael, & Burke, 2007; Rubio, Martinez, Baena, & Moreno, 2012).

Many studies have investigated the implementing of WMA technology in asphalt pavements recycling. According to these studies, using WMA additives makes the using of Recycled Asphalt Pavement (RAP) easier in comparison with HMA mixes (Valdés, Pérez-Jiménez, Miró, Martínez, & Botella, 2011). A field study of Sasobit®

also has reported the fact that the handling and the compaction (by 40% lower compaction effort) of the mixes containing RAP were easier than the HMA mixes (National Asphalt Pavement Association, 2005).

Regarding conveyance of the mixes, investigations showed that the WMA mixes are more applicable in transporting to far distances without losing the required workability and compactability (D'Angelo et al., 2008).

3.1.2 Environmental Benefits

Worldwide, there have been serious worries about the greenhouse gases emissions in recent decades. Due to lower application temperatures of WMA mixes, carbon dioxide (CO_2) and other so called greenhouse gases emissions is lowered in comparison with HMA mixes (D'Angelo et al., 2008). Beside these, evaporation of the less heavy components of bitumen occurs less than conventional applications. This causes less odors in asphalts plants, therefore provides more pleasant working conditions (J.M. Croteau & B. Tessier, 2008). Builders comments indicate that the fumes are rather less in WMA production in comparison with HMA production (J.M. Croteau & B. Tessier, 2008). A recent study on environmental effects of Sasobit® indicated that adding 1% of Sasobit® can possibly decrease the needed energy and CO_2 emissions by 2.8% and 3.0%, respectively (Hamzah, Jamshidi, & Shahadan, 2010).

3.1.3 Economic Benefits

As aforementioned, application temperatures are rather low in WMA technology. As a result, the fuel consumption of this technology is relatively less in comparison with conventional HMA mixtures. Energy consumption for WMA production has been reported as 60 to 80 percent of HMA production (Rubio et al., 2012). other studies have shown the range of 20 to 35 percent of decrease in burner fuel savings with WMA technology (D'Angelo et al., 2008). It has also been reported a potential reduction in fuel consumption of 10 to 30% based on the production temperature reduction while some field practices (The Asphalt Pavement Association of Oregon, 2003).

In Turkey, higher energy costs make WMA technology more valuable for asphalt producers. Although savings may be offset due to extra charges of WMA additives, there is no a distinctive evaluation of life cycle cost for WMA technology.

3.2 WMA Possible Disadvantages

In spite of all WMA advantages, there may be still possible drawbacks of WMA technology like any other new technology (Vaitkus, Cygas, Laurinavicius, & Perveneckas, 2009). The first issue is that this technology is considered as a relatively new technology and there is still no sufficient evaluation of field problems of this technology. The second possible drawback is related to WMA mixtures performance. Some technologies of WMA may not afford a desirable strength for WMA pavements. Due to insufficient cohesion between aggregates and bitumen originated from low mixing temperature (aggregates may not be dried as well as in HMA mixes) moisture induced damages are potential problems of WMA pavements (Hurley & Prowell, 2006). Based on recent studies, anti-stripping additives can partly solve this problem (Xiao & Amirkhanian, 2010). Apart from these, there may be many additional costs such as plant modification, additive production and expert wages in implementing of this technology.

3.3 Classification of WMA Technologies and products

As the major purpose of all existing WMA technologies is to reduce viscosity, there are various additives and techniques, categorized as WMA technologies. Some classifications take the production temperatures in classifying WMA technologies. According to these classifications, Mixes produced at 0 to 30 °C are classified as cold, in temperature range 65 to 100 °C as half-warm mix asphalt, production temperatures between 110–140 °C as WMA and finally for production temperature between 140–180 °C as HMA. Figure 3.1 better demonstrates the WMA classification based on production temperature (D'Angelo et al., 2008).

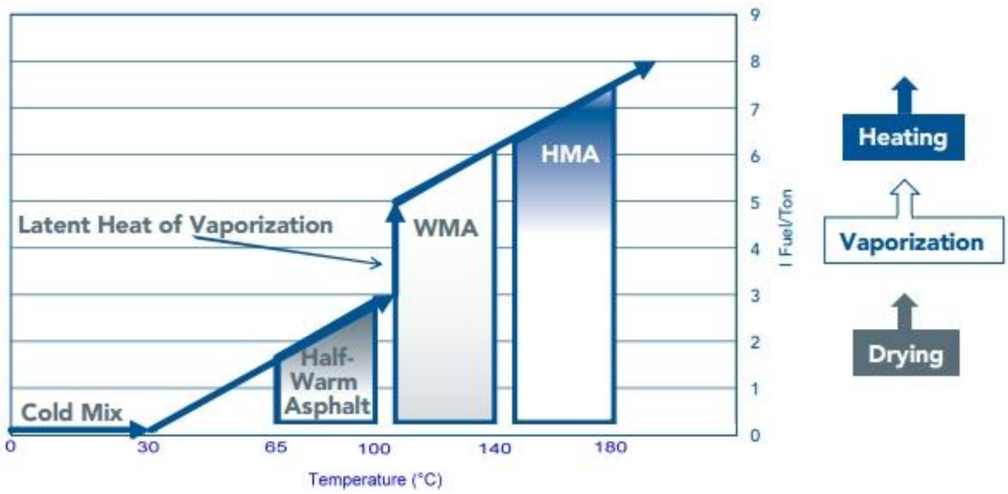

Figure 3.1 Classification by temperature range (D'Angelo et al., 2008) (Fuel usage and temperatures are approximate values)

The production process may differ for each technology. Another classification of WMA technologies is based on production methods. There are three main principles implemented to reduce bitumen viscosity. Some processes use additives (organic, wax, and chemical) in order to modify bitumen for a lower viscosity. Some others use water (as major agent) and additives to provide better coating during mixing. These methods are generally called foaming technologies. Following sections include a brief description about each technology separately, based on the production methods.

3.3.1 Wax and Organic Additives

These groups of additives simply modify bitumen to achieve a lower viscosity. They naturally consist of paraffin which can be dissolved in bitumen when melted. Melting point may vary from 80°C to 120°C depending on the type of additive. Hydrocarbon chains with general structure C_nH_{2n+2} are known as Paraffin waxes. For n>20 (n is the number of carbon atoms) paraffin is more likely to be solid in room temperature (Freund & Mózes, 1982). Waxes used in WMA technology as additives, typically has more than 45 carbon atoms thus their melting point is above 70°C

(D'Angelo et al., 2008). Normally the molecular weight of a hydrocarbon depends on the number of carbon atoms (C_n) participated in the structure of the carbon chain of that particular hydrocarbon (Mount, 2003). concerning paraffins, the long-chain aliphatic hydrocarbon structure of paraffin doesn't cause a phenomenal change in the bitumen's main properties (Sasol wax, 2012b). Sasobit® can be named as the famous example of this additive group. It is a long chain aliphatic hydrocarbon wax with approximate melting point of 100°C. Sasobit® is produced by coal gasification using the Fischer – Tropsch synthetic process (Sasol wax, 2012c). More info about Sasobit® and its properties is presented in Material section of chapter five. Other examples for these types of additives can be found in Table 3.1 (D'Angelo et al., 2008).

Table 3.1 Wax and organic WMA additives (D'Angelo et al., 2008)

Additive	Company	Production Temperature (at plant) °C	Reported Field Practice
Sasobit® (Fischer-Tropsch wax)	Sasol	20–30 C° (Drop from HMA) 130–170 °C (German guideline Recommendation)	Germany and 20other countries worldwide
Asphaltan-B (Montan wax)	Romonta	20–30 C° Drop from HMA) 130–170 °C (German guideline Recommendation)	Germany
Licomont BS 100 (additive) or Sübit (binder)(fatty acid amides)	Clariant	20–30 C° (Drop from HMA) 130–170 °C (German guideline Recommendation)	Germany
3E LT or Ecoflex (proprietary)	Colas	30–40 C° (Drop from HMA)	France

3.3.2 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 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 (Cengel & Boles, 2008). This expansion results in reduction of the mix viscosity and helps coating. WAM-foam is a patented foaming technology developed on the basis of this theory by 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. The process with application temperatures are shown in Figure 3.2 (Shell Bitumen, 2011).

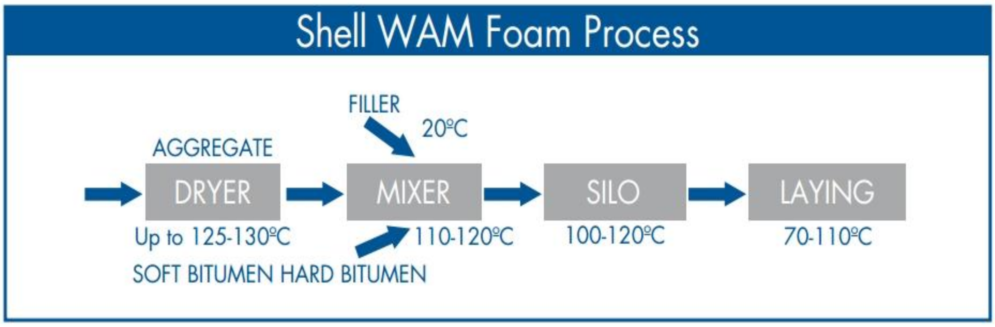

Figure 3.2 WAM-foam process (Shell Bitumen, 2011)

Another method of foaming technology is to add an additive which 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 injection method. Released steam results in more lubricant mix and correspondingly increases the workability. Advera® and Aspha-min® (both are synthetic zeolites) have been developed on the basis of this theory. Zeolites are minerals with micro-porous structure that can absorb and maintain moisture. More examples of foaming technologies are shown in Table 3.2 (D'Angelo et al., 2008).

Table 3.2 Some 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

Some technologies require adding anti-stripping agents in order to overcome moisture induced damages in foaming technologies (D'Angelo et al., 2008).

3.3.3 Chemical Additives

These types of additives modify bitumen chemically. The processing principle is the same as other WMA technologies though some of these additives contain extra agents to improve the bitumen performance. Anti-stripping agents as well as the surfactants can be found within the composition of some of these additives. Rediset® WMX (developed by Akzo Nobel) is a good example for these types of additives. Its combination includes both organic additive and a kind of cationic surfactant (Chowdhury & Button, 2008). The surfactants simply increase the coating ability of the aggregate with the bitumen by “active adhesion.” and the other constituents play role in reducing the viscosity of the bitumen (Prowell & Hurley, 2007). Detailed info about Rediset® WMX is provided in chapter five in materials section.

Table 3.3 Chemical WMA additives (AkzoNobel, 2010; Chowdhury & Button, 2008; D'Angelo et al., 2008; Prowell & Hurley, 2007; Rubio et al., 2012)

Technology	**Company**	**Production Temperature (at plant) °C**	**Reported Field Practice**
Rediset® WMX	AkzoNobel Corporate	10–15 C° (Drop from HMA)	U.S.
Evotherm™	MeadWestvaco	85–115 °C	France, Canada, China, South Africa and U.S.
Revix™	Mathy Technology and Engineering Services, Inc. and Paragon Technical Services, Inc.	15–25 C° (Drop from HMA)	U.S.
Cecabase RT	CECA	30 °C (Drop from HMA)	USA, France
Iterlow T	IterChimica	120 °C	Italy

Another example of chemical additives is Evotherm™. It is a chemical liquid emulsifier which is consisted of materials to enhance workability, adhesion promoters and emulsification agents (Hurley & Prowell, 2006). Based on the catalogue information published by MeadWestvaco Corporation, this products causes 55°C reduction in production temperature (MeadWestvaco, 2012).

Other developed chemical additives are given in Table 3.3 (AkzoNobel, 2010; Chowdhury & Button, 2008; D'Angelo et al., 2008; Prowell & Hurley, 2007; Rubio et al., 2012)

CHAPTER FOUR
EXPERIMENTAL

4.1 Materials

This section consists of the properties of material used within this study. Materials presented in this section are consisted of bitumen, aggregates and WMA additives. As stated before, this study aims to investigate the aging characteristics of four various additives including Sasobit® (organic additive), Rediset® WMX (chemical additive), Advera® WMA (synthetic zeolite) and natural zeolite.

4.1.1 Bitumen

The bitumen used was 50/70 penetration grade bitumen which was provided from TUPRAŞ Aliağa refinery. This grade of penetration is commonly used in İzmir due to climatic conditions. Conventional test results for virgin bitumen conducted at Dokuz Eylül University laboratory of bituminous materials are given in Table 4.1.

Table 4.1 Laboratory test results for virgin bitumen

Test	Standard	Results	Turkish Specifications
Penetration (25°C ; 0.1 mm)	ASTM D5 EN 1426	55	50-70
Softening Point (°C)	ASTM D36 EN 1427	49	46-54
Viscosity (135°C)	ASTM D4402	412.5	-
Viscosity (165°C)	ASTM D4403	137.5	-
TFOT (165°C)	ASTM D1754 EN 12607-1		
Mass change (%)		0.04	0.5 (Maximum)
Penetration Change (%)	ASTM D5 EN 1426	25	-
Softening Point after TFOT (°C)	ASTM D36 EN 1427	54	48 (Minimum)
Ductility (25°C; cm)	ASTM D113	100	-
Specific Gravity	ASTM D70	1.03	-
Flash Point (°C)	ASTM D92 EN 22592	+260	230 (Minimum)

4.1.2 Aggregates

A mix of basalt and limestone aggregates provided from Dere Madencilik Inc. (Quarry located in Belkahve – İzmir) is used in this study. Physical properties of each kind are given in Table 4.2.

Table 4.2 Physical properties of used aggregates

Test	Specification	Results		Limits
		Limestone	Basalt	
Specific gravity (coarse agg.)	ASTM C 127			
Bulk		2.686	2.666	-
Saturated Surface Dry		2.701	2.810	-
Apparent		2.727	2.706	-
Specific gravity (fine agg.)	ASTM C 128			
Bulk		2.687	2.652	-
Saturated Surface Dry		2.703	2.770	-
Apparent		2.732	2.688	-
Specific gravity (Filler)		2.725	2.731	-
Los Angeles Abrasion (%)	ASTM C 131	24.4	14.2	Max 45
Flat and elongated particles (%)	ASTM D 4791	7.5	5.5	Max 10
Sodium sulfate soundness (%)	ASTM C 88	1.47	2.6	Max 10-20
Fine aggregate angularity	ASTM C 1252	47.85	58.1	min 40

After conducting the associated tests based on ASTM C 136, a mix gradation of basalt and limestone is intentionally chosen to provide desired performance in conformity with Turkish specifications concerning the Type 1 wearing course. Basalt plays the role of strengthening constituent as coarse aggregate while limestone participates in fine aggregate framework. The gradation is given in Table 4.3.

Table 4.3 Gradation of the aggregates

Test	19 – 12.5 mm (Basalt)	12.5 – 5 mm (Basalt)	5 – 0 mm (Limestone)	Combined gradation (%)	Specification limits
Mixture ratio (%)	**15**	**45**	**40**		
Gradation					
(3/4) ″	100	100	100	100	100
(1/2) ″	35.7	100	100	90.5	83-100
(3/8) ″	2.5	89	100	80.5	70-90
No 4	0.4	16	100	47.3	40-55
No 10	0.3	1.2	81	33	25-38
No 40	0.2	0.7	33	13.5	10-20
No 80	0.15	0.4	22	9	6-15
No 200	0.10	0.2	13	5.3	4-10

4.1.3 WMA Additives

WMA additives investigated in this study, each are from a specific category of WMA additives. Sasobit® takes place in organic and waxes additive category while Rediset® is from chemical additives category. Advera® WMA and natural zeolite both represent foaming technologies additives. Additive contents tested in this study were chosen as ±1% of the optimum additive content for each additive based on the previous tests within the project studies. Following sections include these additives descriptions and properties.

4.1.3.1 Sasobit®

It is a long chain aliphatic hydrocarbon wax with approximate melting point of 100°C. Sasobit® is produced by coal gasification using the Fischer – Tropsch synthetic process (Sasol wax, 2012c). It is considered as an “asphalt flow improver”, while mixing process and also during compaction process, owing to its ability to reduce the viscosity of the bitumen (Damm, Abraham, Butz, Hildebrand, & Riebeschl, 2002). It is completely soluble in bitumen at temperatures above 140°C (Sasol wax, 2012b). Sasobit® is a kind of F-T wax which is different from a paraffin wax. F-T waxes (with 40 to 115 carbon atoms) have longer chains compered to paraffin waxes (with about 25 to 50 carbon atoms) (Estakhri, Button, & Alvarez, 2010). Reportedly, Sasobit® forms a crystalline structure in the bitumen when congealing. This crystalline structure causes an increase in stiffness of the bitumen and reduces the tender at low temperatures (Damm et al., 2002; Estakhri et al., 2010). The manufacturer claims that the long chain aliphatic hydrocarbon structure of Sasobit® doesn’t cause a phenomenal change in the bitumen’s main properties (Sasol wax, 2012b). Sasobit® can either be added to the bitumen or to the mixture, though it is not recommended to directly add it to the mix because it will not give a homogenous distribution (Estakhri et al., 2010). Sasobit® has been produced in tonnage of over 30 million tons and used in various pavement projects world widely since 1997(Sasol wax, 2012a). Based on the manufacturer claims, it significantly increases the amount of RAP usage in asphalt pavements (Sasol wax, 2012a).

In this study, Sasobit® has been directly added to the bitumen at three dosages of 2%, 3% and 4% by weight of the bitumen.

Sasobit® is produced both in flakes and pellets forms. Figure 4.1 shows Sasobit® additive in pellets form.

