DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE UTILIZATION OF RECYCLED ASPHALT CONCRETE WITH WARM MIX ASPHALT

by
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İZMİR

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We have read the thesis entitled **"THE UTILIZATION OF RECYCLED ASPHALT CONCRETE WITH WARM MIX ASPHALT"** completed by **JÜLİDE OYLUMLUOĞLU** under supervision of **ASSOC. PROF. DR. BURAK ŞENGÖZ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

The asphalt paving industry is facing two major challenges. These include increased demands for environmentally friendly paving mixtures and increasing costs of raw materials. Recycling of reclaimed asphalt pavement (RAP) is a critical necessity to save precious aggregates and to reduce the use of costly bitumen. Warm Mix Asphalt (WMA) technology provides the option of recycling asphalt pavement at a lower temperature than the temperature maintained in Hot Mix Asphalt (HMA) and hence provides recycling higher contents of RAP and saving energy and money.

This study investigated the feasibility of utilizing three different WMA additives (Sasobit®, Rediset®, Advera®) at different doses by weight of the bitumen with different percentages of RAP. Following the determination of the bitumen content, the aggregate gradation of RAP materials, Marshall Stability tests and Indirect Tensile Strength tests were conducted to evaluate the mechanical properties of the mixtures. Besides, cost-benefit analysis was made to investigate the advantages and disadvantages of recycling methods compared to HMA and WMA.

The results indicated that it is possible to produce mixes with RAP that exhibits similar stability values as virgin mixes. Moreover, it was found that samples prepared with RAP exhibits advantage in terms of cost compared to samples prepared with both HMA and WMA.

Keywords: Recycling, warm mix asphalt, Sasobit®, Rediset®, Advera®, reclaimed asphalt, cost-benefit analysis.

GERİ KAZANILMIŞ ASFALT BETONUNUN ILIK KARIŞIM ASFALTLARDA KULLANIMI

ÖZ

Asfalt kaplama endüstrisi, iki önemli problem ile karşı karşıya kalmaktadır. Çevre dostu asfalt karışımları için talep artışı ile birlikte, hızla yükselen hammadde maliyetleri bu iki önemli problemi meydana getirmektedir. Kazılmış asfalt kaplamasının (Reclaimed Asphalt Pavement) yeniden kullanılması, agrega tasarrufu ve pahalı asfalt bitümü kullanımının azaltılması için kritik bir gerekliliktir. Ilık karışım asfalt teknolojisi; geleneksel sıcaklığın çok daha altında geri dönüşüm seçeneği, dolayısıyla içeriği yüksek kazılmış asfalt kaplamasının yeniden kullanımını, enerji ve para tasarufunu sağlamaktadır.

Bu çalışmada, üç faklı ılık karışım asfalt katkısı (Sasobit®, Rediset®, Advera®) ile farklı içeriklerde hazırlanmış geri kazanılmış asfalt karışımları kullanımının fizibilitesi araştırılmaktadır. Geri kazanılmış asfalt karışımının bitüm içeriği ve agrega gradasyonu belirlendikten sonra, karışımın mekanik özelliklerini değerlendirmek amacıyla Marshall stabilite ve İndirekt çekme deneyleri uygulanmıştır. Ayrıca; geri dönüşüm yöntemlerinin avantajlarını ve dezavantajlarını, sıcak karışım ve ılık karışım asfaltlarla karşılaştırmak amacıyla fayda-maliyet analizi yapılmıştır.

Deneysel sonuçlara göre, geri kazanılmış asfalt içermeyen ılık asfalt karışımlarındaki gibi benzer mekanik özellikler gösteren geri kazanılmış asfalt kaplaması ile hazırlanan karışımların üretilebileceği ortaya çıkmıştır. Ayrıca yapılan çalışmalarda elde edilen verilere göre, hem sıcak karışım asfalta hem de ılık karışım asfalta kıyasla geri dönüşüm asfalt kullanımının ekonomik anlamda çok daha avantaj sergilediği saptanmıştır.

Anahtar sözcükler: Geri dönüşüm, ılık karışım asfalt, Sasobit®, Rediset®, Advera®, geri dönüşüm asfalt kaplaması, fayda-maliyet analizi.

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CHAPTER ONE
INTRODUCTION

Recycling of bituminous materials has generated considerable discussion and development in the last decade. Although it is not a new idea, recent studies appear to be in response to the need of many countries to reduce their dependency on imported crude oil and the derivative product as bitumen.

It would appear that the United States of America has led the technological development of modern recycling and while recycling is not practiced nationwide, it has become common practice in many states. Other countries which appear to be interested in developing recycling processes include Germany, France, Finland, India, and South Africa (Sengoz, 1997).

The use of Reclaimed Asphalt Pavement (RAP) provides a very economic method of asphalt (Cold Recycled or Hot Mix Asphalt) pavements construction (Mallick, Kandhal, & Bradbury, 2008). RAP contains both aggregates and bitumen, and hence its use saves natural resources, money while it is eco-friendly (Tao & Mallick, 2009).

A mix produced in the temperature range of 105°C from 135°C (220°F to 275°F) is considered to be warm mix asphalt (WMA) and the goal of such a mix is to obtain strength and durability that is equivalent to or better than Hot Mix Asphalt (Newcomb, 2006). Currently, a common way of achieving this comes through the use of additives. All of the current WMA additives in use facilitate lowering of production temperature by either lowering the viscosity and/or expanding the volume of the bitumen at a given temperature (Button, Estakhri, & Wimsatt, 2007; Hurley & Prowell, 2005). By lowering the viscosity or expanding the volume of the bitumen, the aggregates could be completely coated by the bitumen at a temperature lower than conventional (approximately 150°C) (O'Sullivan & Wall, 2009).

Lowering the temperature decreases energy cost and emission. However, the lowered temperatures are often criticized. Pakula & Mallick (2007), indicated that the only impact on emissions is temperature, therefore additives (Sasobit®, Rediset® and Advera®) may help reduce emissions. Regardless of the reduced energy costs, researchers are concerned that lower compaction temperatures used in WMA will reduce tensile strength, increase moisture damage and the rutting potential. Increased rutting potential may be due to the decreased age of bitumen at lower mixing temperatures (Hurley & Prowell, 2005).

Warm Mix Asphalt (WMA) technology provides a solution to maintain the available state of technology that enables to utilize more recycled asphalt pavement at a relatively lower temperature in HMA mixes. This technology provides a method of attaining low viscosity in the bitumen at relatively low temperatures (Mallick, Kandhal, & Bradbury, 2008). O'Sullivan & Wall (2009), indicated that the utilization of RAP with WMA technologies decreases the environmental impacts by using less virgin material and reducing CO_2 emissions. Mallick, Bradley, & Bradbury (2007), reported that it is possible to manufacture mixes with 75% to 100% RAP with similar properties to HMA mixes through the use of warm mix asphalt additives. The use of WMA additives helps reduce temperatures while achieving desired workability, thus enabling HMA to contain higher percentages of RAP (O'Sullivan & Wall, 2009).

The process used in this research treated the RAP at the contents of 10%, 20%, 30%, 40%, and 50% with WMA additives at recommended contents (Sasobit® at a dose 3% by weight of the bitumen, Rediset® at a dose 2% by weight of the bitumen and Advera® at a dose 5% by weight of the bitumen). The mechanical performances of the samples were evaluated by Marshall Stability test and Indirect Tensile Strength test. Following the experimental studies, cost-benefit analysis was performed to inspect the advantages and disadvantages of Recycled Asphalt Pavement in terms of economy.

CHAPTER TWO
RECYCLING

Recycling is a quite simple and easily applicable method. Recycling of reclaimed asphalt materials obtains new pavement materials and this results in saving virgin bitumen, virgin aggregate, energy and money. On the other side, the utilization of recycling helps to overcome the problem of disposal of old pavement waste. The specific advantages of recycling can be summarized as follows (Kandhal & Mallick, 1997):

- Saving of energy;
- Saving of bitumen and aggregates;
- Protection of environment;
- Preservation of the existing pavement geometrics;
- Cost reduction of construction;
- Less loss of time for users;
- Maintaining of existing roadway profile.

2.1 Recycled Asphalt Pavement

Recycled Asphalt Pavement (RAP) is old asphalt pavement that is milled up or ripped off the roadway. These RAP materials can be reused in the asphalt mixtures so that the bitumen and aggregates carry value. In addition, hot mix asphalt or warm mix asphalt containing RAP can exhibit an outstanding performance as well as mixtures which are made of new materials. Since most of roadways are constructed using high-type bituminous pavements, RAP materials, if properly processed, will consist of high quality, well graded asphalt coated aggregates (Al-Rousan, Asi, Al-Hattamleh, & Al-Qablan, 2008).

The mechanical properties of the recycled mixtures were also investigated by researchers. Kiggundu & Newman (1987), indicated that recycled mixtures had better resistance to the action of water than the virgin mixtures. Dunning &

Mendenhall (1978), showed that the durability of recycled asphalt concrete mixtures was better than that of the conventional mixtures.

While RAP material is reused in a new asphalt pavement mixture, it is essential to take into account the properties of materials in the mixture. Following consideration of RAP materials properties, the aggregate from RAP has to be blended with virgin aggregates to meet certain gradation specifications as well as the old bitumen content of RAP may need to be analyzed.

2.1.1 Recycling as a rehabilitation

National Cooperative Highway Research Program, defined that a feasible rehabilitation strategy is one that addresses the cause of pavement distress and deterioration and is effective in both repairing it and preventing or minimizing its reoccurrence. Recycling is a kind of rehabilitation choice to apply for asphalt pavement. The selection of rehabilitation alternatives depend on many parameters such as observed pavement distress, laboratory and field evaluation of existing material design parameters (Kandhal & Mallick, 1997).

Rehabilitation of pavement is needed for the following reasons:

- Reduction of surface friction;
- Unreasonable user costs;
- Maintenance requirements;
- Inadequate structural capacity;
- Inadequate pavement distress.

However; recycling has some advantages in terms of rehabilitation, recycling method sometimes is not appropriate for other kinds of rehabilitation techniques. For instance, recycling helps reduction of cost as well as save energy, bitumen and aggregates while recycling may not meet specific distress and structural needs of pavements.