Figure 4.1 Granular Sasobit®

4.1.3.2 Rediset® WMX

Rediset® WMX (developed by Akzo Nobel) is a combination of both organic additive and a kind of cationic surfactant (Chowdhury & Button, 2008). The surfactants simply increase the coating ability of the aggregate with the bitumen by "active adhesion." and the other constituents play role in reducing the viscosity of the bitumen (Lai & Tsai, 2008; Prowell & Hurley, 2007). Using Rediset® WMX can reduce the production temperature by about 10°C to 15°C and consequently results in 20% reduction in fuel consumption (D'Angelo et al., 2008; Lai & Tsai, 2008). Rediset® WMX can either be added to the bitumen or to the mixture. Plant modification is not needed or minor changes are sufficient (Lai & Tsai, 2008). The supplier recommendation about the sufficient dosage is 1.5% to 2% by the virgin bitumen weight (Rubio et al., 2012).

Three dosages of Rediset® WMX (1%, 2% and 3% by the bitumen weight) have been evaluated in this study. Figure 4.2 demonstrates the solid granular Rediset® WMX used in this study.

Figure 4.2 Granular Rediset® WMX

4.1.3.3 Advera® WMA

Advera® WMA is a synthetic zeolite (Hydrated Aluminosilicate) which is developed by PQ Corporation in Malvern, Pennsylvania. Implementing Advera® WMA in asphalt mixtures can reduce production temperature of about 10°C to 30°C. The recommended amount of use is 0.25% by total weight of the mix (Rubio et al., 2012). Advera® WMA is presented in white powder form (Figure 4.3) in various packages by supplier. It contains about 18% to 21% water. Porous microstructure of this synthetic zeolite helps fine water particles to be situated within the pores. These particles can be remained within the pores and released at temperatures over the boiling point of water (100°C). Release of tiny steam bubbles for a period of seven hours can protract laying time with an improved workability. This also facilitates the hauling of the mixture. Reduction in viscosity can provide more amount of RAP in the mixture as well.

Figure 4.3 Advera® WMA in powder form

4.1.3.4 Natural Zeolite

The term Zeolite originally was derived from Greek words (Zeo) meaning "to boil" and (lithos) meaning "stone" as it releases adsorbed water in form of steam when heated rapidly. There are plenty of mineral zeolites in nature. Most are made up of Aluminosilicate minerals. Zeolites are commonly used in industry due to their microporous structure. Mineral zeolites are famous for being natural filters. They can absorb pollutions from water and air. Depend on the size of the pores in their structure; Zeolites can be used in different industrial fields.

Some of the more famous mineral zeolites are Analcime, Chabazite, Clinoptilolite, Heulandite, Natrolite, Phillipsite, and Stilbite (Wikipedia, 2012). The most abundant zeolite in Turkey is Clinoptilolite. It can be found plentifully around Manisa – Gördes area. Reports claim about the existence of 18 million tons of visible clinoptilolite and 20 million tons of its volcanic tuff deposits. In Balıkesir – Bigadiç area significant amounts of natural zeolite have been discovered as well (Ayan, 2002).

During studies at bituminous materials laboratory of civil engineering department of Dokuz Eylül University, Clinoptilolite was found a suitable mineral to use in WMA mixtures. 34% micro-porosity has been detected for Clinoptilolite. Laboratory tests showed that it can easily adsorb water by amount of needed in WMA foaming technology (about 20 % by additive weight) and release steam bubbles at temperatures over the boiling point of water. It could remain the moisture within its micro-pores when stored in bags. Figure 4.4 demonstrates the honeycomb micro-structure of a zeolite and the water located within its micro pore.

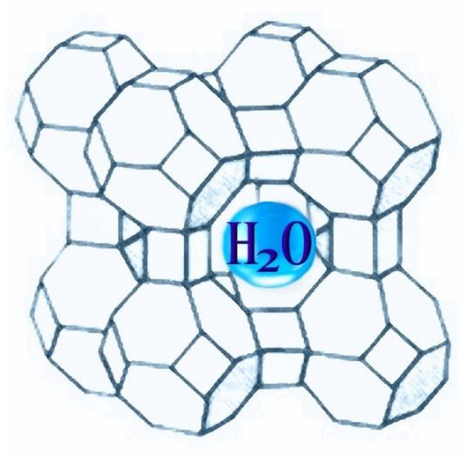

Figure 4.4 the honeycomb micro-structure of a zeolite

Complex formula of Clinoptilolite is as follows:

- $(Na_3.K_3)\ (Al_6Si_{30}O_{72}).24H_2O$

Moisture loss of this mineral (when stored in bags) in several time intervals is presented in Table 4.4.

Table 4.4 Natural zeolite moisture loss in several time intervals when stored in bags

Time	24 hrs. later.	3 Days later	a week later	a month later
Moisture Loss (%)	0	0.4	1.2	4.7

Figure 4.5 illustrates the natural zeolite (Clinoptilolite) powder used in this study.

Figure 4.5 Natural zeolite (Clinoptilolite) in powder form

4.2 Experimental Plan

In this section, the experimental plan of study is explained. The plan includes the way that WMA bitumens and mixtures are produced and then aged. After all, the way that the difference mixtures have been tested by IDT is described and demonstrated.

4.2.1 Production of WMA bitumens

Based on the regarding temperature and mixing time for that particular WMA additive, WMA bitumens were produced just before the mixing process. Production temperature was supplied by a heater similar to Thermosel^{TM} and controlled by a digital industrial thermometer. An industrial stirrer (Figure 4.6) was used in production of WMA bitumens. Stirring was done in normal shear stresses (1000 rpm by a stainless steel stirrer bar with about a 4 cm cross crown) since the production of WMA bitumens don't demand for high shear stresses. Foaming additives also were added directly to the bitumen and been used immediately after being foamed. This was done due to laboratory mixing conditions.

Figure 4.6 Production of WMA bitumens

Mixing temperatures and periods were determined based on trial and error method. In this method, various amounts of a particular additive were added to the bitumen and stirred at a definite temperature for a definite time period. After production process, the viscosity of the new WMA bitumen was determined by rotational viscosity. This was done at a constant temperature for different time periods as well as at altered temperatures for a fixed time period. For different temperatures and mixing periods, the border that the viscosity didn’t change significantly was chosen as the optimum period and temperature. The optimum production period and temperature are important values attributable to preserving bitumen from aging during production process.

Optimum production periods and temperatures for various additives are given in Table 4.5.

Table4.5 production times and temperatures

Additive	Production Temp. (°C)	Production Time (min)
Sasobit®	120	10
Rediset® WMX	150	15
Advera® WMA	120	20
Natural Zeolite	120	20

4.2.2 Preparation of Bituminous Mixtures

Mixing and compaction temperatures for a particular additive were derived from equiviscous method as explained in NCHRP report (2010) in accordance to AASHTO T 312. The graphics for viscosities vs. temperature were plotted for each WMA additive mixture (Figures 4.7 to 4.11). Acceptable temperature for mixing was chosen as the range matching 0.17±0.02 Pa.s and acceptable temperature for compaction was chosen as the range matching 0.28±0.03 Pa.s. Mixing and compaction temperatures for each WMA mixture are given in Table 4.6.

As seen in the results, there is a significant decrease in application temperatures using all WMA additives. All the tested additives were similar in results from the application temperature point of view. Both foaming additives including Advera® WMA and natural zeolite could decrease the application temperatures to similar levels.

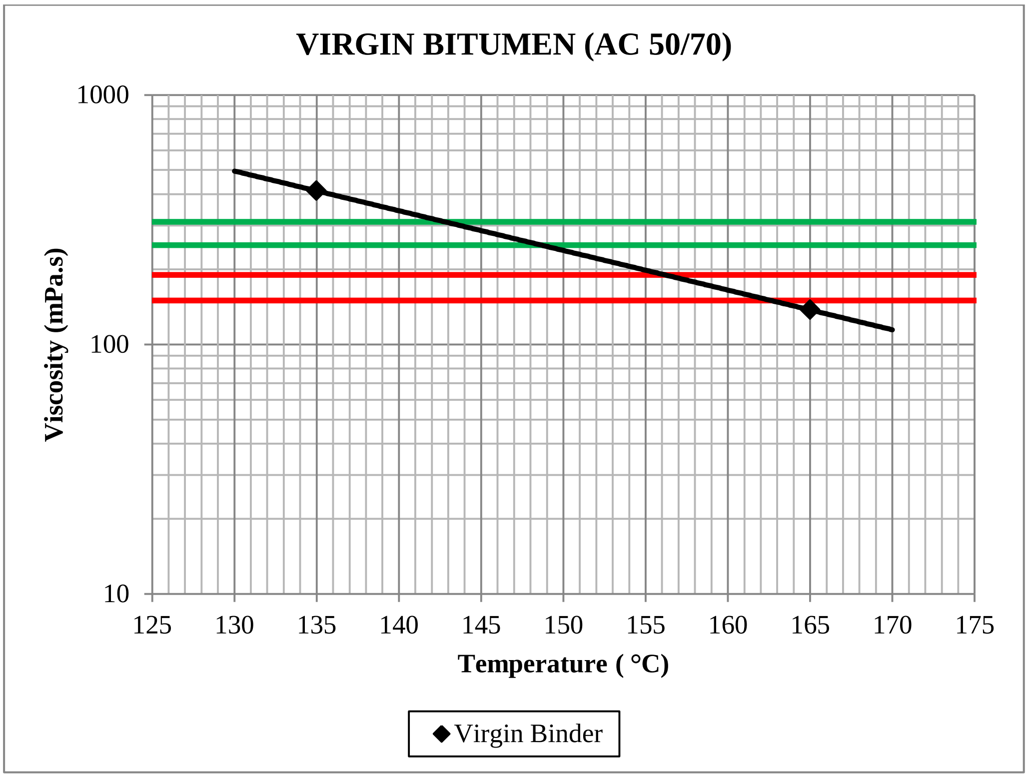

Figure 4.7 Determination of mixing and compaction temperatures for virgin bitumen

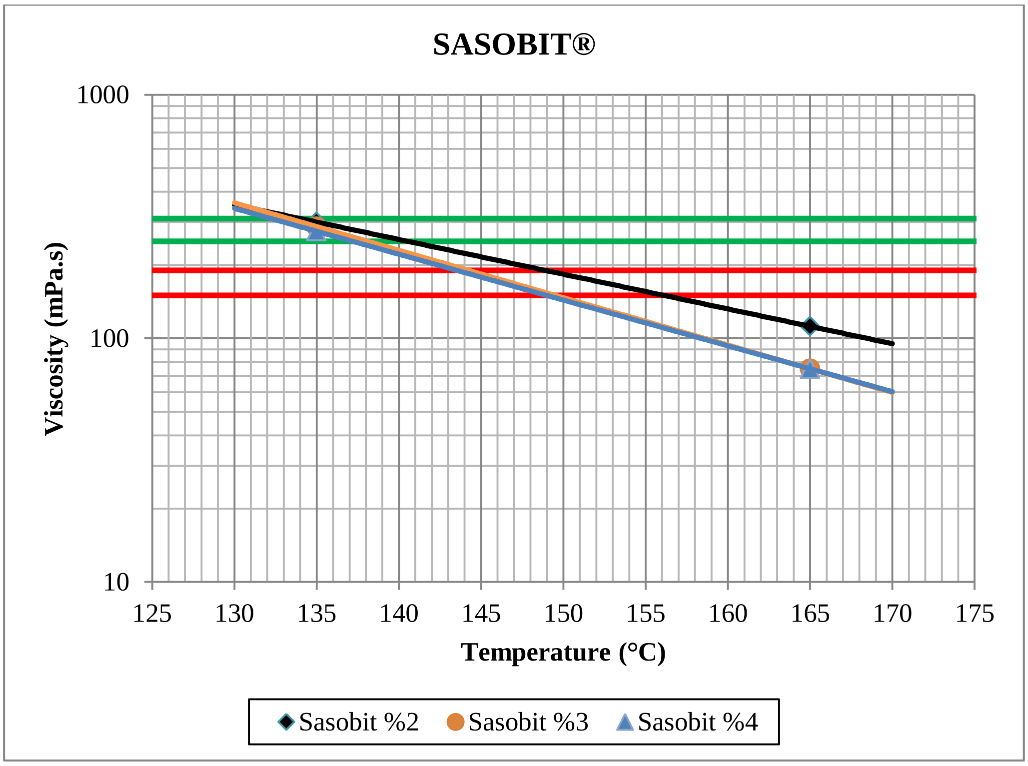

Figure 4.8 Determination of mixing and compaction temperatures for Sasobit® modified bitumens

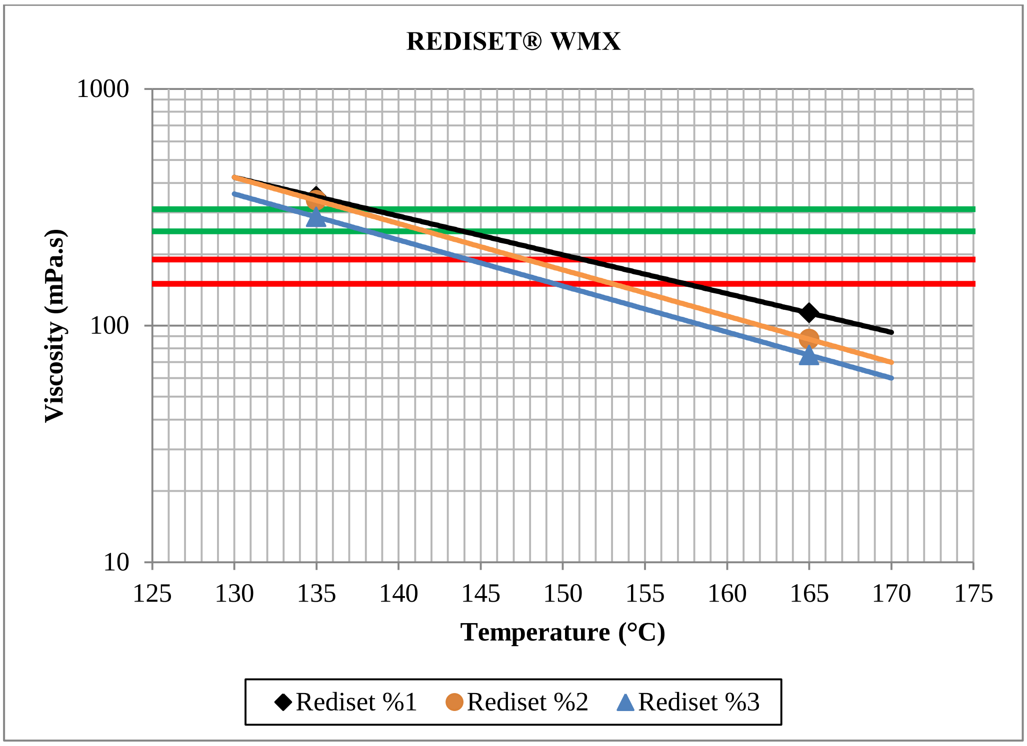

Figure 4.9 Determination of mixing and compaction temperatures for Rediset® WMX modified bitumens

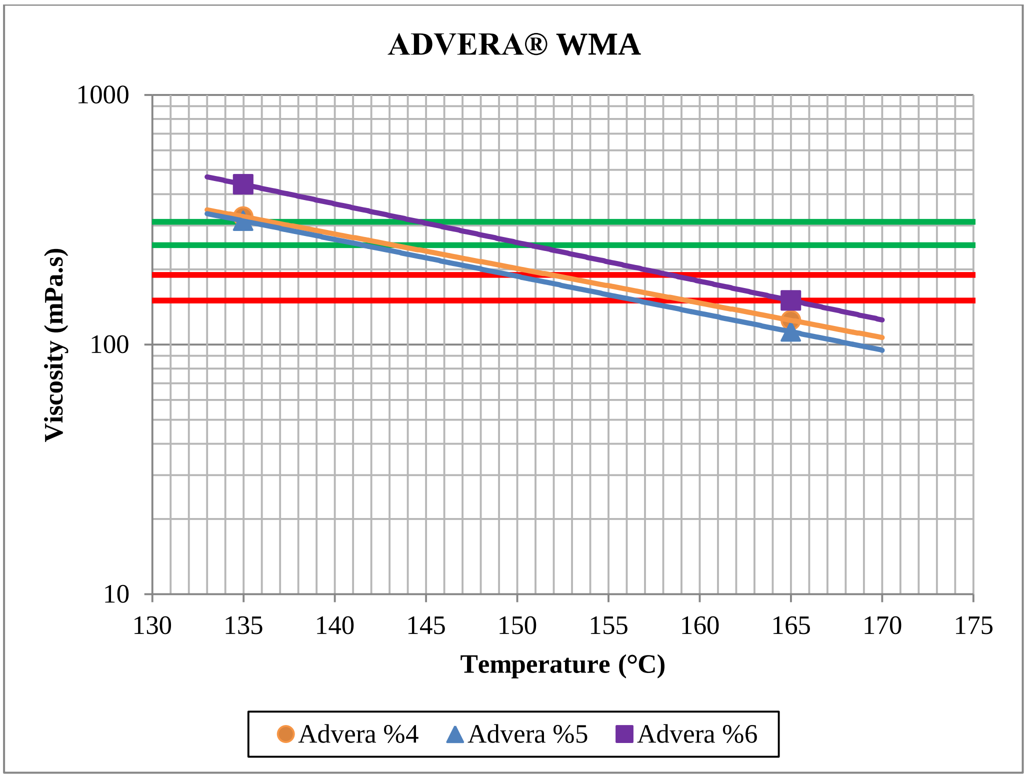

Figure 4.10 Determination of mixing and compaction temperatures for Advera® WMA modified bitumens