2.1.2 Removal of Reclaimed Asphalt Pavement

Recycling has been defined as a method by which reclaimed asphalt pavement (RAP) is combined with new aggregate and an asphalt cement or recycling agent to produce hot mix asphalt (HMA). The RAP may be obtained by pavement milling with rotary drum cold milling machine or from a ripping/crushing operation (Huffman, 2001). When properly designed and constructed, recycled asphalt pavement characteristics should be proved to be at least equal to conventional mixes.

Two current methods for the removal of Reclaimed Asphalt Pavement are cold milling and ripping/crushing. Each of the method has been expressed in the following sections.

2.1.2.1 Cold Milling

Cold milling is the most widely used method of removing an existing pavement. Cold milling can be defined as the method of automatically controlled removal of pavement to a desired depth with special by designed equipment, and restoration of the surface.

There are five different techniques of cold milling. Class I, removes surface irregularities on the existing surface of pavement. Class II, provides a uniform depth as in plans. Class III, creates a uniform depth and cross slope. Class IV, consists of entire depth of existing pavement from the underlying base or sub-grade. Class V is a milling to a variable depth of the existing surface. Figure 2.1 presents a typical surface after from cold milling.

Figure 2.1 A typical surface resulting from cold milling.

2.1.2.2 Ripping and Crushing

The alternative to cold milling is ripping and crushing operations with equipments such as excavators, grid rollers or rippers. Figure 2.2 depicts a typical surface resulting from ripping and crushing. RAP materials are put into trucks and transferred for crushing. Selection of ripping equipment depends on the maximum size of RAP.

The advantage of cold milling with respect to ripping and crushing achieves crushing of RAP at the same time and in higher production rate. Thus, a major advantage is gained to cold milling.

Figure 2.2 A typical surface resulting from ripping and crushing.

2.1.3 Recycling methods

Five broad categories have been defined by Huffman (2001), to describe the various asphalt recycling methods. These categories are:

- Cold Planning (CP)
- Hot Recycling
- Hot In-Place Recycling (HIR)
- Cold Recycling (CR)
- Full Depth Reclamation (FDR)

Moreover, there are several sub-categories which define asphalt recycling. These include as follows:

- HIR
    - Surface recycling
    - Remixing

  - Repaving
- CR
  - Cold In-Place Recycling (CIR)
  - Cold Central Plant Recycling (CCPR)
- FDR
  - Pulverization
  - Mechanical Stabilization
  - Bituminous Stabilization
  - Chemical Stabilization

2.1.3.1 Cold Planning (CP)

CP is the controlled removal of an existing pavement to a desired depth, longitudinal profile and cross-slope by special equipments. In addition, CP can be used to rough pavements to restore low friction numbers and decrease slipperiness.

There are various benefits of CP such as removal of wheel ruts, energy conservation and less disruption to the public compared to other reconstruction methods.

2.1.3.2 Hot Recycling

Hot mix asphalt recycling is the most widespread method for recycling asphalt pavement. Hot recycling is the process which recycled asphalt pavement (RAP) materials are combined with virgin aggregates, virgin bitumen, sometimes a recycling agent in a hot mix plant to produce hot mix asphalt (HMA) mixtures. Some agencies routinely allow 15% or less RAP while others permit larger amounts of RAP. Higher RAP concentrations require adjustments in mix design and binder selection (Santucci, 2007).

Both batch and drum type hot mix plants are used to produce recycled mix. The RAP material can be obtained by milling or ripping and crushing operation. RAP delivery system for batch plant operation is shown in Figure 2.3. RAP may also be added directly to the mixer in a drum mix plant as presented in Figure 2.4 (Santucci, 2007).

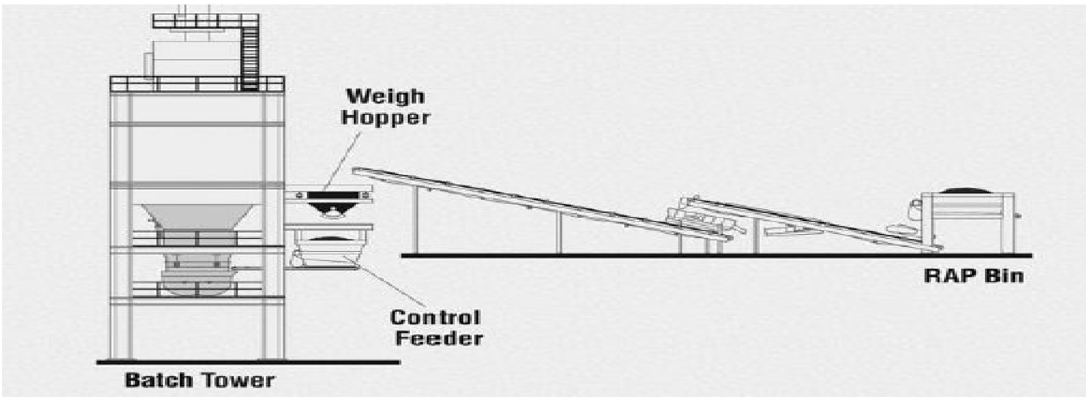

Figure 2.3 Reclaimed asphalt pavement delivery system for batch plants (Santucci, 2007).

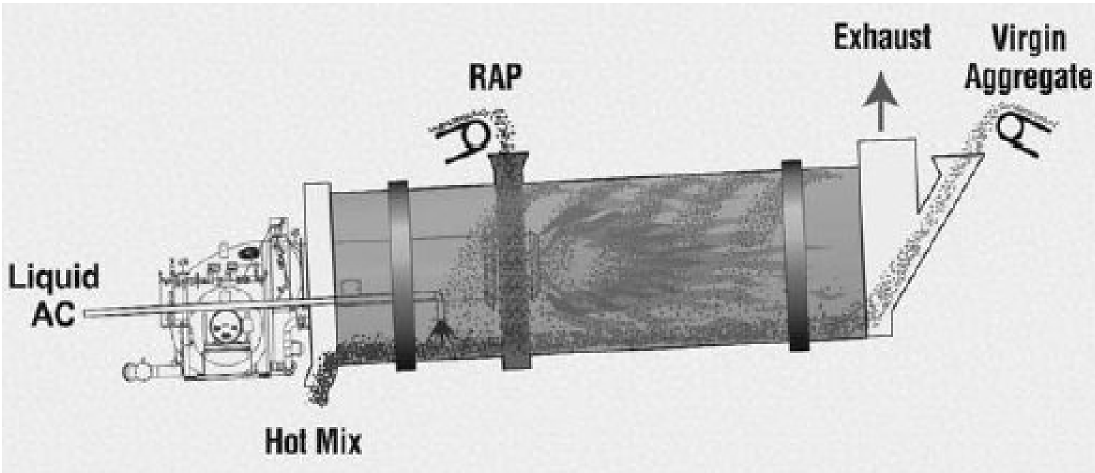

Figure 2.4 The mixer in a drum mix plant (Santucci, 2007).

2.1.3.3 Hot In-Place Recycling (HIR)

Hot In-Place Recycling consisting of the stages of scarifying, heating, mixing, placing and compacting 100 percent recycling on the existing asphalt pavement on site. If it is needed, virgin aggregates, virgin bitumen and recycling agent can be added. This process requires several types of equipments such as pre-heaters, heaters, scarifies, mixers and rollers. The combination of these equipments called as a 'train' (Santucci, 2007).

The advantages of Hot In-Place Recycling are elimination or minimization of cracks on pavement surface and interruption of traffic.

There are three sub-categories in hot in-place recycling which includes Surface Recycling, Remixing, and Repaving.

Surface Recycling is a type of HIR operation in which asphalt surface is heated and scarified to specific depth. Scarified materials are put together with aggregates and an agent. Consequently, the new asphalt mixtures are compacted by rollers.

In the second type of HIR method, Remixing in which the properties of the existing pavement required to be rehabilitated by the combining of virgin aggregates, virgin bitumen, an agent and new hot mix asphalt is added. Following application of these processes, the resultants are thoroughly mixed and recycled asphalt pavement mixture is placed in one layer of pavement.

The Repaving process is the combination of Surface Recycling and Remixing process with overlaying of new hot mix asphalt. The Surface Recycled and Remixed layer and additional new hot mix layer are compacted together which is given in Figure 2.5 (Santucci, 2007).

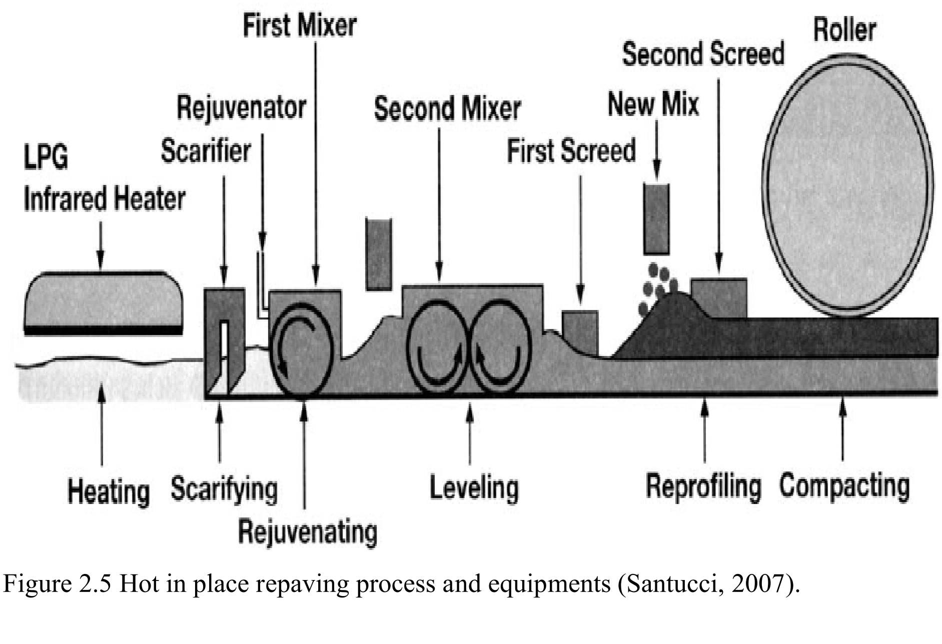

Figure 2.5 Hot in place repaving process and equipments (Santucci, 2007).