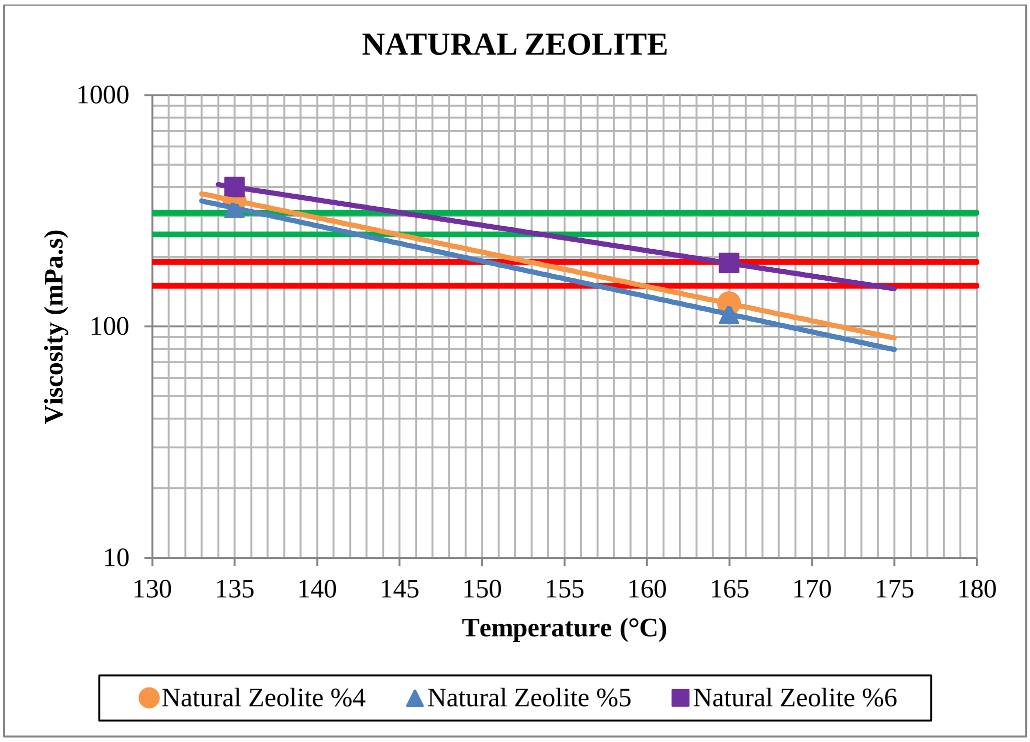

Figure 4.11 Determination of mixing and compaction temperatures for natural zeolite modified bitumens

Table 4.6 Mixing and compaction temperatures

Mixture type	Additive Amount (%) by Bitumen Weight	Mixing Temp. (°C)	Compaction Temp. (°C)
HMA Mixture	0	157 – 164	144 – 150
Sasobit® - Modified	2	147 – 153	134 – 139
	3	142 – 147	133 – 138
	4	142 – 147	132 – 137
Rediset® WMX - Modified	1	151 – 157	138 – 144
	2	145 – 149	136 – 140
	3	144 – 147	133 – 138
Advera® WMA - Modified	4	150 – 155	137 – 142
	5	148 – 153	135 – 141
	6	153 – 160	138 – 145
Natural Zeolite - Modified	4	150 – 155	138 – 143
	5	148 – 153	136 – 141
	6	158 – 165	146 – 151

Following the production of WMA bitumens, WMA mixtures were prepared based on the determined mixing temperatures. The industrial mixer used for mixing the aggregates and the bitumen is shown in Figure 4.12. The aggregates were placed in an oven adjusted for proper temperature the day before to be completely dried and ready for mixing. Controlled specimens were compacted with Marshall compactor (Figure 4.13) regarding their compaction temperatures after mixing process. Conditioning as per AASHTO R 30 standard were done on the specimens intended to be aged. Short-term aged specimens were conditioned in a forced-draft oven set for 135°C for 4 hours (Figure 4.14) then compacted and cured since the long-term aged specimens were conditioned for 124 hours in a forced-draft oven set for 85°C after passing the short-term aging conditions. All processes regarding preparation and conditioning of mixtures are shown on a flowchart in Figure 4.15.

Figure 4.12 Mixer used in mixing of the aggregates and the bitumen

Figure 4.14 Short-term conditioning in a forced-draft oven set for 135°C for 4 hours

Figure 4.13 Automatic Marshall compactor

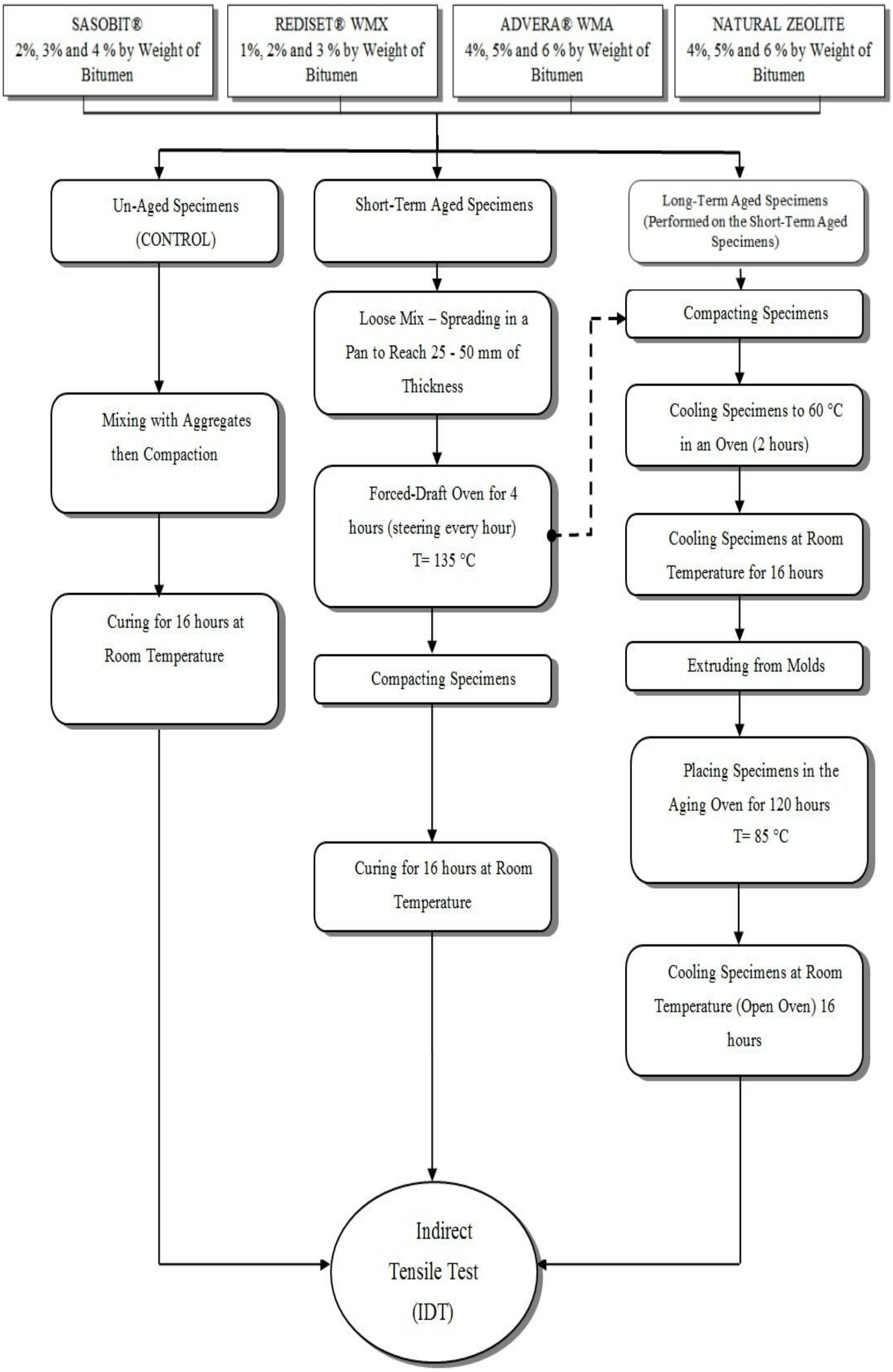

Figure 4.15 Flowchart for preparation and conditioning of the mixtures

4.2.3 Indirect Tensile Test (IDT) ASTM D6931

As aforementioned, to be adequate and unbiased, three specimens for each kind of mixture stated in this study were prepared and tested randomly. After compaction and curing of the specimens, they were ready for conducting IDT test. Indirect tensile strengths of the specimens were measured using IDT device. Figure 4.16 demonstrates a specimen between IDT loading strips and a possible crack pattern.

Figure 4.16 A possible crack pattern for IDT test

To perform this task, the standard test method for indirect tensile (IDT) strength of bituminous mixtures (ASTM D6931) has been taken into account. The following orders were followed and done step by step:

- Specimen height was measured and recorded in accordance with ASTM D3549 test method to the nearest 1 mm.

- To ensure the right linear loading, a random diameter of the specimen was drawn by chalk.

- Specimen then was placed and vacuumed into a heavy duty leak-proof plastic bag and the put into water bath (adjusted for 25°C) for 2 hours.

- After removing the specimen from water bath and removing from plastic bag, it was immediately placed between the lower and upper loading strips. It was ensured that the loading strips are parallel and centered on the vertical diametral plane. (Considering the diameter line drawn on the specimen before). Figure 4.17 shows a true assemble of a specimen between loading strips.

- After assembling the loading frame into test device, a vertical compressive ramp load was applied and recorded when it reached the maximum value.

Figure 4.17 Marshall specimen ready for IDT test

Recorded data from the test device screen is the raw data and should be processed using the following formula to obtain indirect tensile strength:

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \qquad (4.1)$$

where:

S_t = Indirect tensile strength (ITS), kPa

P = Maximum load, N

t = Specimen height immediately before test, mm

D = Specimen diameter, mm

A diagonal crack pattern due to tensile stresses has been shown in Figure 4.18.

Figure 18 A cracked specimen after IDT test

CHAPTER FIVE
RESULTS AND DISCUSSIONS

This chapter includes test results conducted on virgin and different WMA bitumens, Marshall and IDT test results conducted on control and different WMA mixtures and analysis on these results.

5.1 Bitumen Test Results

Conventional bituminous tests results including penetration test, softening point test and rotational viscosity are presented in this section.

5.1.1 Penetration Test Results

Penetration test results before and after TFOT and RTFOT tests are given respectively in Table 5.1 and Table 5.2. First four columns for both tables are the same (results are given in two tables to be easily compared).

Table 5.1 Penetration test results before and after TFOT

Bitumen type	Additive Content (%) by Bitumen Weight	Penetration (0,1mm)	Penetration Index	Penetration (0.1 mm) after TFOT	Penetration Change (%)	Mass Loss During TFOT
Virgin Bitumen	0	55	-1.20	41	25	0.04
Sasobit®	2	43	0.89	37	14	0.07
	3	37	1.95	32	13	0.07
	4	31	3.07	29	6	0.08
Rediset® WMX	1	48	-0.04	39	19	0.06
	2	44	0.04	37	16	0.04
	3	40	0.09	35	13	0.06
Advera® WMA	4	53	-0.22	44	17	0.15
	5	52	0.27	43	16	0.16
	6	45	0.74	40	11	0.16
Natural Zeolite	4	53	-0.10	44	17	0.16
	5	51	0.02	43	15	0.16
	6	45	0.40	41	10	0.17

Table 5.2 Penetration test results before and after RTFOT

Bitumen type	Additive Content (%) by Bitumen Weight	Penetration (0,1mm)	Penetration Index	Penetration (0.1 mm) after RTFOT	Penetration Change (%)	Mass Loss During RTFOT
Virgin Bitumen	0	55	-1.20	41	26	-0.04
Sasobit®	2	43	0.89	36	16	-0.07
	3	37	1.95	31	15	-0.07
	4	31	3.07	28	10	-0.08
Rediset® WMX	1	48	-0.04	38	22	-0.06
	2	44	0.04	36	17	-0.07
	3	40	0.09	33	17	-0.08
Advera® WMA	4	53	-0.22	42	21	-0.17
	5	52	0.27	41	21	-0.18
	6	45	0.74	39	14	-0.18
Natural Zeolite	4	53	-0.10	43	18	-0.17
	5	51	0.02	42	17	-0.17
	6	45	0.40	38	15	-0.17

Obviously, there has been a decrease in penetration value using WMA additives. This is more sensible when discussing about non-foaming WMA additives since the reduction seen in penetration when using foaming additives was not as considerable as when non-foaming additives were used. For a specific additive, generally the penetration value falls when the amount of additive increases. This is better perceptible looking Figures 5.1 to 5.4 respectively for Sasobit®, Rediset® WMX, Advera® WMA and natural zeolite.

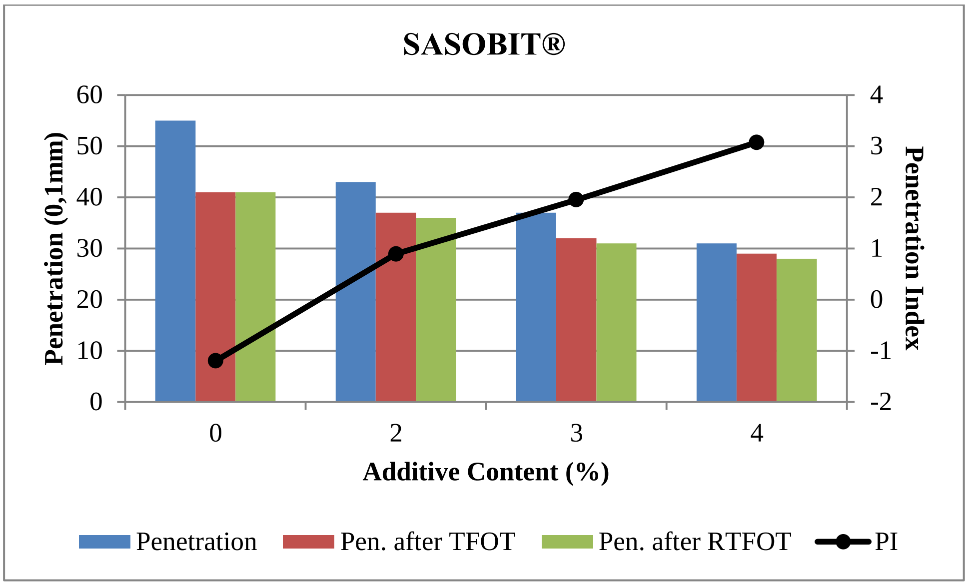

Figure 5.1 Penetration test results for Sasobit® modified bitumens

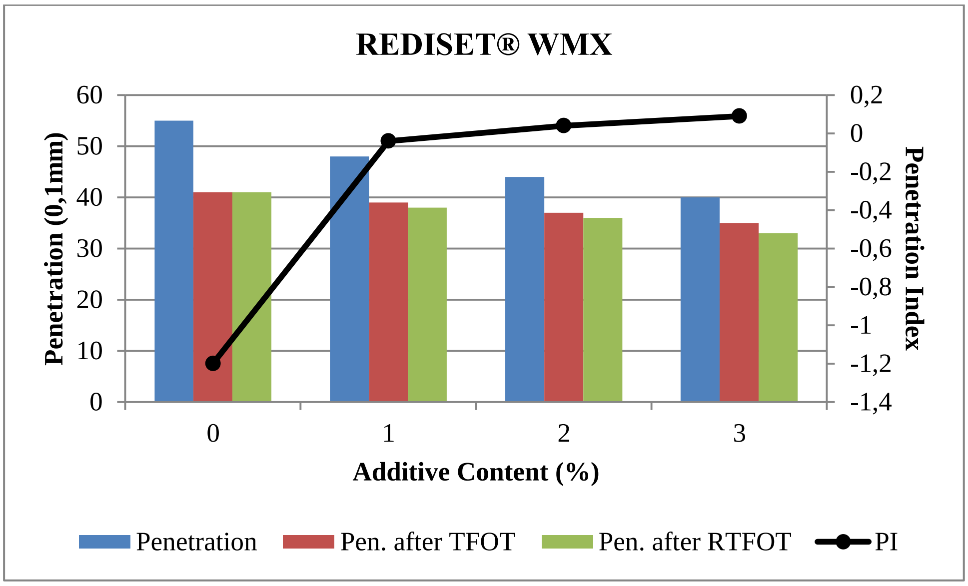

Figure 5.2 Penetration test results for Rediset® WMX modified bitumens

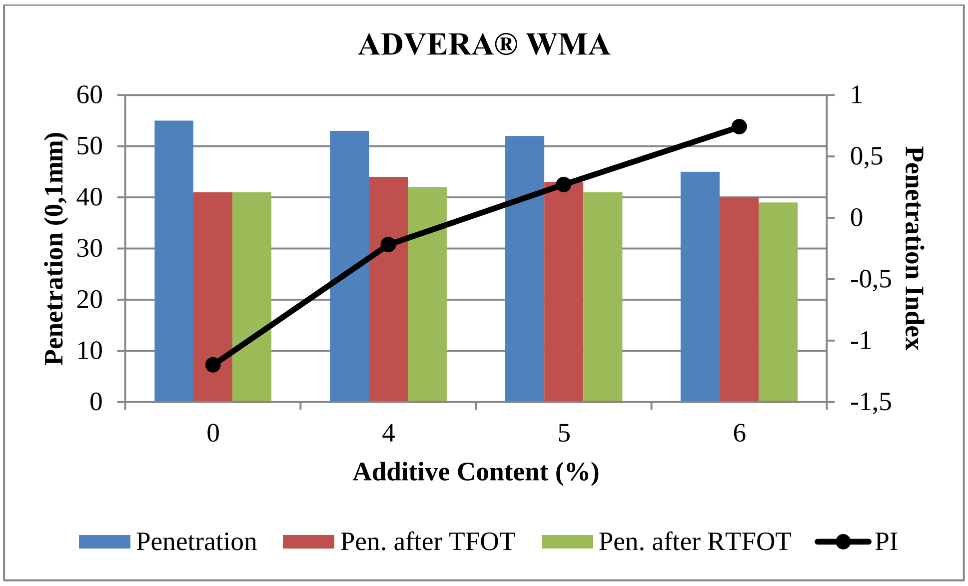

Figure 5.3 Penetration test results for Advera® WMA modified bitumens

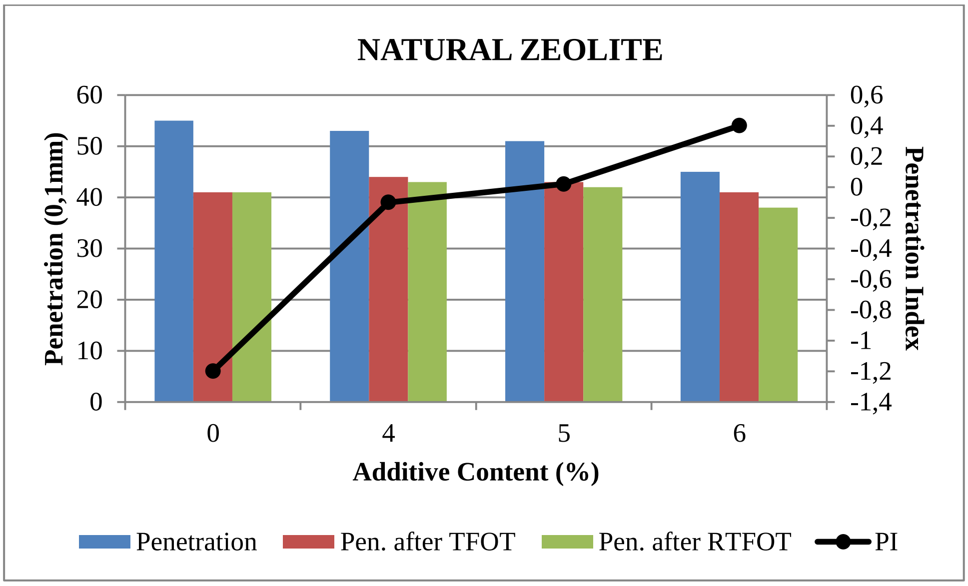

Figure 5.4 Penetration test results for natural zeolite modified bitumens

From aging point of view, as seen in even PI's and also changes for both TFOT and RTFOT, bitumen samples modified with non-foaming additives exhibit better resistance to aging than samples modified with foaming additives. In case of foaming additives, it is assumable that excessive amounts of mass loss would be due to loss of fine water particles as a result of volatilization during aging procedure in high temperature. Despite the mentioned guess, the penetration indices expressly show the participation of both Rediset® WMX and Sasobit® additives in resistance of bitumen sample against aging.

5.1.2 Softening Point Test Results

This section includes softening point test results before and after TFOT and RTFOT. Results are given respectively in Table 5.3 and Table 5.4. First three columns for both tables are the same (results are given in two tables to be easily compared).

Table 5.3 Softening point test results before and after TFOT

Bitumen type	**Additive Content (%) by Bitumen Weight**	**Softening Point (°C)**	**Softening Point (°C) after TFOT**	**Change in Softening Point (°C)**
Virgin Bitumen	0	49.1	54.1	5.0
Sasobit®	2	61.2	65.5	4.3
	3	69.3	73.3	4.0
	4	79.5	82.0	2.5
Rediset® WMX	1	55.4	58.8	3.4
	2	56.7	59.2	2.5
	3	58.0	59.5	1.5
Advera® WMA	4	53.6	58.2	4.7
	5	56.0	60.1	4.1
	6	59.9	63.1	3.3
Natural Zeolite	4	54.1	58.1	4.0
	5	55.0	58.7	3.7
	6	58.2	61.7	3.5

Table 5.4 Softening point test results before and after RTFOT

Bitumen type	Additive Content (%) by Bitumen Weight	Softening Point (°C)	Softening Point (°C) after RTFOT	Change in Softening Point (°C)
Virgin Bitumen	0	49.1	54.4	5.3
Sasobit®	2	61.2	65.7	4.5
	3	69.3	73.6	4.3
	4	79.5	83.0	3.5
Rediset® WMX	1	55.4	59.0	3.6
	2	56.7	59.2	2.5
	3	58.0	60.1	2.1
Advera® WMA	4	53.6	58.3	4.8
	5	56.0	60.5	4.5
	6	59.9	63.5	3.7
Natural Zeolite	4	54.1	58.4	4.3
	5	55.0	58.7	3.7
	6	58.2	61.4	3.2

Results indicate that using WMA additives increases the softening point value. This is more sensible for Sasobit® and it can be derived from the fact that using Sasobit® can be applicable in areas with wide range of climate temperature.

Results of change in softening point after TFOT and RTFOT simply indicate that not only less application temperatures for WMA technologies reduces aging, but also WMA additives structures participate in resistance against aging. Figures 5.5 to 5.8 present penetration and softening point test results.

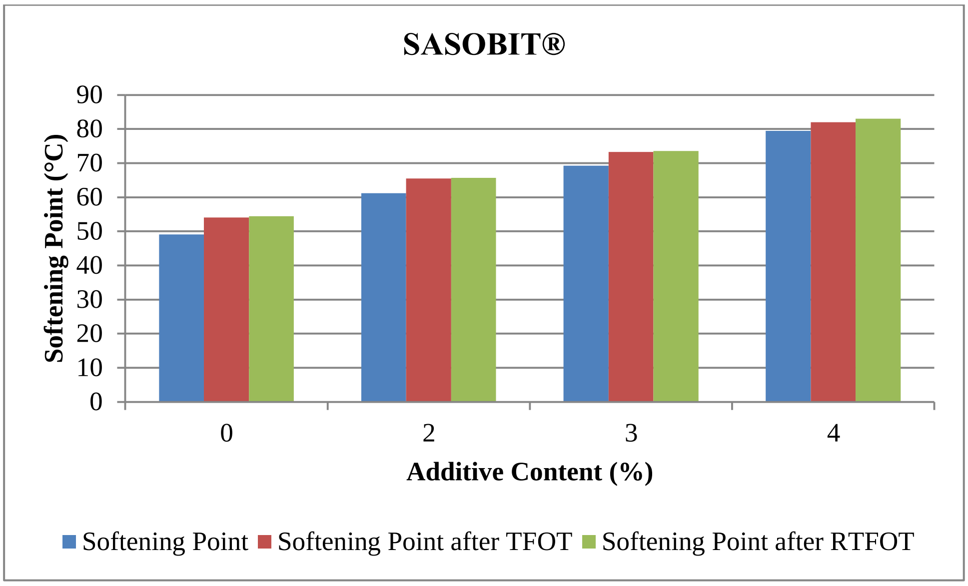

Figure 5.5 Softening point test results for Sasobit® modified bitumens

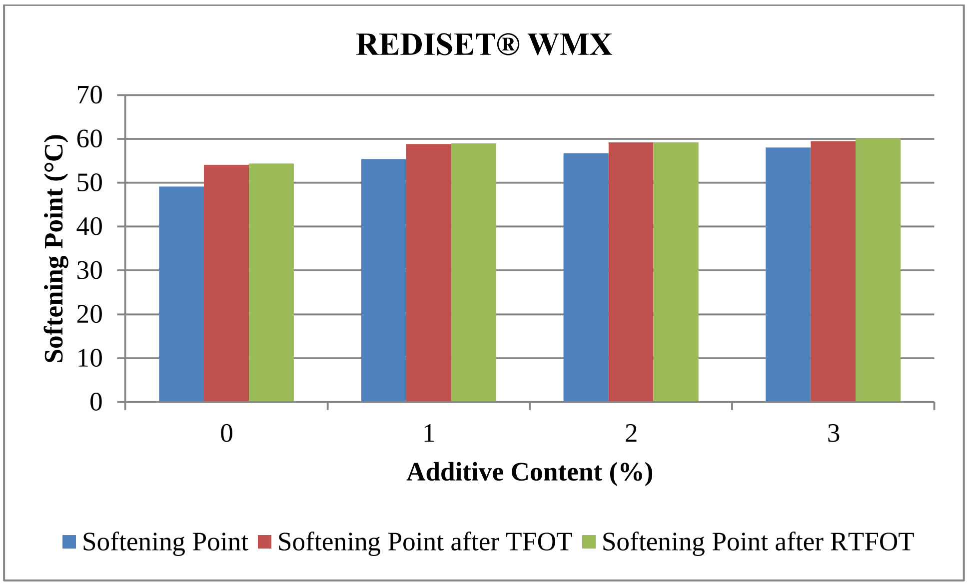

Figure 5.6 Softening point test results for Rediset® WMX modified bitumens

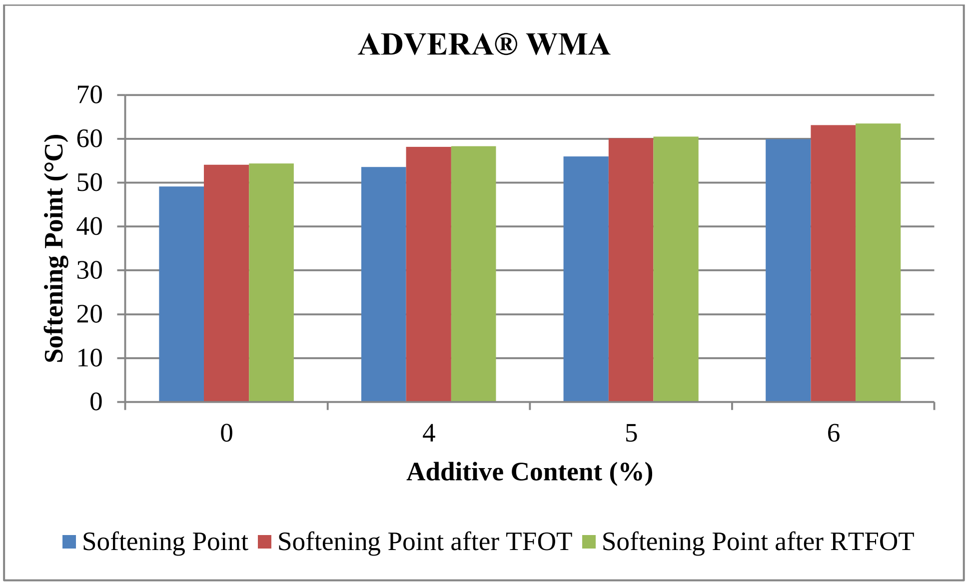

Figure 5.7 Softening point test results for Advera® WMA modified bitumens

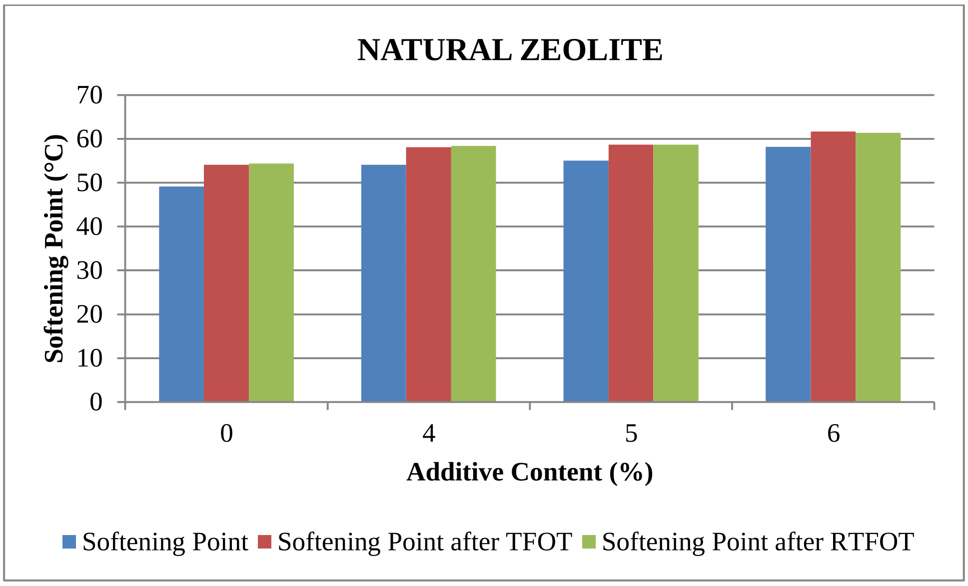

Figure 5.8 Softening point test results for natural zeolite modified bitumens

5.1.3 Brookfield Viscosity Test Results

Viscosity values (@ 135°C & 165°C) measured by Brookfield viscometer as per ASTM D4402-06 are given in Table 5.5. These values were implemented in finding mixing and compaction temperatures of different mixtures. Unfortunately, viscosities of TFOT and RTFOT aged bitumens are not available in this table due to the tight schedule of this study. Future researches can potentially include these values as well as the values for aged bitumens extracted from short- and long-term aged mixtures. There it can be possible estimations on aging indices based on viscosity values.

Table 5.5 Viscosity values @ 135°C & 165°C

Bitumen type	Additive Content (%) by Bitumen Weight	Viscosity	
		@ 135°C (Pa·s)	@165°C (Pa·s)
Virgin Bitumen	0	0.41	0.14
Sasobit®	2	0.3	0.11
	3	0.29	0.75
	4	0.28	0.75
Rediset® WMX	1	0.35	0.14
	2	0.34	0.88
	3	0.29	0.75
Advera® WMA	4	0.33	0.13
	5	0.31	0.11
	6	0.44	0.15
Natural Zeolite	4	0.35	0.13
	5	0.33	0.11
	6	0.4	0.19

5.2 Mixture Test Results

Tests conducted on compacted specimens are presented in this section. Marshall Stability and Flow test results for both control and WMA mixtures together with IDT results are separately presented and evaluated in following parts.

5.2.1 Marshall Stability and Flow Test Results

In order to achieve the optimum bitumen content for control and WMA mixtures, specimens were prepared with various bitumen contents according to Marshall mix design method of AASHTO T 245. The optimum bitumen contents for each WMA technology were measured by obtaining the optimum additive content for each technology based on previous researches in TÜBİTAK MAG.110M567. These optimum additive contents (all by weights of bitumen) are %3 for Sasobit®, %2 for Rediset® WMX, %5 for Advera® WMA and %5 for natural zeolite. After preparing Marshall specimens with various bitumen amounts, required measurements such as height, weight, weight in water and Saturated Surface Dry (SSD) weight were obtained and then specimens were tested for stability and flow by Marshall stability and flow test device. After making sure that all parameters are satisfying values based on Turkish standards, the optimum bitumen content for each kind were retrieved directly as the bitumen content corresponding to 4% air voids on content-air voids graphics based on second degree polynomial trendlines for each kind (Figure 5.9). Graphs are given below for each WMA and control mixtures. The optimum bitumen content for HMA, Sasobit®, Rediset® WMX, Advera® WMA and natural zeolite mixtures were respectively determined as 4.76%, 4.25%, 4.46%, 4.32% and 4.56% all by weight of aggregates. Test results are given in Appendices.

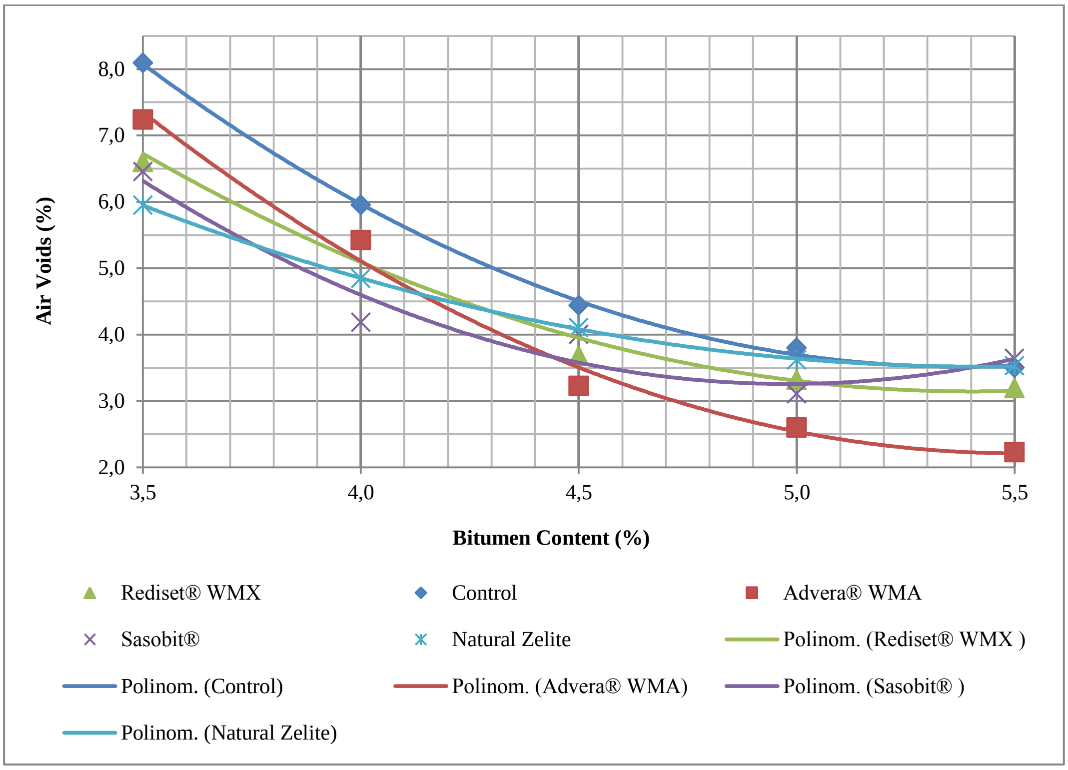

Figure 5.9 Optimum bitumen contents corresponding to 4% air voids based on second degree polynomial trendlines

According to the results, all WMA mixtures require less bitumen content than HMA mixture where Sasobit® has the minimum optimum bitumen content among all tested technologies. This simply proves the fact that compaction becomes easier using WMA technologies. Desired air voids can be achieved with less bitumen content while the other Marshall parameters remain acceptable. Another study conducted on mix design of some WMA technologies has shown a reduction in design bitumen content for WMA mixtures in comparison to HMA to some degree (Bonaquist, 2011).