Repaving may be used when heater-scarification alone cannot restore the pavement’s necessary surface requirement or when a conventional operation to place an additional thick overlay is not needed or is inapplicable (Park, 2007).

2.1.3.4 Cold Recycling (CR)

Cold Mix Recycling is a method of recycling combined with RAP, new aggregate and emulsifier without heating operation in a cold mix plant. Construction delay can be caused by inadequate curing. Curing varies with several factors such as environment, moisture of mix, compaction level and voids content of mixture. This negativity can be prevented by using of lime or cement.

The two sub-categories of Cold Recycling are Cold In-Place Recycling and Cold Central Plant Recycling.

In the first type of CR method: Cold In-Place Recycling which is applied on site. The CIR uses a plenty numbers of equipments such as tanker trucks, milling machines, crushing, screening units, mixers, pavers and rollers. Combination of these equipments is called ‘train’ just like in Hot In-Place Recycling. Densification of CR mixes requires more energy than conventional HMA due to the high internal friction developed between the particles, the higher viscosity of the bitumen and colder compaction temperatures (Huffman, 2001).

Cold Central Plant Recycling (CCPR) takes place in a central location using a stationary cold mix plant. The RAP, which are used in CCPR, comes into ripping, removing and crushing operations.

2.1.3.5 Full Depth Reclamation (FDR)

Full Depth Reclamation is defined as a recycling method in which all parts of asphalt pavement and some amounts of base material is treated to construct a stabilized base course. It is basically a cold mix recycling process in which different types of additives such as asphalt emulsions and chemical agents such as calcium chloride, Portland cement, fly ash, and lime are added to obtain an improved base course (Kandhall & Mallick, 1997).

The advantages of Full Depth Reclamation can be summarized as:

- Production of non-renewable resources;
- Energy conservation compared to other reconstruction methods;
- Less equipment are required;
- Elimination of bumps and dips, rutting, potholes, patches, and cracks;
- Problems with existing aggregate gradation can be corrected;
- Deteriorated base can be reshaped to restore surface profile and drainage;
- Significant structural improvement with the addition of stabilizations;
- Produces thick, bound layers that are homogeneous.

2.2 Objectives of Recycling and Recycling Strategies

Recycling is one of the widespread pavement rehabilitation techniques. The recent increase in price of bitumen is a major factor in prompting the development of recycling. On the other hand, the asphalt industry is constantly encouraging the development of technologies that are cost effective, reduce energy consumption, and environmentally friendly (Hodo, Kvasnak, & Brown, 2009).

Over the years recycling has become one of the most desirable pavement rehabilitation alternatives. According to the continuous accumulation of performance data, field and laboratory evaluations of recycled mixes, it is expected that recycling will continue to be the most attractive rehabilitation technique.

The choice of rehabilitation technique should be based on energy conservation, economic consideration, engineering consideration, environmental effects.

2.2.1 Energy Conservation

The road industry has years been seeking to minimize the amount of energy required to manufacture asphalt mixture and to lower asphalt plant emissions, combining energy savings and environmental benefits for many years(Romier, Audeon, David, Martineau, & Olard, 2007).

Recycling processes conserve energy. Reusing aggregates reduces necessities of quarrying, transportation and the subsequent processing in recycling methods. Consequently, cost of energy is saved in these processes.

Recycled asphalt reduces the demand for new bitumen and saves energy at the refinery. Moreover, electric power consumption visibly decreases because of reduced demand for bitumen.

2.2.2 Economic Consideration

Recycling techniques can be reviewed in terms of the cost of the pavements. The cost of pavements is described in two different ways. The first way, present worth (PW) that is defined as the money needed at present to receive money for all costs of the pavement. The second way, equivalent uniform annual costs (EUAC) is an equivalent amount of money over the analyzing period.

On the other hand, life cycle costs of the rehabilitation alternatives must also be considered in economic analysis. Life cycle costs include the initial construction cost as well as the cost of maintenance activities during the life cycle. This analyzing period consists of costs components which are given as:

- Initial rehabilitation costs;
- Future rehabilitation costs;
- Maintenance costs;
- Residual value;

- Engineering costs;
- Costs for travel time, vehicle operation, accidents, delays and extra operating.

2.2.3 Engineering Consideration

Before selecting a rehabilitation alternative, the engineer should take care about environment, drainage factors and practical limitations. Engineering consideration also depends on the type of original surface where the new pavement layer will be replaced.

The most important consideration should be amount and severity of distress condition on the existing pavement because different recycling techniques can remedy different types of distresses, the most appropriate method should be considered.

2.2.4 Environmental Effects

Increasing environmental concerns have encouraged the development of using pollution-free, recyclable engineering materials that consume less energy to manufacture (Chiu, Hsu, & Yang, 2007).

The most indispensable effect of recycling is the benefit to environment. Before strengthening of deteriorated urban or rural roads, bituminous materials are generally removed and deposited outside of way. This inevitability represents an economic loss and creates environmental problems. The utilization of recycling techniques can provide significant benefits to the nature.

CHAPTER THREE
WARM MIX ASPHALT

In recent years, environmental protection is increasingly becoming a major issue in transportation including asphalt production. Despite of the fact that hot mix asphalt (HMA) is widely used around the world, some recent studies suggest using another process that reduces the production and placement temperature of asphalt mixes. There is a new technology is called the warm mix asphalt (WMA), and is used mostly in European countries (Wasiuddin, Selvamohan, Zaman, & Guegan, 2007).

Warm Mix Asphalt (WMA) is a technology that allows 20°C to 55°C lowering of the production and paving temperature compared to typical HMA. The reduction of temperature enables various benefits over HMA such as lowering the greenhouse gas emission, reduced smoke and consternation from the public, lowering energy consumption, fuel cost saving, improvement working conditions, acceptable workability and compaction.

Warm asphalt processes have been identified with the utilization of Sasobit®, Rediset®, Advera® (Kanitpong, Nam, Martono, & Bahia, 2008; Rubio, Martínez, Baena, & Moreno, 2012; Xiao, Punith, & Amirkhanian, 2012). These additives are either applied directly to bitumen under manufacturing temperature or duration. It forms a homogeneous solution with virgin binder and obtains a significant reduction in the bitumen's viscosity.

3.1 Warm Mix Asphalt Technology

The utilization of Warm Mix Asphalt is not a new technology. The first time, Prof. Ladis Csanyi produced asphalt with bitumen that was foamed by steam in 1956 at Iowa State University, US (Sargand, Figueroa, Edwards, & Al-Rawashdeh, 2009). Then, foaming technology started to spread out different countries such as Australia, US and Europe.

Scientists have introduced the utilization of waxes as viscosity modifier for the last twenty years. Initially, waxes were used for efficient workability of asphalt, not for lowering the temperature purpose.

The world focuses on the development of WMA technologies due to two distinctive events such as the 1992 United Nations' discussions on the environment and the 1996 Germany's consideration to review asphalt fumes exposure limits. Reduction of mixing and placement temperatures became the obvious answer and triggered the development of WMA concepts and technologies (Croteau & Tessier, 2008).

In conjunction with developing modern WMA technologies, laboratory studies have been conducted to show potential benefits of Warm Mix Asphalt and to evaluate the performance compared to traditional Hot Mix Asphalt. First research reports are from Europe in mid 90'ies then a lot of testing and field trials have been conducted in US with publically available reports (Zaumanis, 2010).

HMA is produced at temperatures ranging from 138°C to 160°C. This high temperature is used to decrease the viscosity of bitumen and dry the aggregates in order to cover them by bitumen. However; in warm mix asphalt, temperature and viscosity are decreased by additional of chemicals or wax as lubricants in mixing processes. The additives are simply an adhesion agent, which may play a significant role in Warm Mix Asphalt Technology. The mixing of additives reduces viscosity of bitumen and increase workability of mixture.

The selection of these additives is based on many factors. Based on discussions with industry experts and a scan of available literature, these WMA additives are the most predominantly specified and utilized both nationally and regionally in northeast for field trials (O'Sullivan & Wall, 2009).

Decreasing asphalt production emissions and lowering compaction emissions in the plant are the most important benefits of utilization of warm mix asphalt.

Lowering of mixing and compaction temperatures reduce energy consumption because of saving fuel. The detailed information related to the benefits of using WMA will be discussed in the further chapters.

3.1.1 Classification of the Methods Related to WMA Technology

Figure 3.1 illustrates various application temperatures for asphalt concrete with different level of temperature reduction (D'Angelo, Harm, Bartoszek, Baumgardner, Corrigan, Cowsert, Harman, Jamshidi, Jones, Newcomb, Prowell, Sines, & Yeaton, 2008). The ranges of production temperatures define four types of asphaltic concrete such as:

- Cold Mix Asphalt (0 C°-30 C°)
- Half Warm Mix Asphalt (65 C°-100 C°)
- Warm Mix Asphalt (100 C°-140 C°)
- Hot Mix Asphalt (above 140 C°)

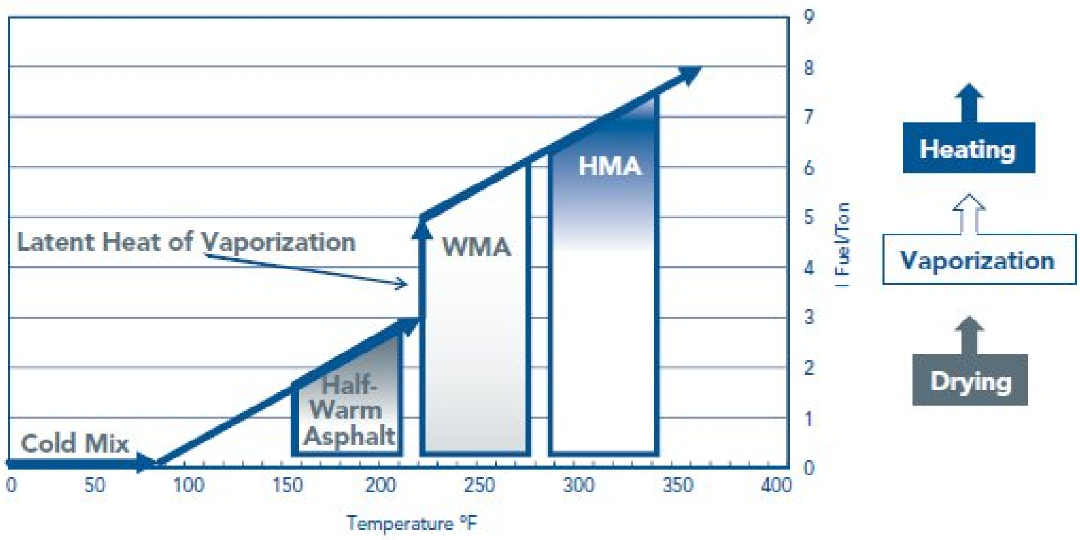

Figure 3.1 Classification by temperature ranges (D'Angelo et al., 2008).