Marshall stability values for the specimens prepared with optimum bitumen content for each WMA mixtures as well as the HMA mixture were controlled in accordance with Turkish standards. All values met the specifications and were in desired criteria. These results (retrieved from the equation of second degree polynomial trendlines) are shown in Figure 5.10 for all mixtures.

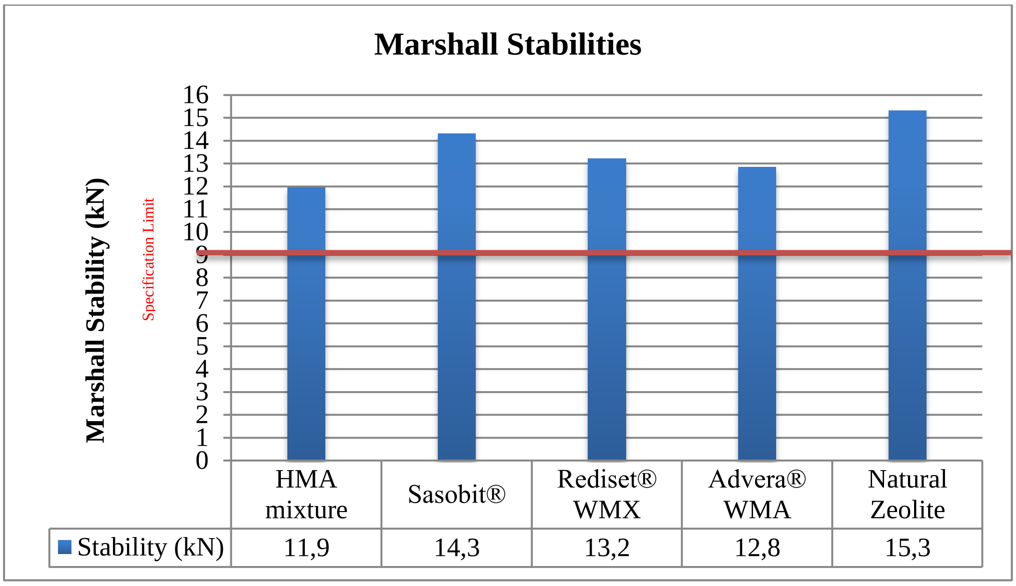

Figure 5.10 Stability values corresponding to optimum bitumen contents

The results showed that all WMA technologies bring about more Marshall stability compared to HMA mixture. Based on the previous tests on the bituminous laboratory of Dokuz Eylül University it can be said that a mixed gradation of basalt and limestone obviously has been contributed in gaining more stability for a Marshall specimen in comparison to a specimen prepared simply with a limestone gradation. The specimens contained natural zeolite additive presented the highest stability among all WMA specimens. This can be explained as the natural zeolite plays the filler role in the mixture.

5.2.2 Indirect Tensile Strength Test Results

As mentioned before, nine Marshall Specimens were prepared for each kind of WMA mixtures and also for control specimens with no additive amount. Three of these nine specimens were tested for ITS in un-aged mode while three of them were tested as short-term aged and three as long-term aged specimens. Result tables are given in appendices. After obtaining the averages for each three of a kind specimens, two aging indices including short-term Aging Index (SAI) and Long-term Aging Index (LAI) were calculated as the ratio of aged ITS values over un-aged ones. These indices are presented in the following section titled as Statistical Analysis.

ITS results of un-aged specimens for optimum additive content for each additive (the median content) showed that the specimens prepared with non-foaming additives such as Sasobit® and Rediset® WMX have more ITS values than those prepared with foaming additives such as Advera® WMA and natural zeolite. This can be explained as these foaming additives cause stripping phenomenon in mixture since the moisture directly affects the adhesion between aggregates and the bitumen. Figure 5.11 shows the ITS results for un-aged specimens prepared with optimum bitumen content (using virgin and modified bitumens prepared with optimum additive contents).

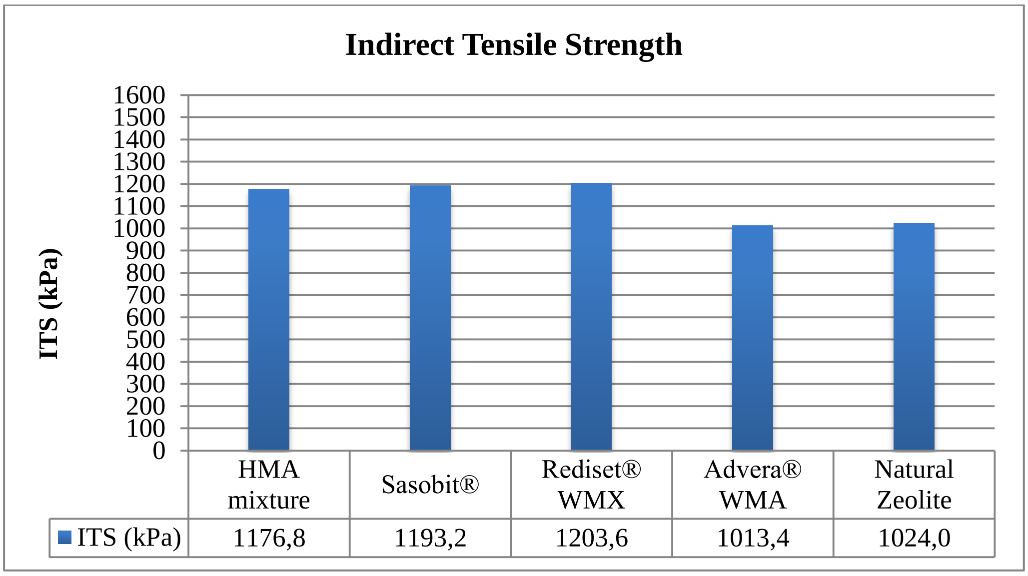

Figure 5.10 ITS values for un-aged specimens

5.3 Statistical Analysis

Indices for evaluation of aging characteristics of WMA additives on bituminous mixtures are presented in this section. As mentioned in previous sections, these indices were calculated as the ratio of ITS results of short-term and long-term aged specimens over ITS results of HMA control specimens. The calculating formulas for Short-term Aging Index (SAI) and Long-term Aging Index (LAI) are as follows.

$$SAI = \frac{ITS\ value\ of\ Short - term\ Aged\ Specimen}{ITS\ value\ of\ Un - aged\ Specimen}$$

$$LAI = \frac{ITS\ value\ of\ Long - term\ Aged\ Specimen}{ITS\ value\ of\ Un - aged\ Specimen}$$

By means of these indices, we are able to see how hardened an aged specimen has been after the aging process. The results for each additive are demonstrated in Figures 5.11 to 5.14 respectively for Sasobit®, Rediset® WMX, Advera® WMA and natural zeolite.

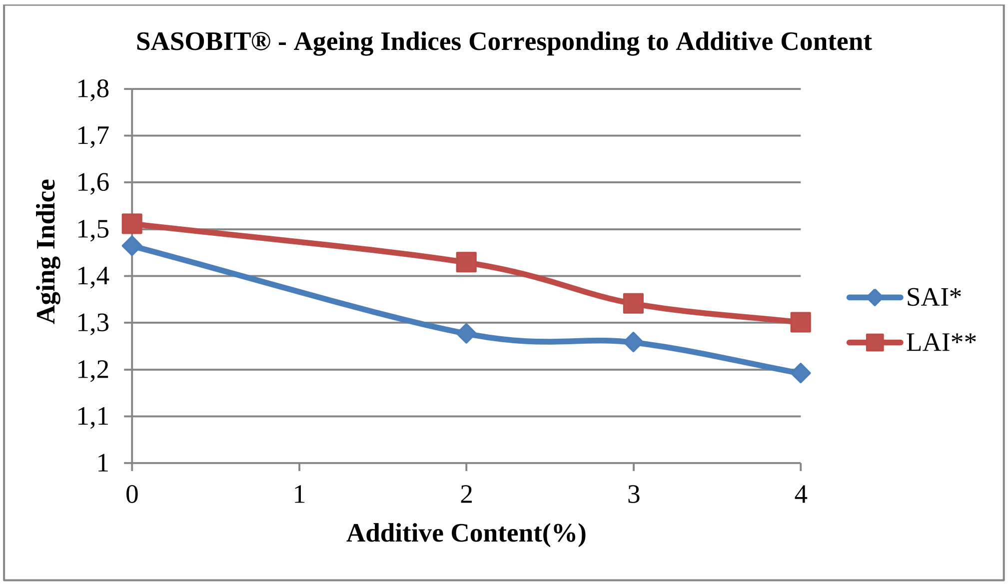

Figure 5.11 AI values corresponding to additive contents for Sasobit®

Note: *SAI = Short-term Aging Index & **LAI = Long-term Aging Index

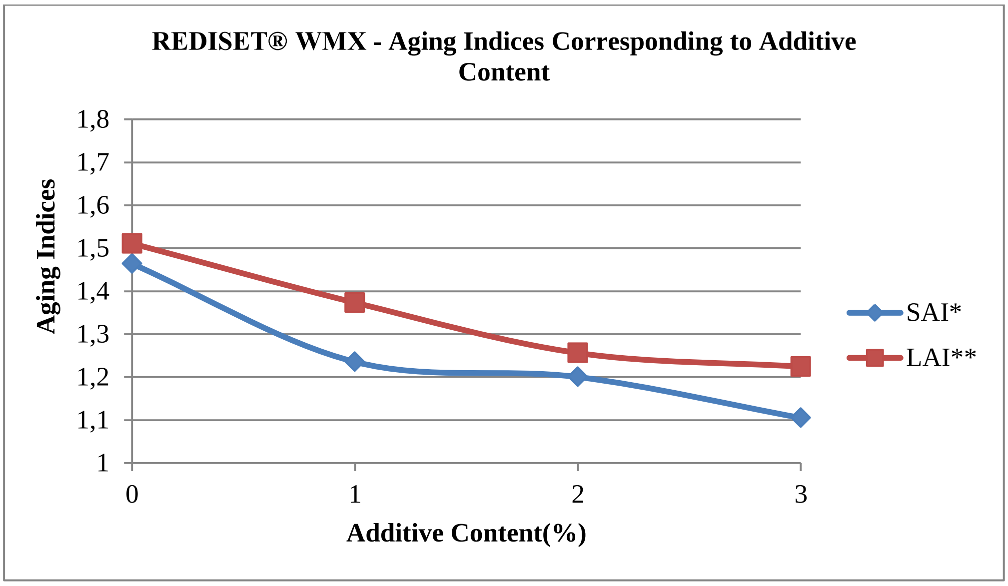

Figure 5.12 AI values corresponding to additive contents for Rediset® WMX

Note: *SAI = Short-term Aging Index & **LAI = Long-term Aging Index

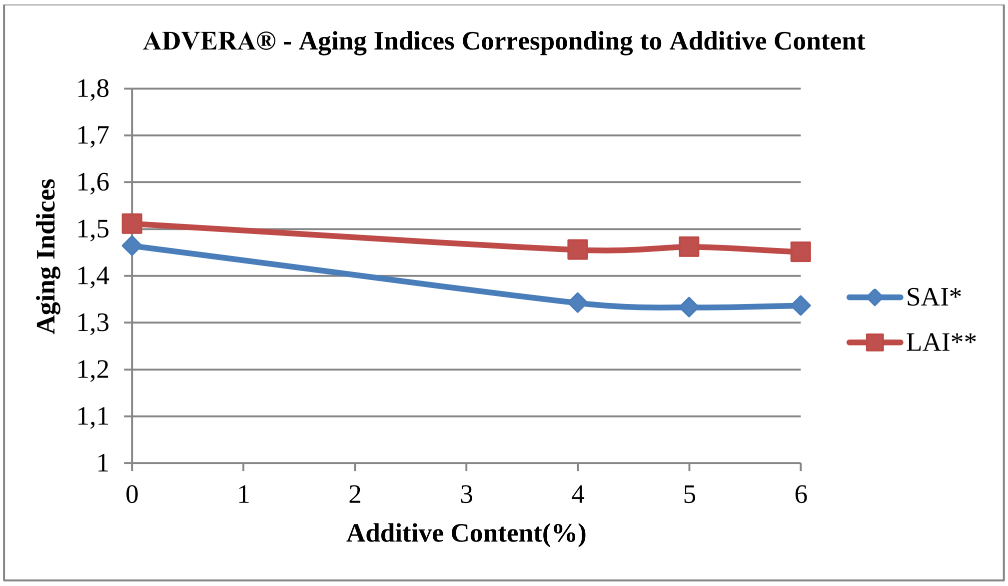

Figure 5.13 AI values corresponding to additive contents for Advera® WMA

Note: *SAI = Short-term Aging Index & **LAI = Long-term Aging Index

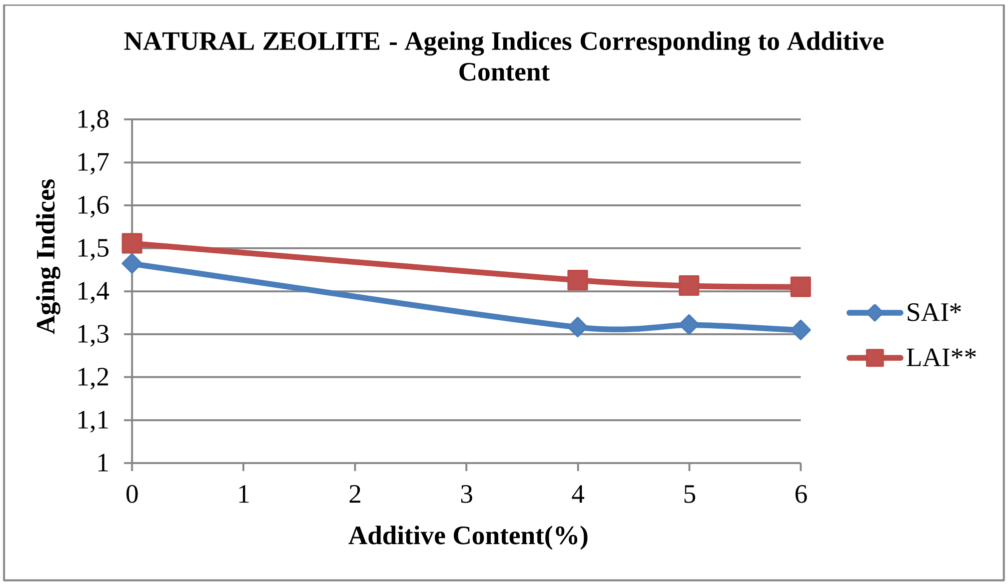

Figure 5.14 AI values corresponding to additive contents for natural zeolite

Note: *SAI = Short-term Aging Index & **LAI = Long-term Aging Index

As seen in the graphs, almost all WMA specimens exhibited lower aging indices than control specimens as it was expected. As discussed before, temperature is a vital factor in occasion of the aging. Lower application temperatures can cause less aging especially in case of short-term aging. Having a glance on the slope of the trendlines for both SAI and LAI values in all the above graphics simply proves this fact. Obviously the drop in SAI is more than the drop in LAI for all the additives. This is due to application temperatures during construction phase. The short-term aging occurs during production, storage and hauling in particular temperatures. These temperatures differ for WMA and HMA pavements, since the long term conditions for both pavement types are mostly equal during the service life of the pavements.

When discussing about foaming additives, although they demonstrated less indices than HMA mixture, but the reduction in hardening was not sensible for these additives. Increasing the additive content seemed not to have a considerable effect on aging indices.

SAI and LAI values unveiled that non-foaming additives acted better than foaming additives in terms of aging. Rediset® WMX demonstrated the best strength against aging among all additives tested within the scope of this research. Sasobit®

could exhibit itself as an acceptable interceptor against aging. For both Sasobit® and Rediset® WMX, it was observed that the hardening became less when the additive content increased. The reduction slope seemed to become less in step by step increasing in additive content.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Like every structure in civil engineering, an asphalt pavement has a service life. The more the service life of an asphalt pavement, the more economic that asphalt pavement is. In terms of engineering economy, simply considering the initial cost of a structure is not the only important factor that an engineer should perform, but it is important to consider the service life of that structure. Although WMA technologies have a lot of economic benefits in comparison to HMA pavements in terms of energy, it is essential to consider the service life of these kinds of pavement. As aforementioned, this dissertation was allocated to evaluate the aging effects of some WMA technologies in terms of service life.

As a conclusion, generally WMA technologies can be categorized as acceptable alternatives for conventional HMA pavements in terms of aging. Applying these kinds of pavement in lower temperatures is the dominating advantage of WMA technologies from the aging point of view. Rather than lower application temperatures, it was observed that Rediset® WMX and Sasobit® contain anti-aging components within their chemical structure which helped reduce aging.

The results showed that some of long-term characteristics of WMA pavements are better than conventional HMA pavements. In summary, non-foaming additives represented better aging indices in comparison to foaming additives. Rediset® WMX exhibited the best performance against aging between all WMA additives tested in this study. Sasobit® followed Rediset® WMX having well aging index. When discussing about Sasobit®, rather than having pleasant aging index, this additive can be used in areas having wide range of climate change since the bitumen modified with this wax sustains its rheological properties in good conditions while having increased softening point. Although the aging indices of both Advera® WMA and natural zeolite additives were better than HMA mixture but they seemed not having a functional effect against hardening while the aging indices for these additives remain in acceptable criteria.

6.2 Recommendations for Future Research

This study mainly aimed to evaluate the effect of WMA additives on aging characteristics of bituminous mixtures by means of ITS results. Within the scope of this study, a special attempt was made to be unbiased. In some cases, tests were repeated when it was necessary. The aggregate should be provided from quarry in one batch and be tested before being aged and oxidized by weather. On the other hand, attention should be given to use virgin fresh bitumen especially in case of aging tests.

Since the WMA technologies are relatively new, the future research for these technologies include a wide research area. The following suggestions are potentially new research topics in terms of pavement service life:

- Evaluating the effect of WMA additives on bitumen aging characteristics
- Evaluating the aging characteristics of foamed WMA mixtures using anti stripping additives
- Evaluating of aging characteristics of WMA additives using RAP
- Defining new methods and temperatures for aging procedure of WMA mixtures
- Life cycle cost of WMA mixtures

Rather than suggested future researches, there are other tests which can be used approaching the aim of this study as well. One of the major methods in order to check how a specimen has been hardened is testing its un-aged resilient modulus and the resilient modulus of that particular specimen after being aged. Then defining similar aging indices based on resilient modules of the specimens.

Other similar aging indices can be defined and used in evaluating of WMA bitumens based on viscosity values. The bitumens which are supposed to be aged can be rather aged artificially by TFOT or RTFOT. The bitumen of aged specimens used in this study can also be extracted and tested for viscosity to use in evaluating the aging characteristics of WMA bitumens.

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APPENDIX A
MARSHAL MIX DESIGN

Table A.1 Marshall mix design data for virgin bitumen

Specimen No.	Bitumen %		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity	Max. teo. specific gravity	Voids (%)	VMA	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	Wa	**Wb**	**1**	**2**	**3**	**Avg.**	**A**	**C**	**B**	**V**	**Dp**	**Dt**	**Vh**	**%**	**%**	**mm**	**kgf**		**kgf**
1	4.0	3.8	66.74	66.86	67.00	66.9	1180.0	662.0	1192.0	530.0	2.226	2.3697	6.047	16.38	63.1	2.02	1240	0.925	1147
2	4.0	3.8	66.62	66.34	65.82	66.3	1177.0	663.5	1189.5	526.0	2.238	2.3697	5.57	15.95	65.1	2.77	1287	0.938	1207
3	4.0	3.8	65.16	65.28	65.52	65.3	1176.0	664.5	1188.5	524.0	2.244	2.3697	5.293	15.70	66.3	1.85	1246	0.956	1191
Avg.											2.236		5.638	16.01	64.8	2.21			1182
1	4.5	4.3	66.26	66.00	66.18	66.1	1183.5	662.0	1191.0	529.0	2.237	2.3550	5.001	16.37	69.4	2.69	1392	0.941	1310
2	4.5	4.3	65.00	65.06	65.20	65.1	1180.5	665.0	1189.5	524.5	2.251	2.3550	4.429	15.87	72.1	2.18	1374	0.960	1319
3	4.5	4.3	66.00	65.64	65.90	65.8	1181.5	663.0	1189.0	526.0	2.246	2.3550	4.621	16.04	71.2	2.14	1380	0.947	1307
Avg.											2.245		4.684	16.09	70.9	2.34			1312
1	5.0	4.8	65.62	66.00	65.60	65.7	1189.5	678.0	1207.5	529.5	2.246	2.3407	4.025	16.43	75.5	2.08	1329	0.949	1261
2	5.0	4.8	65.70	65.72	65.70	65.7	1198.0	679.5	1213.5	534.0	2.243	2.3407	4.153	16.54	74.9	2.31	1354	0.949	1285
3	5.0	4.8	64.64	64.78	64.62	64.7	1183.5	672.0	1198.5	526.5	2.248	2.3407	3.965	16.37	75.8	2.06	1394	0.970	1352
Avg.											2.246		4.048	16.45	75.4	2.15			1299
1	5.5	5.2	64.14	64.44	64.42	64.3	1200.0	688.5	1224.5	536.0	2.239	2.3266	3.774	17.11	77.9	2.14	1219	0.980	1195
2	5.5	5.2	65.00	65.00	65.28	65.1	1200.0	681.5	1218.0	536.5	2.237	2.3266	3.863	17.18	77.5	2.65	1172	0.960	1125
3	5.5	5.2	64.66	64.30	64.52	64.5	1196.0	682.5	1217.5	535.0	2.236	2.3266	3.915	17.23	77.3	3.46	1177	0.975	1148
Avg.											2.237		3.851	17.17	77.6	2.75			1156

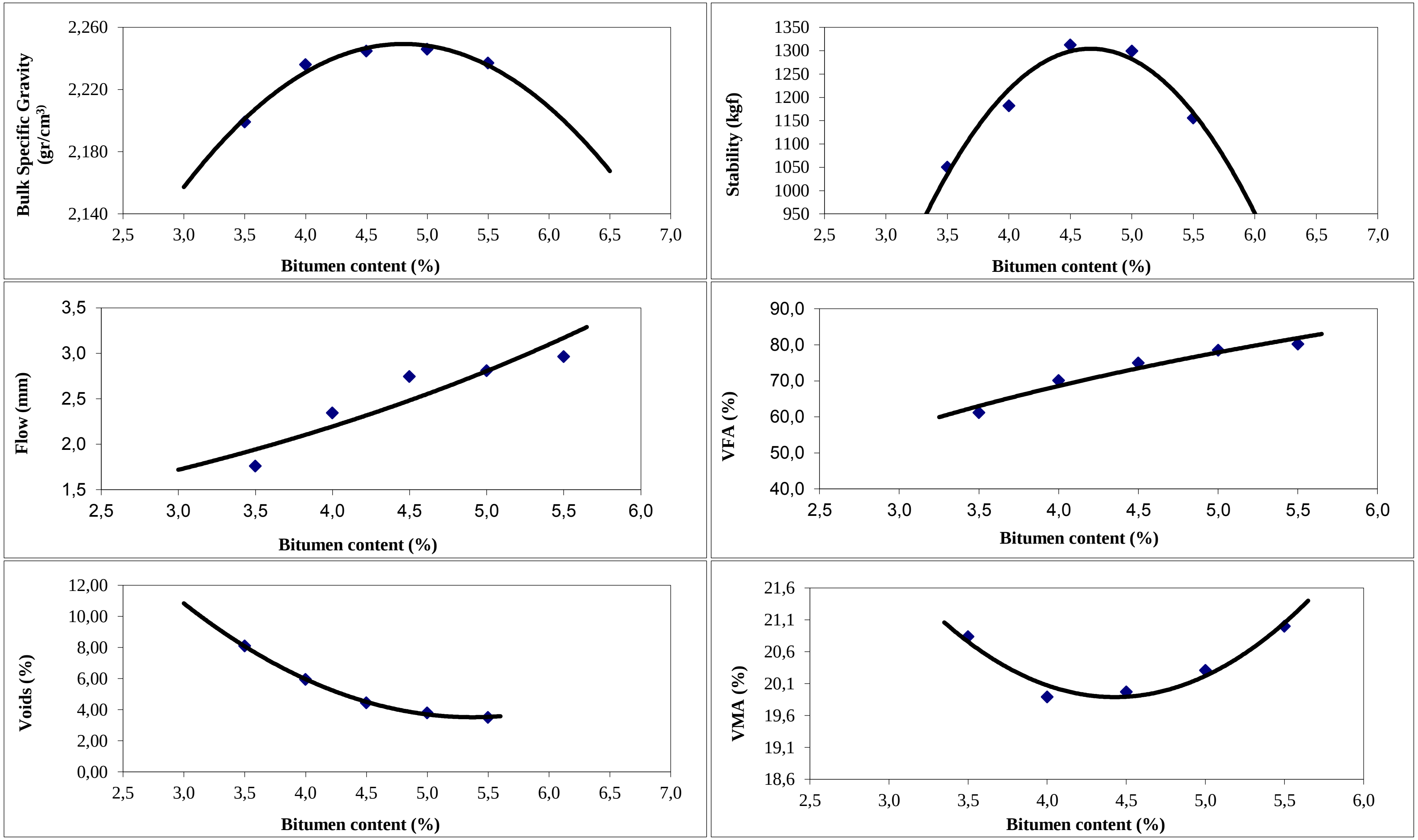

Figure A.1 Marshall mix design graphics for virgin bitumen

Table A.2 Marshall mix design data for Sasobit® modified bitumen

Specimen No.	Bitumen %		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity	Max. teo. specific gravity	Voids (%)	VMA	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	Wa	**Wb**	**1**	**2**	**3**	**Avg.**	**A**	**C**	**B**	**V**	**Dp**	**Dt**	**Vh**	**%**	**%**	**mm**	**kgf**		**kgf**
1	3.5	3.4	66.60	66.40	66.54	66.5	1167.0	654.0	1185.5	531.5	2.196	2.3796	7.730	20.96	63.1	1.73	1427	0.934	1333
2	3.5	3.4	65.40	65.42	65.34	65.4	1171.5	660.0	1182.0	522.0	2.244	2.3796	5.689	19.21	70.4	1.55	1438	0.954	1372
3	3.5	3.4	65.80	65.60	65.28	65.6	1169.5	659.0	1181.5	522.5	2.238	2.3796	5.940	19.43	69.4	1.57	1432	0.951	1362
Avg.											2.226		6.453	19.87	67.6	1.6			1356
1	4.0	3.8	64.72	64.52	64.66	64.6	1176.0	665.0	1183.0	518.0	2.270	2.3647	3.994	18.67	78.6	2.93	1525	0.973	1484
2	4.0	3.8	65.38	65.22	65.50	65.4	1174.0	663.0	1180.0	517.0	2.271	2.3647	3.972	18.65	78.7	2.56	1503	0.954	1434
3	4.0	3.8	65.82	65.74	65.52	65.7	1175.5	662.5	1183.5	521.0	2.256	2.3647	4.588	19.17	76.1	2.76	1535	0.949	1457
Avg.											2.266		4.185	18.83	77.8	2.8			1458
1	4.5	4.3	65.30	65.28	65.22	65.3	1175.5	666.5	1188.0	521.5	2.254	2.3502	4.088	19.63	79.2	2.45	1547	0.956	1479
2	4.5	4.3	65.26	65.42	65.20	65.3	1172.5	664.0	1185.0	521.0	2.250	2.3502	4.241	19.76	78.5	2.31	1518	0.956	1451
3	4.5	4.3	65.66	65.62	65.64	65.6	1176.0	669.0	1188.5	519.5	2.264	2.3502	3.678	19.29	80.9	2.21	1554	0.951	1478
Avg.											2.256		4.002	19.56	79.6	2.3			1469
1	5.0	4.8	65.42	65.44	65.48	65.4	1175.0	659.5	1179.0	519.5	2.262	2.3359	3.173	19.74	83.9	2.97	1183	0.954	1129
2	5.0	4.8	65.52	65.52	65.52	65.5	1176.5	660.0	1179.5	519.5	2.265	2.3359	3.049	19.64	84.5	3.15	1220	0.953	1163
3	5.0	4.8	65.54	65.56	65.54	65.5	1177.0	662.0	1182.0	520.0	2.263	2.3359	3.101	19.68	84.2	3.02	1214	0.953	1157
Avg.											2.263		3.107	19.69	84.2	3.0			1149
1	5.5	5.2	65.80	65.76	65.42	65.7	1172.0	665.5	1187.0	521.5	2.247	2.3219	3.212	20.63	84.4	4.12	1118	0.949	1061
2	5.5	5.2	65.42	65.20	65.38	65.3	1172.5	660.5	1186.0	525.5	2.231	2.3219	3.908	21.20	81.6	3.68	1125	0.956	1076
3	5.5	5.2	65.62	65.64	65.82	65.7	1176.0	658.5	1185.0	526.5	2.234	2.3219	3.804	21.12	82.0	3.95	1165	0.949	1106
Avg.											2.237		3.641	20.99	82.7	3.9			1081

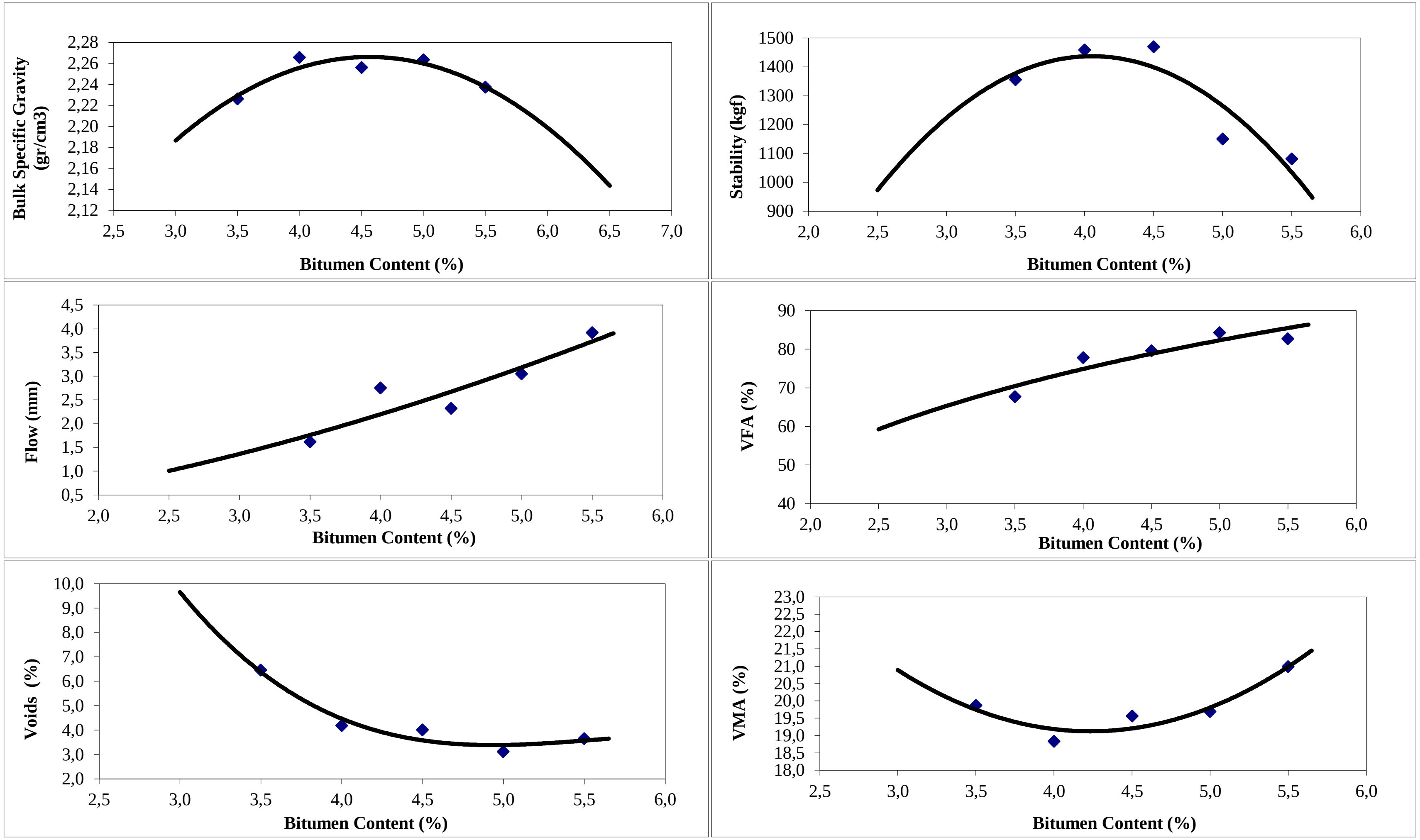

Table A.2 Marshall mix design graphics for Sasobit® modified bitumen

Table A.3 Marshall mix design data for Rediset® WMX modified bitumen

Specimen No.	Bitumen %		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity	Max. teo. specific gravity	Voids (%)	VMA	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	Wa	Wb	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	3.4	66.10	66.00	66.10	66.1	1174.0	661.0	1189.0	528.0	2.223	2.3814	6.630	19.96	66.8	2.08	1435	0.941	1350
2	3.5	3.4	65.90	65.82	65.84	65.9	1164.0	653.0	1177.5	524.5	2.219	2.3814	6.808	20.11	66.1	2.05	1440	0.945	1361
3	3.5	3.4	66.76	66.48	66.20	66.5	1177.5	663.5	1191.5	528.0	2.230	2.3814	6.352	19.72	67.8	2.05	1423	0.934	1329
Avg.											2.224		6.597	19.93	66.9	2.1			1347
1	4.0	3.8	67.50	66.78	66.92	67.1	1180.5	659.5	1187.5	528.0	2.236	2.3665	5.521	19.90	72.3	2.43	1567	0.920	1442
2	4.0	3.8	65.10	65.08	65.00	65.1	1179.5	658.5	1184.5	526.0	2.242	2.3665	5.242	19.67	73.3	2.40	1490	0.960	1430
3	4.0	3.8	65.42	65.40	65.48	65.4	1180.0	661.5	1189.5	528.0	2.235	2.3665	5.561	19.94	72.1	2.51	1497	0.954	1428
Avg.											2.238		5.442	19.84	72.6	2.4			1433
1	4.5	4.3	66.00	65.78	65.66	65.8	1187.5	668.5	1193.0	524.5	2.264	2.3519	3.733	19.28	80.6	2.15	1353	0.947	1281
2	4.5	4.3	66.10	65.92	65.88	66.0	1195.0	676.5	1204.0	527.5	2.265	2.3519	3.676	19.23	80.9	2.36	1327	0.943	1251
3	4.5	4.3	65.62	65.50	65.68	65.6	1191.0	671.0	1196.5	525.5	2.266	2.3519	3.633	19.19	81.1	2.28	1334	0.951	1269
Avg.											2.265		3.681	19.23	80.9	2.3			1267
1	5.0	4.8	65.30	65.28	65.64	65.4	1190.5	673.5	1200.5	527.0	2.259	2.3376	3.361	19.84	83.1	2.89	1246	0.954	1189
2	5.0	4.8	65.00	65.00	64.82	64.9	1193.0	679.0	1207.0	528.0	2.259	2.3376	3.341	19.83	83.1	2.84	1248	0.967	1207
3	5.0	4.8	65.28	65.30	65.52	65.4	1188.5	672.5	1198.0	525.5	2.262	2.3376	3.248	19.75	83.6	2.82	1252	0.954	1194
Avg.											2.260		3.316	19.81	83.3	2.9			1197
1	5.5	5.2	65.12	65.14	64.80	65.0	1195.5	679.5	1211.0	531.5	2.249	2.3236	3.197	20.57	84.5	3.61	1097	0.963	1056
2	5.5	5.2	65.28	65.20	65.00	65.2	1202.0	683.5	1218.0	534.5	2.249	2.3236	3.217	20.58	84.4	3.45	1038	0.958	994
3	5.5	5.2	65.78	65.48	65.52	65.6	1197.0	681.0	1213.0	532.0	2.250	2.3236	3.167	20.54	84.6	3.16	1086	0.951	1033
Avg.											2.249		3.194	20.56	84.5	3.4			1028