Among them, WMA technology can be classified based on the utilization of water as well as organic and chemical additives:

- Foaming techniques (water-based and water containing)
- Organic or wax additives
- Chemical additives

Table 3.1 presents a summary overview of WMA technologies and there use to date throughout the world (Middleton & Forfylow, 2008).

Table 3.1 Overview of WMA technology (Middleton & Forfylow, 2008)

WMA Process	Company	Additive	Production Temperature (°C)	Country Used
Sasobit®	Sasol	Yes	Varies, 20-30°C drop from HMA	Germany and 20 other countries worldwide
Advera® (Zeolite)	Eurovia, PQ Corporation	Yes	Varies, 20-30°C drop from HMA	France, Germany, United States
WAM-Foam®	Kolo Veidekke, Shell Bitumen	Soft Grade Asphalt Binder	110-120°C	France, Norway, England, Canada, Italy, Netherlands, Sweden
Evotherm®	MeadWestvaco	Yes	85-115°C	France, Canada, China, South Africa, United States

The amount of WMA additive usually depends on the materials, their proportion and especially on the grade and type of bitumen used. Additives constitute a significant portion in evaluation of Warm Mix Asphalt. There are two different methods to add additives in the plant.

- The dry method
- The wet method

The difference between the two methods is the addition in the asphalt plant production system. The first method is the dry method where additive adds directly in mixing chamber. In the wet method, the additive is mixed homogenously with bitumen and then mixed together with aggregates in the mixing chamber.

3.1.1.1 Foaming Technologies

Small amounts of water is added into the hot bitumen in foaming technology. Injected water evaporates and causes producing large volume of foam. The large volume of foam results in increasing expansion of the bitumen and decreasing the viscosity of bitumen, which improves coating and workability of asphalt pavement mixtures. However; the using of water creates some stripping problems, anti-stripping additives can be used to minimize moisture susceptibility and to provide chemical adhesion between bitumen and aggregate surfaces.

At present one type of water-containing additives in WMA technologies is Advera®. Advera® which is presented in Figure 3.2 with bitumen mixture. Advera® manufactures and markets in North America by PQ Corporation. It is powdered synthetic zeolite (sodium aluminum silicate hydrate) that has been hydro-thermally crystallized. It contains about 18-21% water of crystallization which is released by increasing temperature above 85^{o}C. The expansion of water causes foaming of asphalt bitumen.

Figure 3.2 Bitumen mixture produced with Advera® and Advera® additive

When the additive is added to the bitumen and heated together above 57^{o}C to 71^{o}C, 21% of water is released in weight. This foaming action of the liquid bitumen acts as a temporary asphalt volume extender and mixture lubricant, enabling the aggregate particles to be rapidly coated and the mix to be workable and compactable at temperatures significantly lower than those of typically used for HMA (Estakhri, Button, & Alvarez, 2010).

3.1.1.2 Organic or Wax Additives

Organic or wax additives are used to achieve the temperature reduction by reducing viscosity of bitumen. A decrease of viscosity produces asphalt mixtures at low temperatures above the melting point of the organic or wax additives.

Sasobit® is a wax additive known as an “asphalt flow improver” since it effectively lowers the viscosity of asphalt bitumen. With a lower bitumen viscosity, the working temperatures can be decreased by 18°C - 54°C (Hurley & Prowell, 2005). Made of Sasol Wax, Sasobit® is a long-chain aliphatic polymethlene hydrocarbon produced from the Fischer-Tropsch (FT) chemical process with a congealing temperature of 102°C and a melting temperature of 120°C. The longer chains help keeping of the wax in solution, and it reduces bitumen viscosity at typical asphalt production and compaction temperatures. Sasobit® has been used as a compaction aid and a temperature reducer. The Sasobit® process incorporates a low melting point organic additive that chemically changes the temperature viscosity curve of the bitumen (Button, Estakhri & Wimsatt, 2007). Figure 3.3 shows Sasobit® sample.

Figure 3.3 Sasobit® sample

Although literature review indicates the susceptibility increment in the rutting potential (permanent deformation) of mixes with respect to mixing and compaction temperature reduction, the rutting potential of the asphalt mixtures decreases because of the stabilizing effect in the bitumen by Sasobit®'s forming a crystalline network structure (Zhang, 2010).

The utilization of Sasobit® content is based on the past research made by O'Sullivan & Wall (2009) whom concluded that the Sasobit® should be added at a rate of 3.0% by weight of bitumen for maximum effectiveness.

3.1.1.3 Chemical Additives

Commonly used the third type of Warm Mix Asphalt technology is chemical additives. The different chemical additives are used for particular products. Chemical additives are combination of emulsification agents, polymers and additives to enhance workability, compaction and adhesion. Temperature reduction is provided without addition of water.

Rediset® WMX is a chemical additive that uses a combination of cationic surfactants and organic additive based rheology modifier. Rediset® chemically modifies the bitumen and obtains active adhesion force which improves coating of aggregates with bitumen (Zaumanis & Haritonovs, 2010). Rediset® can also encourage both processing of asphalt mixture at lower temperatures and combination with high contents of Reclaimed Asphalt Pavement.

Rediset® usually does not require any additional antistripping agent in the mixture due to this product provides anti-stripping properties. Rediset® can be blended with bitumen or can be added to the mixture right after the addition of bitumen. If it is directly blended with bitumen at the refinery, it does not require any modification at the plant. Rediset® sample is given in Figure 3.4. Other benefits of Rediset® WMA additive can be summarized as:

- To reduce mix, laydown and compaction temperatures;
- To prevent moisture effect in warm mix asphalt;
- To maintain grade of bitumen;
- To reduce temperature without adding water;
- To suit a wide range of mix types and aggregates.

The recommended rate of Rediset® is 1.5-2.0% by weight of bitumen and it allows 15-30^{o}C production temperature reduction compared to HMA (Chowdhury & Button, 2008).

Figure 3.4 Rediset® sample

3.2 Benefits of Warm Mix Asphalt

Researches identified lots of tremendous benefits of Warm Mix Asphalt. The obvious benefit is lowering mixing and compaction temperatures of asphalt mixes. However, other benefits of WMA can be summarized as:

- Lower mixing and compaction temperatures;
- Less fuel and energy consumption;
- Less fuel and energy cost;
- Long term paving season;
- Expanded market areas;
- Expanded pavement service life;
- Lower dust production because of lower temperatures and short heating time;
- Good working conditions for plant and pavement crew;
- Reduced thermal segregation in the mat;
- Less aging of binder during plant mixing and placement;
- Decreased emissions from plant and during placement;
- Easy applications for plant site in urban areas.

The most important economic benefit of WMA comes from the energy saving. The big reduction is shown in WMA compared to HMA depend on how much the production temperature is lowered as well as the type and cost of the fuel used.

3.2.1 Environmental Benefits

Emissions from Hot Mix Asphalt are big trouble to environment during the laying and compaction steps. The gaseous emissions in Hot Mix Asphalt include nitrogen oxides, carbon monoxide, sulfur dioxide and volatile components.

The WMA additive Sasobit, and construction temperatures affect on carbon dioxide emissions (Mallick, Bergendahl, & Pakula, 2009). This result means that carbon dioxide emission depends on temperature. Thus, decreasing of asphalt mixing or compaction temperatures is a way to decrease amount of carbon dioxide emissions during pavement construction.

The percentage of reduction in the emission during processes with WMA compared to HMA is shown Table 3.2 (Gandhi, 2008). According to table, there is a significant benefit in terms of reduction in emission compared to HMA.

Table 3.2 Emission reduction during WMA processes (Gandhi, 2008)

	Sasobit®	**Aspha-min®**	**Evotherm®**	**WAM-Foam®**
Sulfur Dioxide	N/A	17.60%	81%	N/A
Carbon Dioxide	18%	3.20%	46%	31%
Carbon Monoxide	N/A	N/A	63%	29%
Nitrogen Oxides	34%	6.10%	58%	62%
Total Particulate Matter	N/A	35.30%	N/A	N/A
Volatile Organic Compounds	8%	N/A	25%	N/A

3.2.2 Pavement Benefits

The mechanism that allows WMA to be produced at lower temperatures than HMA is the WMA techniques that reduce the viscosity of the binder. The reduction of binder viscosity allows the aggregate to be well coated at temperatures lower compared to HMA.

In spite of the fact that pavement benefits have not been a serious force in the development of Warm Mix Asphalt technology since WMA was discovered, they are particularly attractive to agencies.

Pavement benefits can be given as compaction of mixes with less effort, ability to incorporate higher percentage of RAP, adjuvant transportation, ability to haul the mixes longer distance and still obtain workability and placement thick lifts and opening to traffic in a short time period.

Warm Mix Asphalt technology facilitates compaction. ‘Flow Improvers’ are defined to generate compact ability of bitumen mixes in cold weather conditions. WMA systems modify temperature and viscosity relationship at lower temperatures, while adequate viscosity is maintained at service temperatures. Flow improvers offer benefit to ease of compaction in the field and lead to better resistance both rutting and fatigue deformations.

WMA technologies also obtain the utilization of high percentages of RAP. Warm Mix Asphalt (WMA) technology offers a solution to utilize the current state of technology that enables to utilize more RAP at a relatively lower temperature in HMA mixes. Mallick, Bradley, & Bradbury (2007), reported that it is possible to manufacture mixes with 75% to 100% RAP with similar properties to HMA mixes through the use of warm mix asphalt additives. The use of WMA additives helps reduce temperatures while achieving desired workability, thus enabling HMA to contain higher percentages of RAP (O’Sullivan & Wall, 2009).

3.2.3 Fuel and Energy Benefits

An additional important benefit of the Warm Mix Asphalt technology is the reduction in energy consumption required by burning fuels to heat traditional hot mix asphalt (HMA) to typically found at the production plant. With the decreased production temperature come the additional benefit of reduced emissions at the plant and during lay down.

Fuel savings with Warm Mix Asphalt typically range from 20 to 30 percent. These rates can be higher than 50% or more with processes as low energy concrete. The reduced fuel and energy usage gives a reduction of the production of green house gases and reduces the carbon footprint.

CHAPTER FOUR
EXPERIMENTAL

4.1 Materials

In this section, the conventional bitumen tests on base bitumen and bitumen prepared with WMA additives will be performed. Aggregate tests will also be conducted to find out properties of aggregates used in experiments.

4.1.1 Bitumen

The base bitumen with a 50/70 penetration grade had been obtained from Aliaga/Izmir Oil Terminal of the Turkish Petroleum Refinery Corporation. In order to characterize the properties of the base bitumen, conventional test such as: penetration test, softening point test, ductility test, etc. were performed. These tests were conducted in conformity with the relevant test methods that are presented in Table 4.1.

Table 4.1 Properties of the base bitumen

Test	*Specification*	*Results*	*Specification limits*
Penetration (25 °C; 0.1 mm)	ASTM D5 EN 1426	55	50–70
Softening Point (°C)	ASTM D36 EN 1427	49.1	46–54
Viscosity at (135 °C)-Pa.s	ASTM D4402	0.413	–
Thin Film Oven Test (TFOT) (163°C; 5 hr)	ASTM D1754 EN 12607-1		
Change of Mass (%)		0.04	0.5 (max)
Retained Penetration after TFOT(%)	ASTM D5 EN 1426	25	–
Softening Point Diff. after TFOT (°C)	ASTM D36 EN 1427	5	7 (max)
Ductility (25°C)-cm	ASTM D113	100	–
Specific Gravity	ASTM D70	1.030	–
Flash Point (°C)	ASTM D92 EN 22592	+260	230 (min)

4.1.2 Aggregates

The asphalt mixtures were produced with limestone aggregates. Fine and coarse limestone aggregates were procured from Dere Beton/Izmir quarry. In order to find out the properties of the limestone aggregate used in this study, sieve analysis, specific gravity, Los Angeles abrasion resistance test, sodium sulfate soundness test, fine aggregate angularity test and flat and elongated particles tests were conducted on limestone aggregates. The results are presented in Table 4.2.

Table 4.2 The properties of limestone aggregate

Test	***Specification***	***Result***	***Specification limits***
Specific Gravity (Coarse Agg.)	ASTM C 127		
Bulk		2.704	–
SSD		2.717	–
Apparent		2.741	–
Specific Gravity (Fine Agg.)	ASTM C 128		
Bulk		2.691	–
SSD		2.709	–
Apparent		2.739	–
Specific Gravity (Filler)		2.732	–
Los Angeles Abrasion (%)	ASTM C 131	22.6	Max. 30
Flat and Elongated Particles (%)	ASTM D 4791	7.5	Max. 10
Sodium Sulfate Soundness (%)	ASTM C 88	1.47	Max. 10–20
Fine Aggregate Angularity	ASTM C 1252	47.85	Min. 40

Grading of aggregate had been chosen in conformity with the Type I Wearing Course of Turkish Specifications. Table 4.3 presents the final gradation chosen for limestone aggregates.

Table 4.3 Gradation for limestone aggregates

Sieve Size/No.	Grading Passing (%)	Specification	Specification Limits
¾”	100	Type I Wearing Course	100
½”	92		83–100
3/8’’	73		70–90
No.4	44,2		40–55
No.10	31		25–38
No.40	12		10–20
No.80	8		6–15
No.200	5.3		4–10

4.1.3 Warm Mix Asphalt Additives

In many of the WMA field trials, the agency or researchers have relied on information from the WMA additive sales representative to specify the amount to be used. In other cases, plant restrictions have limited the amount of the WMA additive that can be added.

Based on the available literature, dosage for Sasobit® ranged from 1.0% to 4.0% by weight of the binder (D’Angelo et al., 2008). Austerman, Mogawer, & Bonaquist (2009), selected Sasobit® at dosage of 1.5% and 3.0% in their studies.

Besides, dosage of Sasobit® was recommended that the optimum percentage of Sasobit® addition was 3% by weight of bitumen, considering the effectiveness of using such an additive and the overall economics (Kanitpong et al., 2008).

A recent study related to the utilization of Sasobit® content was made by O'Sullivan & Wall (2009), whom concluded that Sasobit® should be added at a rate of 3.0% by mass of bitumen for maximum effectiveness. Thus; in laboratory tests, the Sasobit® in the base bitumen was chosen as 3% by weight of the bitumen.

The used percentages (by weight of bitumen) of Rediset® additive were generally based on the recommendations by the suppliers and literatures. Xiao, Punith, & Amirkhanian (2012), preferred Rediset® at dosage of 1.5%; Zaumanis & Haritonovs (2010), used 2% and 3% by weight of the bitumen in their experimental studies. Besides, the recommended rate of Rediset® is 1.5-2.0% by weight of bitumen and it allowed 15-30^{o}C production temperature reduction compared to HMA (Chowdhury & Button, 2008). The Rediset application rate was determined by AkzoNobel. A rate of 2.0 percent by weight of bitumen was used for all their tests (Jones, Tsai, & Signore, 2010). In laboratory studies, the Rediset® in the base bitumen was chosen as 2% by weight of the bitumen.

Based on literature, Advera® has generally been specified by weight of mixture. Austerman, Mogawer, & Bonaquist (2009), utilized the maximum percentage of Advera® to add to the bitumen was the 0.3% and 0.1% by weight of mixture (dosage rate was 6.3% by weight of the bitumen and 2.1% by weight of the bitumen).

Advera® manufactures and markets by PQ Corporation that recommended the addition of 0.25% additive by weight of the mixture (Estakhri, Button, & Alvarez, 2010). Based on the research in question, in laboratory studies, the Advera® in the base bitumen was chosen as 5% by weight of the bitumen (0.25 percent by weight of mixture).

4.1.4 Preparation of Bitumen Samples with WMA Additives

Each WMA additive needs to be blended into the base bitumen prior to fabricating any testing specimens. The appropriate mixing temperatures and time of mixing should be designated for preparation of the bitumen samples with WMA additives. Brookfield Rotational Viscometer test was utilized for this purpose as shown in Figure 4.1.

Figure 4.1 Brookfield rotational viscometer

Brookfield viscometer was employed to measure the viscosity of bitumen in according to ASTM D4402. Approximately 30 gr. of bitumen was heated in an oven so that it was sufficiently fluid to pour into the sample chamber. The amounts of bitumen used varied with the different sizes of the spindles. The sample chamber containing the bitumen sample was then placed in the thermo container. After the desired temperature was stabilized for about 30 min, the spindle was lowered into the chamber to test the viscosity (Wu, Cong, Yu, Luo, & Mo, 2006).

In order to determine the exact time of mixing as well as temperature; first of all, the temperature was kept constant and the time of mixing was increased. While the viscosity values got fixed, the time and temperature were designated as required temperature and time. However; if no stable viscosity values were maintained, procedures would be repeated by increasing the temperature. Details of the production time and temperature are presented in Table 4.4.

Table 4.4 Details of the production time and temperature

ADDİTİVES	**SASOBIT®**	**REDISET®**			**ADVERA®**
Production Time (min.)	**120 °C**	**120 °C**	**135 °C**	**150 °C**	**120 °C**
5	675	662.5	303.0	125.0	1150.0
10	650	712.5	325.0	137.5	1175.0
15	650	725.0	337.5	187.5	1125.0
20	650	737.5	312.5	187.5	1112.5
30	650	762.5	—	200.0	1100.0
45	650	737.5	—	187.5	1100.0
60	650	862.5	—	187.5	1100.0

As indicated in Table 4.4, the production time and temperature of Sasobit®, Rediset® and Advera® are 10 min., 120^{o}C; 15 min., 150^{o}C and 20 min., 120^{o}C respectively.

Following the preparation of the samples with WMA additives, they were subjected to the following conventional bitumen tests; penetration (ASTM D5-97), ring and ball softening point (ASTM D36-95 (2000)), thin film oven test (TFOT)

(ASTM D 1754), penetration and softening point after TFOT and storage stability test (EN 13399). In addition, the temperature susceptibility of the bitumen samples has been calculated in terms of penetration index (PI) using the results obtained from penetration and softening point tests. The conventional properties of the bitumen prepared with Sasobit®, Rediset®, Advera® are presented in Table 4.5 as a decrease in penetration and increase in softening point.

Table 4.5 Conventional properties of bitumen prepared with Sasobit®, Rediset®, Advera®

Property	***Base Bitumen***	***Sasobit® Content* 3%**	***Rediset® Content* 2%**	***Advera® Content* 5%**
Penetration (1/10 mm)	55	37	44	52
Softening Point (°C)	49.1	69.3	56.7	56
Penetration Index (PI)	-1.20	1.95	0.04	0.27
Change of Mass (%)	0.036	0.07	0.04	0.16
Retained Penetration after TFOT (%)	25	13	16	16
Softening Point Difference after TFOT (°C)	5	4	2.5	4.1
Storage Stability (°C)	—	1.6	0.5	1.6
Viscosity at 135°C (Pa.s)	0.413	0.288	0.338	0.313

The increase in softening point is favorable since bitumen with higher softening point may be less susceptible to permanent deformation (rutting) (Sengoz &

Isikyakar, 2008). Organic WMA additive, Sasobit®; chemical WMA additive Rediset®; foaming WMA additive Advera®; reduces temperature susceptibility (as determined by the penetration index-PI) of the bitumen. Lower values of PI indicate higher temperature susceptibility. Asphalt mixtures containing bitumen with higher PI are more resistant to low temperature cracking as well as permanent deformation (Sengoz & Isikyakar, 2008).