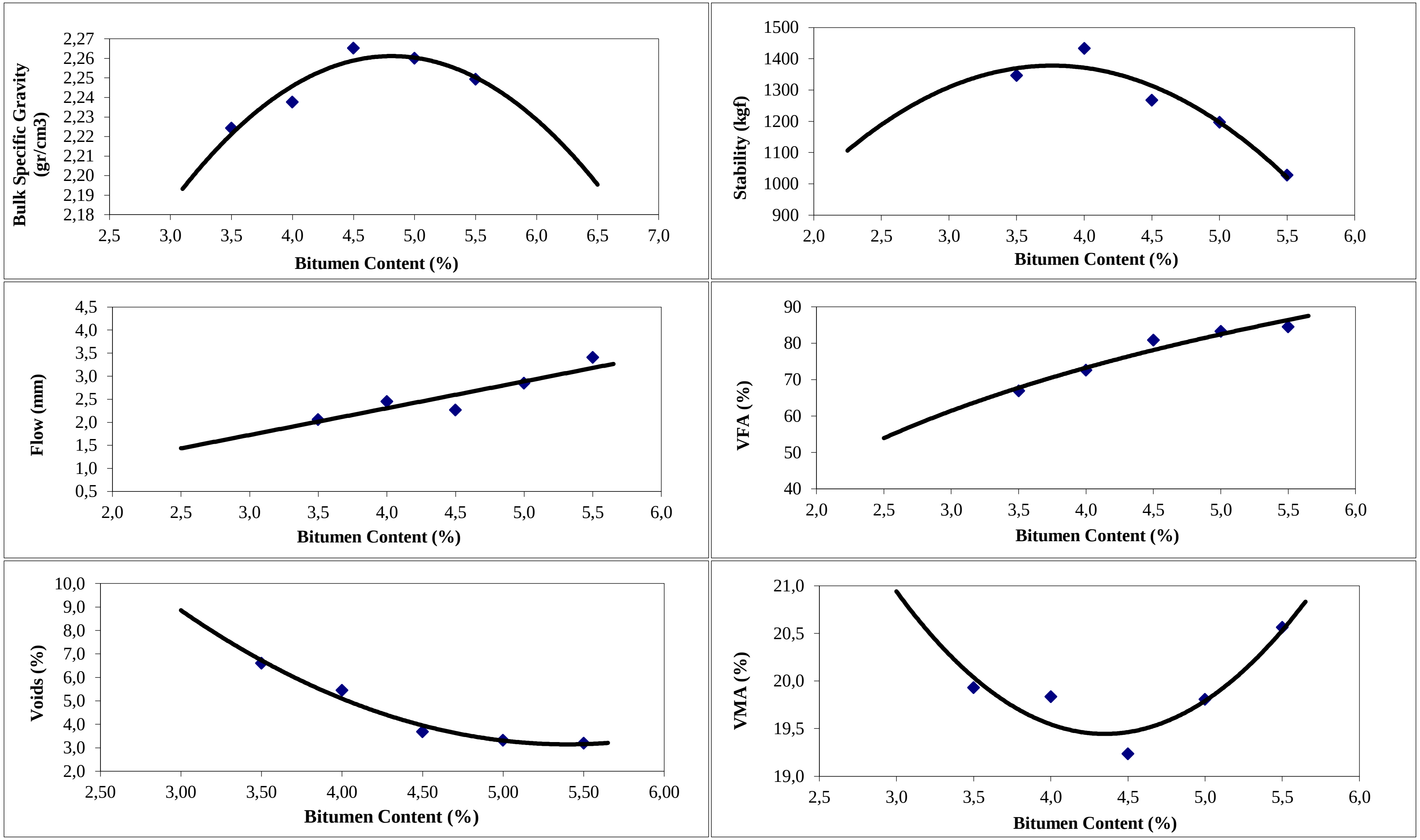

Figure A.3 Marshall mix design graphics for Rediset® WMX modified bitumen

Table A.4 Marshall mix design data for Advera® WMA modified bitumen

Specimen No.	Bitumen %		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity	Max. teo. specific gravity	Voids (%)	VMA	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	Wa	Wb	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	3.4	65.48	65.46	65.58	65.5	1174.3	659.2	1188.2	529.0	2.220	2.3911	7.160	20.09	64.4	2.39	960	0.953	915
2	3.5	3.4	65.30	65.38	65.42	65.4	1174.0	662.3	1191.9	529.6	2.217	2.3911	7.289	20.20	63.9	1.87	997	0.954	951
3	3.5	3.4	65.36	65.44	65.40	65.4	1172.2	660.5	1189.2	528.7	2.217	2.3911	7.274	20.19	64.0	1.83	843	0.954	804
Avg.											2.218		7.241	20.16	64.1	2.03			890
1	4.0	3.8	65.84	65.72	65.86	65.8	1180.4	666.2	1189.6	523.4	2.255	2.3760	5.080	19.21	73.5	1.95	1345	0.947	1274
2	4.0	3.8	66.52	66.32	66.78	66.5	1178.4	663.4	1192.8	529.4	2.226	2.3760	6.315	20.26	68.8	2.39	1251	0.934	1168
3	4.0	3.8	65.36	65.22	65.56	65.4	1174.8	662.3	1182.1	519.8	2.260	2.3760	4.876	19.03	74.4	2.51	1250	0.954	1193
Avg.											2.247		5.424	19.50	72.3	2.28			1212
1	4.5	4.3	64.52	64.78	64.56	64.6	1179.4	666.4	1183.4	517.0	2.281	2.3612	3.386	18.67	81.9	2.16	1256	0.973	1222
2	4.5	4.3	64.40	65.42	64.52	64.8	1180.3	668.1	1184.2	516.1	2.287	2.3612	3.144	18.46	83.0	2.20	1272	0.968	1231
3	4.5	4.3	64.38	64.76	64.40	64.5	1185.1	669.6	1187.8	518.2	2.287	2.3612	3.144	18.46	83.0	2.24	1278	0.975	1246
Avg.											2.285		3.225	18.53	82.6	2.20			1233
1	5.0	4.8	64.82	64.88	64.92	64.9	1190.5	671.5	1193.4	521.9	2.281	2.3468	2.798	19.06	85.3	2.64	1452	0.966	1403
2	5.0	4.8	64.04	64.26	64.54	64.3	1188.7	674.9	1190.9	516.0	2.304	2.3468	1.835	18.26	89.9	2.87	1540	0.98	1509
3	5.0	4.8	64.62	64.70	64.68	64.7	1186.4	669.1	1191.2	522.1	2.272	2.3468	3.170	19.37	83.6	2.66	1450	0.97	1407
Avg.											2.286		2.601	18.89	86.3	2.72			1439
1	5.5	5.2	63.78	63.74	63.88	63.8	1196.9	676.9	1200.7	523.8	2.285	2.3326	2.040	19.30	89.4	2.62	1258	0.993	1249
2	5.5	5.2	63.86	64.00	63.90	63.9	1191.3	671.5	1194.2	522.7	2.279	2.3326	2.293	19.51	88.2	2.58	1250	0.990	1238
3	5.5	5.2	64.10	64.28	64.22	64.2	1193.7	673.1	1197.2	524.1	2.278	2.3326	2.358	19.56	87.9	2.62	1251	0.983	1230
Avg.											2.281		2.230	19.46	88.5	2.61			1239

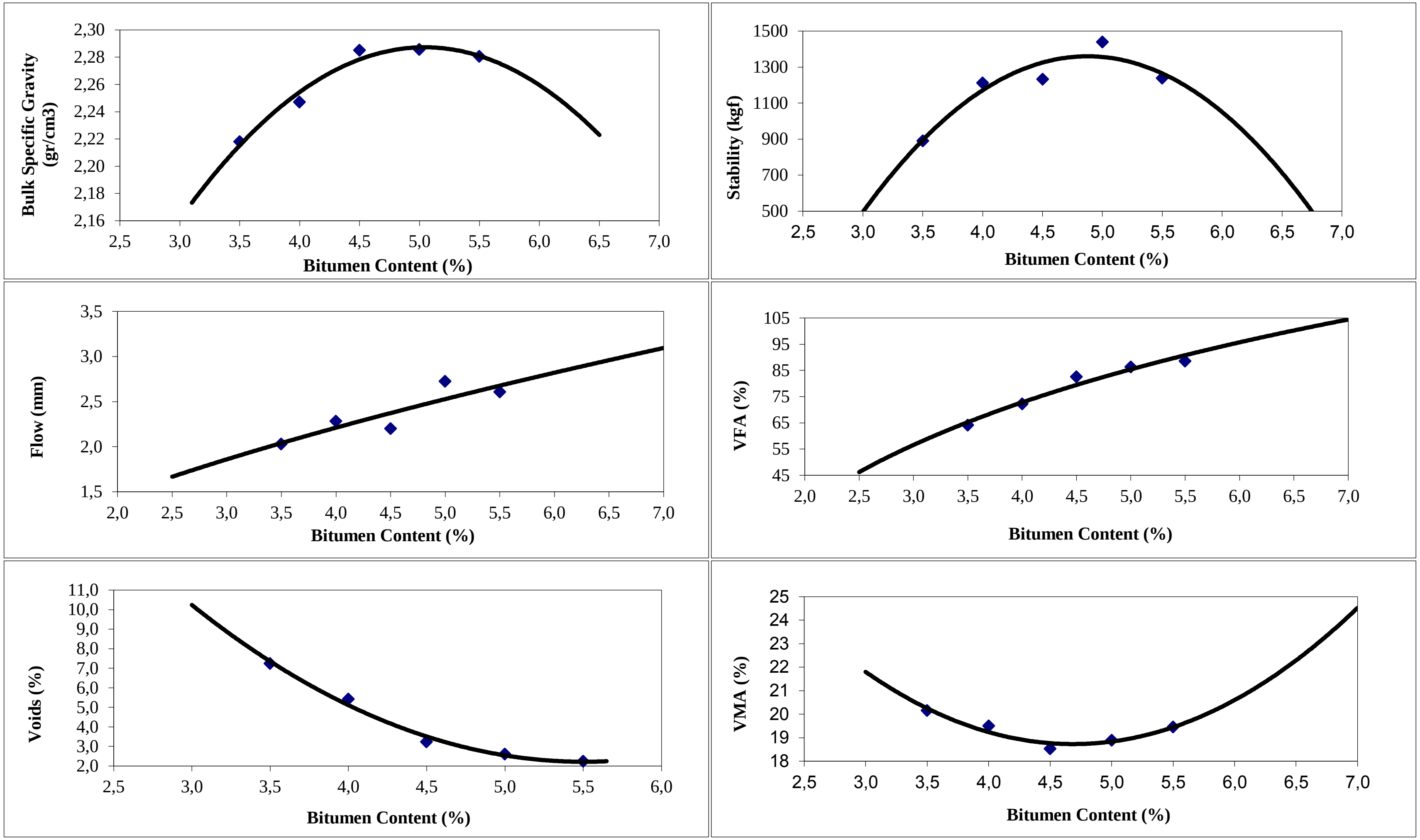

Figure A.4 Marshall mix design graphics for Advera® WMA modified bitumen

Table A.5 Marshall mix design data for natural zeolite modified bitumen

Specimen No.	Bitumen %		Specimen Height (mm)				Weight in air (gr.)	Weight in water (gr.)	SSD weight (gr.)	Volume	Bulk specific gravity	Max. teo. specific gravity	Voids (%)	VMA	VFA	Flow (mm)	Stability (kgf)	Correlation fact.	Corr. Stability (kgf)
	Wa	Wb	1	2	3	Avg.	A	C	B	V	Dp	Dt	Vh	%	%	mm	kgf		kgf
1	3.5	3.4	65.80	65.40	65.42	65.5	1179.5	670.5	1196.5	526.0	2.242	2.3884	6.114	19.28	68.3	1.98	1417	0.953	1350
2	3.5	3.4	65.22	65.38	65.66	65.4	1179.0	671.5	1195.5	524.0	2.250	2.3884	5.795	19.00	69.5	2.10	1409	0.954	1344
3	3.5	3.4	65.18	65.30	65.28	65.3	1179.5	670.0	1195.0	525.0	2.247	2.3884	5.935	19.12	69.0	2.03	1421	0.956	1358
Avg.											2.246		5.948	19.14	68.9	2.04			1351
1	4.0	3.8	65.80	65.76	65.46	65.7	1187.0	675.5	1201.5	526.0	2.257	2.3734	4.918	19.16	74.3	2.35	1575	0.949	1495
2	4.0	3.8	65.46	66.00	65.82	65.8	1188.0	676.0	1202.0	526.0	2.259	2.3734	4.838	19.09	74.7	2.47	1600	0.947	1515
3	4.0	3.8	65.10	65.14	65.12	65.1	1186.5	675.5	1200.5	525.0	2.260	2.3734	4.777	19.04	74.9	2.51	1591	0.960	1527
Avg.											2.258		4.844	19.09	74.6	2.44			1512
1	4.5	4.3	65.74	65.92	65.68	65.8	1191.0	678.0	1204.5	526.5	2.262	2.3586	4.093	19.35	78.8	2.55	1610	0.947	1525
2	4.5	4.3	65.62	65.66	65.66	65.6	1189.0	678.0	1204.5	526.5	2.258	2.3586	4.254	19.48	78.2	2.31	1622	0.951	1543
3	4.5	4.3	65.72	65.56	65.58	65.6	1188.0	679.0	1203.5	524.5	2.265	2.3586	3.970	19.24	79.4	2.59	1618	0.951	1539
Avg.											2.262		4.106	19.36	78.8	2.48			1535
1	5.0	4.8	65.12	65.18	65.18	65.2	1180.0	670.5	1193.0	522.5	2.258	2.3442	3.663	19.86	81.6	2.68	1508	0.958	1445
2	5.0	4.8	65.20	65.38	65.32	65.3	1182.5	671.5	1195.5	524.0	2.257	2.3442	3.735	19.92	81.3	2.61	1501	0.956	1435
3	5.0	4.8	65.80	65.46	65.52	65.6	1181.5	672.5	1194.5	522.0	2.263	2.3442	3.448	19.69	82.5	2.64	1502	0.951	1428
Avg.											2.259		3.616	19.83	81.8	2.64			1436
1	5.5	5.2	66.00	65.98	65.88	66.0	1179.5	669.5	1195.5	526.0	2.242	2.3302	3.766	20.81	81.9	2.89	1311	0.943	1236
2	5.5	5.2	65.78	65.80	65.78	65.8	1181.0	673.0	1197.0	524.0	2.254	2.3302	3.276	20.41	83.9	2.74	1309	0.947	1240
3	5.5	5.2	65.62	65.62	65.66	65.6	1184.5	674.0	1201.0	527.0	2.248	2.3302	3.542	20.62	82.8	2.76	1312	0.951	1248
Avg.											2.248		3.528	20.61	82.9	2.80			1241