The additives also reduce the viscosity of bitumen. This indicates that, Sasobit®, Rediset®, Advera® increase the workability and make relatively reductions for mixing and compaction temperatures.

4.1.5 Determination of Mixing and Compaction Temperatures

Most bitumen is Non-Newtonian fluids at mixing and compacting temperature range in situ currently. The effect of viscosity on asphalt bitumen's workability is very important in selecting proper mixing and compacting temperatures (Yu, Cong, & Wu, 2009). Brookfield viscometer was employed to inspect the mixing and compaction temperatures.

The test was performed at 135°C and 165°C. The temperatures corresponding to bitumen viscosities 170±20 mPa.s and 280±30 mPa.s were chosen as mixing and compaction temperatures respectively. The results are presented both in Figure 4.2 and Table 4.6.

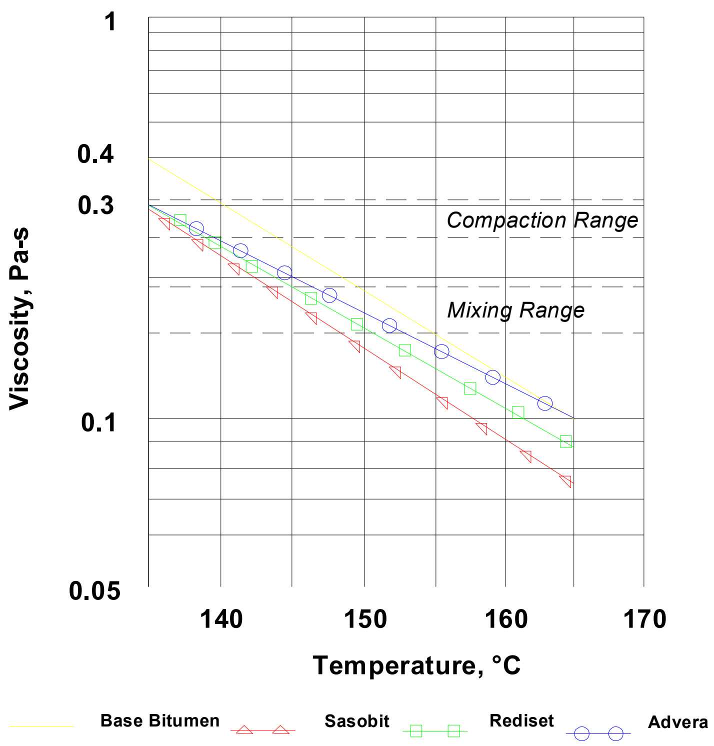

Figure 4.2 Brookfield viscometer tests results for each additives

It is evident that the addition of Sasobit® reduces the mixing and compaction temperature by 15°C and 10°C in comparison with the base bitumen. Addition of Rediset® reduces the mixing and compaction temperature by 12°C and 8°C. Similarly, addition of Advera® reduces both the mixing and compaction temperature by 9°C.

Table 4.6 Mixing and compaction temperatures

ADDITIVES	***DOSAGE OF ADDITIVES (%)***	***TEMPERATURES (°C)***	
		Mixing	***Compaction***
Base Bitumen	0	157-164	144-150
Sasobit®	3	142-147	133-138
Rediset®	2	145-149	136-140
Advera®	5	148-153	135-141

4.2 Determination of Optimum Bitumen Contents with WMA Additives

To determine the optimum bitumen content for a particular gradation of aggregates by Marshall method of mix design (ASTM D 1559), a series of test specimens were prepared for a range of different bitumen contents so that the test data curves showed a well defined optimum value. Three test specimens were prepared for each bitumen contents used in order to provide adequate data. Thus, a warm-mix design study using four different bitumen contents normally required 12 test specimens. Before preparing mixtures, approximately 1150 grams of the mix aggregates, the filler and required quantity of the first trial percentage of bitumen were heated and thoroughly mixed at the desired temperatures. Besides, the compaction molds were cleaned and heated to a temperature of 145°C. The filter paper was inserted into the bottom of the mold to prevent adhesion between the mixture and the mold. The mix was placed in a preheated mould and compacted by a Marshall hammer with 75 blows (for wearing course) on either side at the desired temperatures which were given in section 4.1.5. After the specimens had been removed from the mold, they were allowed to cool to room temperature and they were weighted in air and water for determination of density.

The Marshall stability of a test specimen was the maximum load required to produce failure when the specimen was preheated (placed into the 60 °C water bath for 20 min. to 30 min.) to a prescribed temperature placed in the special test head and the load was applied at a constant strain (50.8 mm. per minute). While the stability test was in progress, the dial gauge was used to measure the vertical deformation of the specimen; the deformation read at the load failure point was expressed in units of 0.25 mm and was called the Marshall Flow value of the specimen.

The test was repeated for other specimens of each bitumen contents and an average value for each bitumen was taken. Since the specific gravity of aggregates and asphalt, bulk density, stability and flow value of the specimen were known; the following graphical curves were plotted:

- Corrected Marshall Stability versus bitumen content.
- Marshall flow versus bitumen content.
- Percentage of void (Vh) in the total mix versus bitumen content.
- Unit weight or bulk specific gravity (Dp) versus bitumen content.
- Percentage of void filled with asphalt (VFA) versus bitumen content.
- Percentage of void in mineral aggregate (VMA) versus bitumen content.

Consequently, the optimum bitumen content was determined by the bitumen content corresponding to the median of designed limits of percent air voids (Vh) in the total mix.

Following chapters include the determination of the optimum bitumen contents with WMA additives.

4.2.1 The Optimum Bitumen Content With Sasobit® Additive

After determining the properties of the materials used in this study, WMA mixture samples were prepared with Sasobit® at a dose 3% by weight of the bitumen. Based on the explanations given in 4.2, The Marshall Stability test was conducted on the specimens that contain different bitumen content (3.5%, 4.0%, 4.5% and 5%) in order to determine the optimum bitumen content. The results of Marshall Stability Test are presented in Table 4.7 and Figure.4.3. The optimum asphalt content that corresponds to 4% air voids was found as 4.30%.

Table 4.7 Marshall mix design for Sasobit® additive

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	61.91	61.89	61.88	**61.9**	1178.0	666.5	1180.0	513.5	2.294	2.5397	9.671	17.91	46.0	2.45	1234	1.040	1283
2	3.5	3.4	61.74	61.80	61.50	**61.7**	1178.0	666.0	1179.0	513.0	2.296	2.5397	9.583	17.83	46.2	2.45	1241	1.09	1348
3	3.5	3.4	61.00	60.82	61.00	**60.9**	1176.0	665.5	1178.5	513.0	2.292	2.5397	9.736	17.97	45.8	2.44	1234	1.07	1322
Avg.											**2.294**	**2.540**	**9.663**	**17.901**	**46.02**	**2.45**			**1318**
1	4.0	3.8	60.10	60.00	60.00	**60.0**	1166.5	685.0	1173.0	488.0	2.390	2.5219	5.216	14.87	64.9	2.61	1329	1.1	1461
2	4.0	3.8	60.02	60.14	60.00	**60.1**	1166.0	688.5	1173.5	485.0	2.404	2.5219	4.670	14.38	67.5	2.58	1319	1.1	1446
3	4.0	3.8	60.12	60.10	60.12	**60.1**	1167.0	689.0	1174.0	485.0	2.406	2.522	4.588	14.31	67.9	2.60	1322	1.1	1449
Avg.											**2.400**	**2.522**	**4.825**	**14.522**	**66.80**	**2.60**			**1452**
1	4.5	4.3	60.88	60.90	60.98	**60.9**	1187.5	705.0	1199.0	494.0	2.404	2.5045	4.021	14.80	72.8	2.20	1144	1.07	1225
2	4.5	4.3	61.38	61.60	61.48	**61.5**	1196.0	708.5	1200.0	491.5	2.433	2.5045	2.842	13.76	79.3	2.86	1045	1.05	1100
3	4.5	4.3	61.12	61.16	61.14	**61.1**	1190.0	706.0	1205.0	499.0	2.385	2.5045	4.782	15.48	69.1	2.28	1102	1.07	1174
Avg.											**2.407**	**2.505**	**3.882**	**14.68**	**73.76**	**2.45**			**1166**
1	5.0	4.8	62.16	62.12	62.16	**62.1**	1203.0	719.5	1215.0	495.5	2.428	2.4876	2.401	14.36	83.3	2.38	1099	1.04	1137
2	5.0	4.8	61.16	61.60	61.40	**61.4**	1195.5	715.0	1207.5	492.5	2.427	2.4876	2.419	14.38	83.2	2.98	1088	1.06	1149
3	5.0	4.8	61.18	61.18	61.60	**61.3**	1196.0	715.0	1209.0	494.0	2.421	2.4876	2.675	14.60	81.7	3.70	1149	1.06	1217
Avg.											**2.425**	**2.488**	**2.498**	**14.45**	**82.71**	**3.02**			**1168**

Specific Gravity of the Bitumen (Gb) = 1.03	%Coarse Aggr. (K%) = 55.8	Bulk Spc. Gr. Of the Coarse Aggr. (Gkh) = 2.704
Penetration of the Bitumen = 55	%Fine Aggr. (I%) = 38.9	Bulk Spc. Gr. Of the Fine Aggr. (Gih) = 2.691
Bitumen Absorption of the Aggr.(Pba) = 0.25	%Filler (F%) = 5.3	Bulk Spc. Gr. Of the Filler (Gf) = 2.732
Effective Spc. Gr. Of the Agg. Mix. (Gef).=.2.677	Bulk Spc. Gr. Of the Agg. Mix (Gsb) = 2.7	Aggr. Content in the Briquette (gr.) = 1150

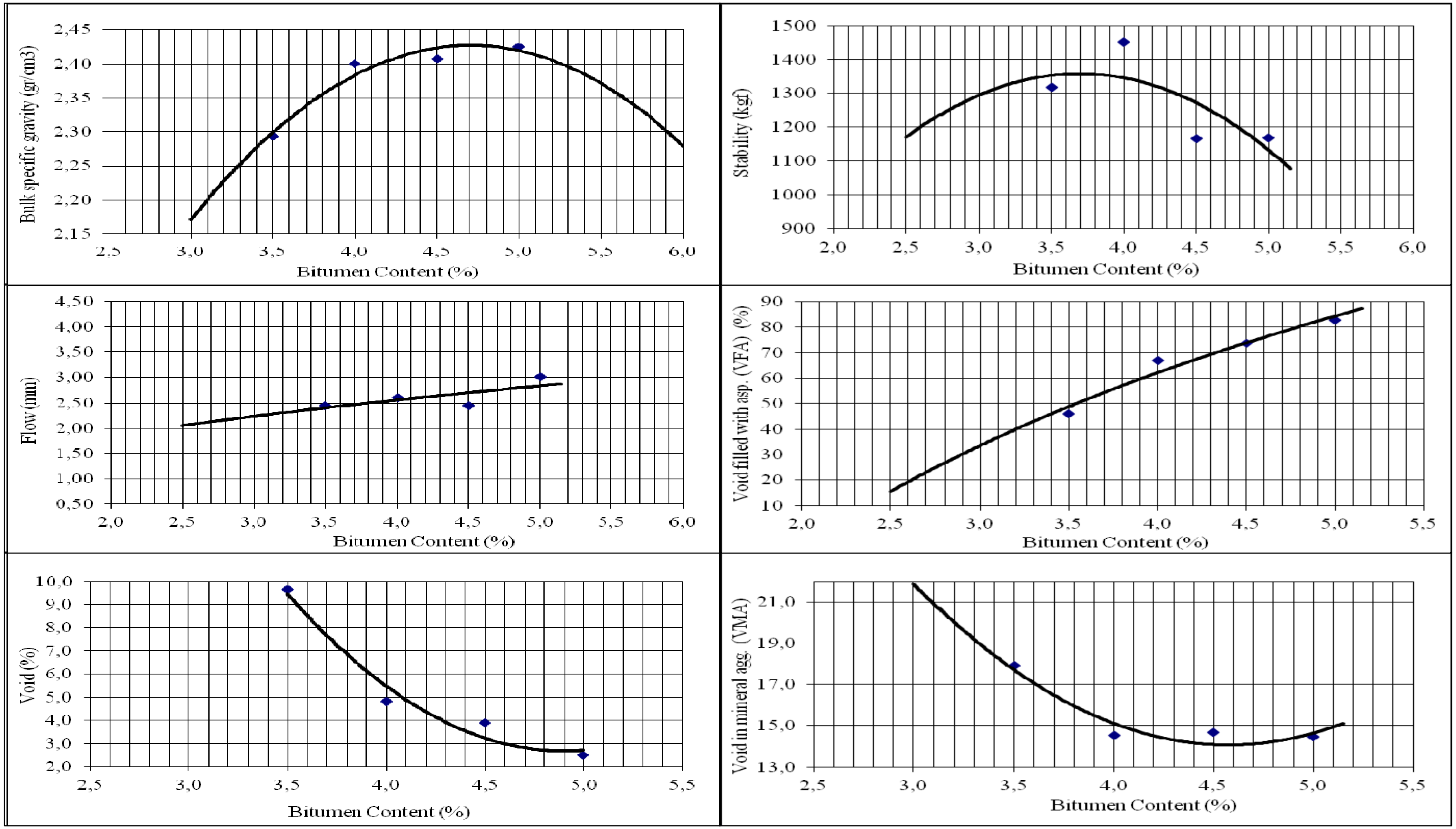

Figure 4.3 Marshall mix design results for Sasobit® additive

4.2.2 The Optimum Bitumen Content With Rediset® Additive

WMA mixture samples were prepared with Rediset® at a dose 2% by weight of the bitumen. The Marshall Stability test was conducted on the specimens that contain different bitumen content (3.5%, 4.0%, 4.5% and 5%) in order to determine the optimum bitumen content. The result of Marshall Mix Design is presented in Table 4.8 and Figure.4.4. The optimum asphalt content that corresponds to 4% air voids was found as 4.53%.

Table 4.8 Marshall mix design for Rediset® additive

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**	**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	61.24	61.88	61.50	**61.5**	1183.5	696.4	1188.0	491.6	2.407	2.5649	6.138	13.85	55.7	2.16	1306	1.053	1375
2	3.5	3.4	61.56	61.48	62.12	**61.7**	1182.9	695.0	1187.2	492.2	2.403	2.5649	6.300	14.00	55.0	2.12	1312	1.046	1372
3	3.5	3.4	61.88	61.46	61.38	**61.6**	1180.5	691.6	1185.8	494.2	2.389	2.5649	6.868	14.52	52.7	1.85	1328	1.049	1393
Avg.											**2.400**		**6.435**	**14.12**	**54.5**	**2.00**			**1380**
1	4.0	3.8	61.88	61.92	62.24	**62.0**	1187.4	701.2	1189.7	488.5	2.431	2.5466	4.552	13.44	66.1	2.34	1256	1.038	1304
2	4.0	3.8	61.00	61.12	61.18	**61.1**	1190.4	704.3	1193.0	488.7	2.436	2.5466	4.350	13.25	67.2	2.42	1342	1.065	1429
3	4.0	3.8	61.12	61.20	61.12	**61.1**	1190.0	694.5	1192.7	498.2	2.389	2.5466	6.205	14.94	58.5	2.21	1233	1.065	1313
Avg.											**2.418**		**5.036**	**13.88**	**63.9**	**2.30**			**1349**
1	4.5	4.3	61.88	61.74	61.32	**61.65**	1184.0	694.5	1185.8	491.3	2.410	2.5288	4.701	14.59	67.8	2.46	1186	1.049	1244
2	4.5	4.3	61.46	61.18	61.48	**61.37**	1190.7	703.6	1192.7	489.1	2.434	2.5288	3.730	13.72	72.8	2.40	1189	1.056	1256
3	4.5	4.3	61.62	61.24	61.20	**61.35**	1195.7	708.6	1197.9	489.3	2.444	2.5288	3.366	13.39	74.9	2.52	1172	1.056	1238
Avg.											**2.429**		**3.932**	**13.90**	**71.8**	**2.50**			**1246**
1	5.0	4.8	61.92	61.28	61.30	**61.50**	1186.2	693.6	1187.5	493.9	2.402	2.5114	4.368	15.28	71.4	2.81	1067	1.053	1124
2	5.0	4.8	61.18	61.10	61.18	**61.15**	1201.6	706.1	1202.9	496.8	2.419	2.5114	3.692	14.69	74.9	3.06	1006	1.062	1068
3	5.0	4.8	61.08	61.06	61.60	**61.25**	1199.1	705.6	1200.4	494.8	2.423	2.5114	3.504	14.52	75.9	3.04	1036	1.062	1100
Avg.											**2.415**		**3.855**	**14.83**	**74.0**	**3.00**			**1097**

Specific Gravity of the Bitumen (Gb) = 1.03	%Coarse Aggr. (K%) = 55.8	Bulk Spc. Gr. Of the Coarse Aggr. (Gkh) = 2.704
Penetration of the Bitumen = 55	%Fine Aggr. (I%) = 38.9	Bulk Spc. Gr. Of the Fine Aggr. (Gih) = 2.691
Bitumen Absorption of the Aggr.(Pba) = 0.25	%Filler (F%) = 5.3	Bulk Spc. Gr. Of the Filler (Gf) = 2.732
Effective Spc. Gr. Of the Agg. Mix. (Gef) = 2.706	Bulk Spc. Gr. Of the Agg. Mix (Gsb) = 2.7	Aggr. Content in the Briquette (gr.) = 1150