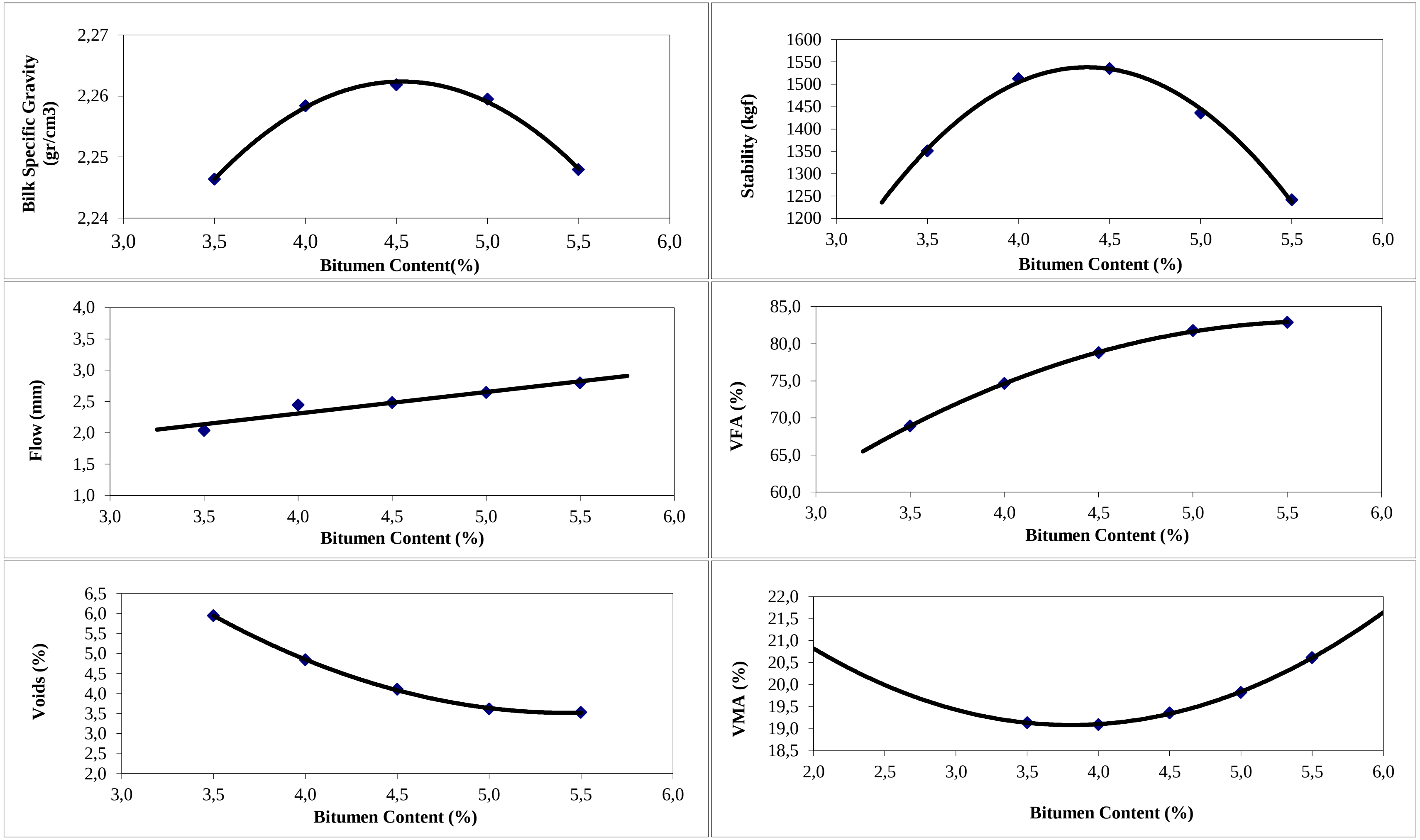

Figure A.5 Marshall mix design graphics for natural zeolite modified bitumen

APPENDIX B
INDIRECT TENSILE STRENGTH

Table A.6 Indirect tensile strength data for Sasobit® modified bitumen

Sasobit	Content (%)	Specimen Name/No.	Specimen Thickness (cm)				Diameter	Load	Load	ITS
			1	2	3	Ave.	(mm)	(kgf)	(N)	(kPa)
Unaged	0	1	62.9	62.9	62.8	62.9	101.6	1259	12346.57	1230.72
		2	63.4	63.3	63.1	63.3	101.6	1224	12003.34	1188.56
		3	63.1	63.4	63.1	63.2	101.6	1143	11209.00	1111.20
		Average								1176.83
	2	1	64.9	65.0	65.0	65.0	101.6	1187	11640.49	1122.71
		2	64.8	64.8	64.9	64.8	101.6	1163	11405.13	1102.04
		3	64.4	64.5	64.7	64.5	101.6	1201	11777.79	1143.70
		Average								1122.82
	3	1	63.5	63.9	64.0	63.8	101.6	1205	11817.01	1160.33
		2	64.1	64.6	64.4	64.4	101.6	1246	12219.09	1189.62
		3	63.5	64.1	63.7	63.8	101.6	1276	12513.29	1229.73
		Average								1193.23
	4	1	65.1	65.0	65.0	65.0	101.6	1224	12003.34	1156.76
		2	63.3	63.1	63.9	63.5	101.6	1253	12287.73	1213.40
		3	63.9	63.9	64.3	64.0	101.6	1304	12787.87	1252.00
		Average								1207.39
Shor-Tem Aged	0	1	64.0	64.3	64.1	64.1	101.6	1805	17701.00	1729.42
		2	64.7	64.8	64.9	64.8	101.6	1796	17612.74	1703.97
		3	63.9	64.1	64.3	64.1	101.6	1810	17750.04	1735.29
		Average								1722.89
	2	1	64.3	64.5	64.5	64.4	101.6	1548	15180.69	1476.43
		2	64.7	65.0	64.6	64.8	101.6	1477	14484.42	1401.32
		3	64.4	64.0	64.1	64.2	101.6	1486	14572.68	1422.74
		Average								1433.50
	3	1	64.2	64.2	64.2	64.2	101.6	1569	15386.63	1501.74
		2	64.6	64.9	64.7	64.7	101.6	1589	15582.77	1508.82
		3	64.8	64.8	64.9	64.8	101.6	1574	15435.67	1491.96
		Average								1500.84
	4	1	63.9	64.0	64.1	64.0	101.6	1486	14572.68	1427.04
		2	64.5	64.9	64.7	64.7	101.6	1494	14651.14	1419.05
		3	63.7	63.3	63.8	63.6	101.6	1523	14935.53	1470.69
		Average								1438.93
Long-Term Aged	0	1	64.2	64.4	64.5	64.4	101.6	1880	18436.50	1795.12
		2	63.7	64.0	63.7	63.8	101.6	1829	17936.36	1761.94
		3	64.3	64.7	64.4	64.4	101.6	1865	18289.40	1778.40
		Average								1778.49
	2	1	65.4	65.4	65.5	65.4	101.6	1670	16377.11	1568.12
		2	64.4	64.4	64.3	64.4	101.6	1713	16798.79	1635.15
		3	64.0	64.2	63.8	64.0	101.6	1676	16435.95	1609.50
		Average								1604.26
	3	1	64.6	64.9	64.7	64.7	101.6	1662	16298.65	1577.97
		2	64.9	65.3	64.9	65.0	101.6	1681	16484.98	1588.65
		3	64.6	65.1	64.8	64.8	101.6	1723	16896.86	1632.69
		Average								1599.77
	4	1	64.8	64.7	64.8	64.8	101.6	1681	16484.98	1595.19
		2	64.2	64.3	64.4	64.3	101.6	1636	16043.68	1563.92
		3	64.6	64.4	64.3	64.4	101.6	1628	15965.23	1552.25
		Average								1570.45

Table A.7 Indirect tensile strength data for Rediset® WMX modified bitumen

Rediset	Content (%)	Specimen Name/No.	Specimen Thickness (cm)				Diameter	Load	Load	ITS
			1	2	3	Ave.	(mm)	(kgf)	(N)	(kPa)
Unaged	0	1	62.9	62.9	62.8	62.9	101.6	1259	12346.57	1230.72
		2	63.4	63.3	63.1	63.3	101.6	1224	12003.34	1188.56
		3	63.1	63.4	63.1	63.2	101.6	1143	11209.00	1111.20
		Average								1176.83
	1	1	63.7	63.4	63.5	63.5	101.6	1198	11748.37	1158.92
		2	64.1	64.4	64.3	64.3	101.6	1185	11620.88	1132.56
		3	64.3	64.7	64.6	64.5	101.6	1186	11630.69	1129.06
		Average								1140.18
	2	1	63.8	64.1	64.1	64.0	101.6	1290	12650.58	1238.30
		2	64.4	64.8	64.8	64.7	101.6	1217	11934.69	1156.66
		3	64.0	63.8	63.9	63.9	101.6	1264	12395.61	1215.75
		Average								1203.57
	3	1	64.2	64.0	63.6	63.9	101.6	1287	12621.16	1236.97
		2	64.1	64.0	64.0	64.0	101.6	1244	12199.47	1193.77
		3	63.8	63.7	63.8	63.8	101.6	1310	12846.71	1262.50
		Average								1231.08
Shor-Term Aged	0	1	64.0	64.3	64.1	64.1	101.6	1805	17701.00	1729.42
		2	64.7	64.8	64.9	64.8	101.6	1796	17612.74	1703.97
		3	63.9	64.1	64.3	64.1	101.6	1810	17750.04	1735.29
		Average								1722.89
	1	1	64.2	64.3	64.2	64.2	101.6	1495	14660.94	1430.02
		2	64.6	64.4	64.7	64.5	101.6	1459	14307.90	1389.10
		3	64.0	64.2	64.1	64.1	101.6	1468	14396.16	1407.41
		Average								1408.84
	2	1	64.1	64.0	64.0	64.0	101.6	1552	15219.92	1489.65
		2	65.3	65.1	65.4	65.3	101.6	1512	14827.65	1423.39
		3	65.0	65.2	65.4	65.2	101.6	1508	14788.43	1421.36
		Average								1444.80
	3	1	63.4	63.7	63.6	63.5	101.6	1406	13788.15	1359.85
		2	63.5	63.8	63.3	63.5	101.6	1410	13827.38	1363.86
		3	64.5	64.6	64.7	64.6	101.6	1428	14003.90	1358.18
		Average								1360.63
Long-Term Aged	0	1	64.2	64.4	64.5	64.4	101.6	1880	18436.50	1795.12
		2	63.7	64.0	63.7	63.8	101.6	1829	17936.36	1761.94
		3	64.3	64.7	64.4	64.4	101.6	1865	18289.40	1778.40
		Average								1778.49
	1	1	64.0	64.1	64.3	64.1	101.6	1633	16014.26	1564.30
		2	64.1	64.2	64.0	64.1	101.6	1603	15720.06	1537.32
		3	64.5	64.4	64.7	64.5	101.6	1677	16445.75	1596.66
		Average								1566.09
	2	1	64.2	64.6	64.4	64.4	101.6	1599	15680.83	1525.86
		2	64.6	64.5	64.8	64.6	101.6	1568	15376.83	1490.72
		3	64.5	65.0	64.7	64.7	101.6	1600	15690.64	1519.58
		Average								1512.05
	3	1	64.0	64.1	64.1	64.1	101.6	1587	15563.15	1522.45
		2	64.2	64.2	64.4	64.3	101.6	1605	15739.67	1534.44
		3	64.3	64.3	64.5	64.4	101.6	1536	15063.01	1466.05
		Average								1507.65

Table A.8 Indirect tensile strength data for Advera® WMA modified bitumen

Advera	Content (%)	Specimen Name/No.	Specimen Thickness (cm)				Diameter	Load	Load	ITS
			1	2	3	Ave.	(mm)	(kgf)	(N)	(kPa)
Unaged	0	1	62.9	62.9	62.8	62.9	101.6	1259	12346.57	1230.72
		2	63.4	63.3	63.1	63.3	101.6	1224	12003.34	1188.56
		3	63.1	63.4	63.1	63.2	101.6	1143	11209.00	1111.20
		Average								1176.83
	4	1	64.3	64.8	64.5	64.5	101.6	1098	10767.70	1045.61
		2	65.0	64.8	64.8	64.9	101.6	1106	10846.15	1047.92
		3	64.3	64.5	64.4	64.4	101.6	1087	10659.83	1037.28
		Average								1043.60
	5	1	64.4	64.6	64.5	64.5	101.6	1084	10630.41	1032.49
		2	64.5	64.9	64.5	64.6	101.6	1056	10355.82	1004.16
		3	64.6	64.2	64.5	64.4	101.6	1052	10316.60	1003.57
		Average								1013.41
	6	1	63.9	63.9	64.0	63.9	101.6	986	9669.36	947.47
		2	64.1	64.1	64.0	64.1	101.6	1037	10169.50	994.82
		3	64.3	64.4	64.2	64.3	101.6	1062	10414.66	1015.42
		Average								985.90
Shor-Tem Aged	0	1	64.0	64.3	64.1	64.1	101.6	1805	17701.00	1729.42
		2	64.7	64.8	64.9	64.8	101.6	1796	17612.74	1703.97
		3	63.9	64.1	64.3	64.1	101.6	1810	17750.04	1735.29
		Average								1722.89
	4	1	65.0	64.9	65.0	65.0	101.6	1436	14082.35	1358.22
		2	64.8	64.6	64.6	64.7	101.6	1508	14788.43	1433.24
		3	64.9	64.7	64.8	64.8	101.6	1487	14582.49	1409.79
		Average								1400.42
	5	1	64.7	65.0	64.9	64.8	101.6	1440	14121.58	1364.81
		2	64.9	65.1	64.9	65.0	101.6	1453	14249.06	1373.74
		3	65.3	65.6	65.3	65.4	101.6	1397	13699.89	1312.58
		Average								1350.37
	6	1	64.3	64.2	64.0	64.1	101.6	1386	13592.02	1327.83
		2	64.5	64.8	64.7	64.6	101.6	1397	13699.89	1328.15
		3	64.9	64.8	65.0	64.9	101.6	1369	13425.30	1296.31
		Average								1317.43
Long-Term Aged	0	1	64.2	64.4	64.5	64.4	101.6	1880	18436.50	1795.12
		2	63.7	64.0	63.7	63.8	101.6	1829	17936.36	1761.94
		3	64.3	64.7	64.4	64.4	101.6	1865	18289.40	1778.40
		Average								1778.49
	4	1	64.0	64.1	64.1	64.0	101.6	1586	15553.35	1521.65
		2	64.1	64.3	64.2	64.2	101.6	1601	15700.45	1532.37
		3	64.4	64.5	64.5	64.5	101.6	1576	15455.28	1502.36
		Average								1518.79
	5	1	64.1	64.2	64.2	64.2	101.6	1524	14945.33	1459.43
		2	63.7	63.8	63.6	63.7	101.6	1587	15563.15	1530.73
		3	64.1	64.2	64.2	64.2	101.6	1518	14886.49	1453.98
		Average								1481.38
	6	1	63.9	63.9	63.8	63.9	101.6	1487	14582.49	1430.68
		2	64.4	64.4	64.6	64.5	101.6	1502	14729.59	1431.52
		3	64.2	64.3	64.1	64.2	101.6	1493	14641.33	1428.41
		Average								1430.20

Table A.9 Indirect tensile strength data for natural zeolite modified bitumen

N.zeolite	Content (%)	Specimen Name/No.	Specimen Thickness (cm)				Diameter	Load	Load	ITS
			1	2	3	Ave.	(mm)	(kgf)	(N)	(kPa)
Unaged	0	1	62.9	62.9	62.8	62.9	101.6	1259	12346.57	1230.72
		2	63.4	63.3	63.1	63.3	101.6	1224	12003.34	1188.56
		3	63.1	63.4	63.1	63.2	101.6	1143	11209.00	1111.20
		Average								1176.83
	4	1	64.4	64.5	64.2	64.4	101.6	1142	11199.19	1090.44
		2	64.3	64.8	64.2	64.4	101.6	1112	10904.99	1060.37
		3	64.8	64.6	64.7	64.7	101.6	1089	10679.44	1034.05
		Average								1061.62
	5	1	64.5	64.3	64.6	64.5	101.6	1096	10748.09	1044.57
		2	64.3	64.5	64.4	64.4	101.6	1054	10336.21	1005.89
		3	64.3	64.1	64.2	64.2	101.6	1068	10473.50	1021.69
		Average								1024.05
	6	1	64.6	64.7	64.8	64.7	101.6	1053	10326.40	999.97
		2	63.9	63.9	63.8	63.9	101.6	1032	10120.46	992.61
		3	64.1	64.2	64.0	64.1	101.6	1037	10169.50	994.41
		Average								995.66
Shor-Tem Aged	0	1	64.0	64.3	64.1	64.1	101.6	1805	17701.00	1729.42
		2	64.7	64.8	64.9	64.8	101.6	1796	17612.74	1703.97
		3	63.9	64.1	64.3	64.1	101.6	1810	17750.04	1735.29
		Average								1722.89
	4	1	64.8	64.3	64.6	64.5	101.6	1436	14082.35	1367.34
		2	64.3	64.4	64.1	64.2	101.6	1482	14533.46	1417.59
		3	65.0	64.9	64.9	64.9	101.6	1487	14582.49	1407.04
		Average								1397.32
	5	1	65.1	65.2	64.9	65.1	101.6	1439	14111.77	1358.41
		2	64.9	64.6	64.6	64.7	101.6	1409	13817.57	1337.90
		3	65.3	65.0	65.4	65.2	101.6	1448	14200.03	1364.25
		Average								1353.52
	6	1	64.3	64.4	64.5	64.4	101.6	1358	13317.43	1296.42
		2	65.0	65.0	64.8	64.9	101.6	1413	13856.80	1337.43
		3	64.3	64.3	64.4	64.3	101.6	1337	13111.49	1277.17
		Average								1303.67
Long-Term Aged	0	1	64.2	64.4	64.5	64.4	101.6	1880	18436.50	1795.12
		2	63.7	64.0	63.7	63.8	101.6	1829	17936.36	1761.94
		3	64.3	64.7	64.4	64.4	101.6	1865	18289.40	1778.40
		Average								1778.49
	4	1	64.3	64.8	64.5	64.5	101.6	1623	15916.19	1545.40
		2	64.9	64.8	65.1	64.9	101.6	1578	15474.89	1493.30
		3	65.1	65.3	65.1	65.2	101.6	1593	15621.99	1502.40
		Average								1513.70
	5	1	64.8	64.7	65.1	64.9	101.6	1498	14690.36	1419.19
		2	65.0	65.1	65.0	65.0	101.6	1549	15190.50	1464.05
		3	64.8	64.9	64.8	64.8	101.6	1537	15072.82	1456.59
		Average								1446.61
	6	1	64.1	64.2	64.0	64.1	101.6	1469	14405.97	1408.66
		2	64.4	64.4	64.6	64.4	101.6	1468	14396.16	1399.69
		3	64.7	64.6	64.4	64.5	101.6	1473	14445.20	1402.57
		Average								1403.64