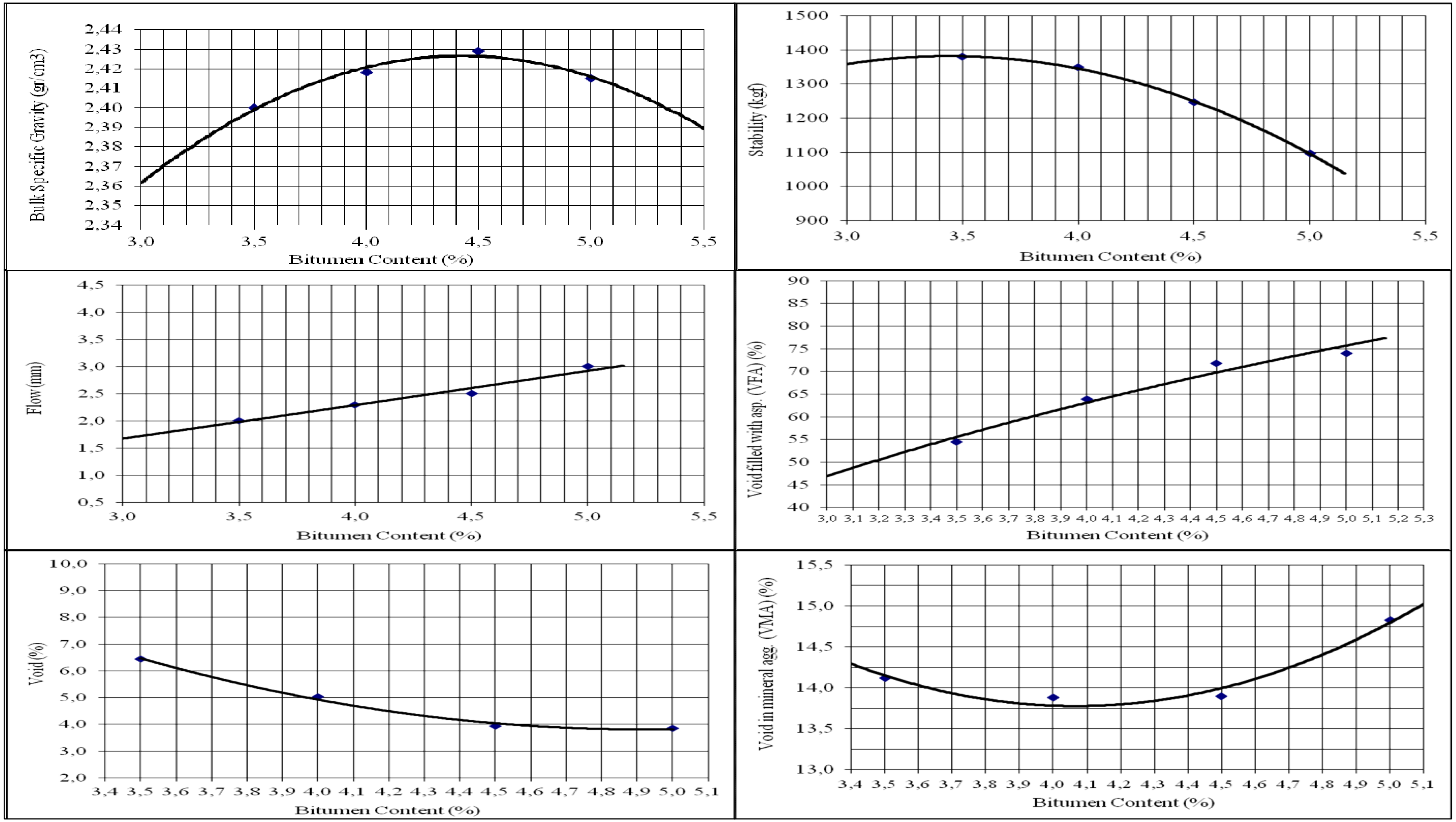

Figure 4.4 Marshall mix design results for Rediset® additive

4.2.3 The Optimum Bitumen Content With Advera® Additive

WMA mixture samples were prepared with Advera® at a dose 5% by weight of the bitumen. The Marshall Stability test was conducted on the specimens that contain different bitumen content (3.5%, 4.0%, 4.5% and 5%) in order to determine the optimum bitumen content. The result of Marshall Mix Design is presented in Table 4.9 and Figure.4.5. The optimum asphalt content that corresponds to 4% air voids was found as 4.50%.

Table 4.9 Marshall mix design for Advera® additive

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	61.24	61.88	61.50	61.5	1183.5	696.4	1188.0	491.6	2.407	2.5692	6.296	13.85	54.5	1.97	1106	1.053	1165
2	3.5	3.4	61.56	61.48	62.12	61.7	1182.9	695.0	1187.2	492.2	2.403	2.5692	6.458	14.00	53.9	2.12	1012	1.046	1059
3	3.5	3.4	61.88	61.46	61.38	61.6	1180.5	691.6	1185.8	494.2	2.389	2.5692	7.025	14.52	51.6	1.85	1085	1.049	1138
Avg.											**2.400**		**6.593**	**14.12**	**53.3**	**2.00**			**1120**
1	4.0	3.8	61.90	61.58	61.50	61.7	1185.5	694.0	1188.3	494.3	2.398	2.5509	5.980	14.59	59.0	2.25	1222	1.046	1278
2	4.0	3.8	61.80	61.70	61.54	61.7	1184.1	694.8	1187.1	492.3	2.405	2.5509	5.709	14.34	60.2	2.14	1130	1.046	1182
3	4.0	3.8	61.18	61.22	61.58	61.3	1183.3	696.3	1185.3	489.0	2.420	2.5509	5.137	13.82	62.8	1.87	1181	1.059	1251
Avg.											**2.408**		**5.609**	**14.25**	**60.7**	**2.10**			**1237**
1	4.5	4.3	62.26	61.12	61.34	61.6	1194.4	707.5	1196.9	489.4	2.441	2.5330	3.650	13.50	73.0	2.34	1172	1.049	1229
2	4.5	4.3	61.18	61.16	61.10	61.1	1192.1	709.7	1194.4	484.7	2.459	2.5330	2.903	12.83	77.4	2.28	1116	1.065	1189
3	4.5	4.3	61.18	61.12	61.04	61.1	1195.1	705.8	1197.4	491.6	2.431	2.5330	4.025	13.84	70.9	2.40	1085	1.065	1156
Avg.											**2.444**		**3.526**	**13.89**	**73.8**	**2.30**			**1191**
1	5.0	4.8	60.52	60.70	60.72	60.6	1192.7	701.9	1196.4	494.5	2.412	2.5155	4.117	14.92	72.4	2.52	1092	1.081	1180
2	5.0	4.8	61.38	61.18	61.28	61.3	1208.0	716.6	1211.3	494.7	2.442	2.5155	2.927	13.87	78.9	2.68	1166	1.059	1235
3	5.0	4.8	61.00	61.18	61.20	61.1	1198.7	712.0	1203.2	491.2	2.440	2.5155	2.988	13.92	78.5	2.71	1076	1.065	1146
Avg.											**2.431**		**3.344**	**14.24**	**76.6**	**2.60**			**1187**

Specific Gravity of the Bitumen (Gb) = 1.03	%Coarse Aggr. (K%) = 55.8	Bulk Spc. Gr. Of the Coarse Aggr. (Gkh) = 2.704
Penetration of the Bitumen = 555	%Fine Aggr. (I%) = 38.9	Bulk Spc. Gr. Of the Fine Aggr. (Gih) = 2.691
Bitumen Absorption of the Aggr.(Pba) = 0.25	%Filler (F%) = 5.3	Bulk Spc. Gr. Of the Filler (Gf) = 2.732
Effective Spc. Gr. Of the Agg. Mix. (Gef) = 2.711	Bulk Spc. Gr. Of the Agg. Mix (Gsb) = 2.7	Aggr. Content in the Briquette (gr.) = 1150

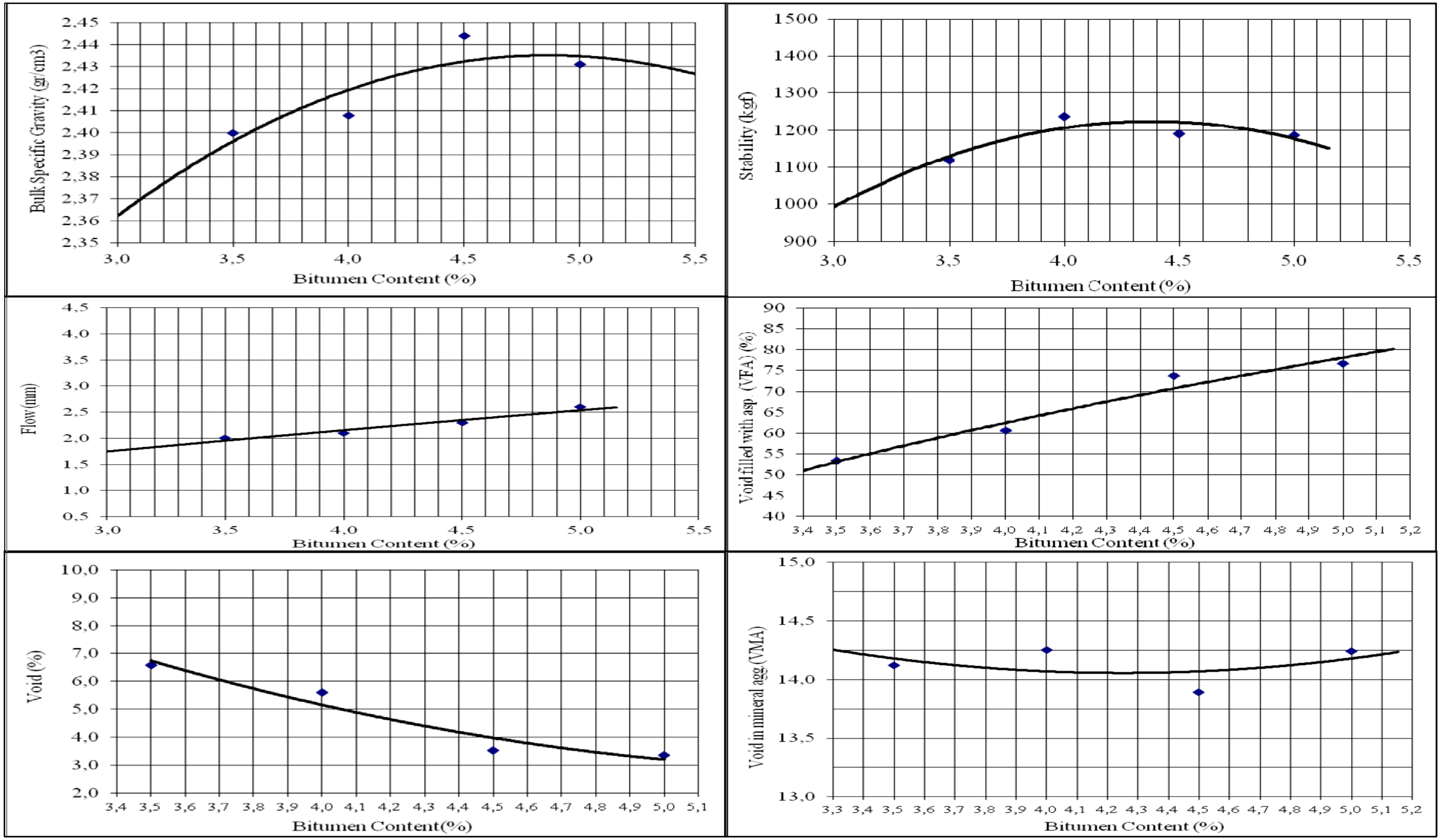

Figure 4.5 Marshall mix design results for Advera® additive

Following the determination of optimum bitumen content for each of the additives, the values (Stability, Voids, Flow, Void in Mineral Aggregate (VMA) and Void Filled with Asphalt (VFA)) corresponding to optimum bitumen contents were determined and compared with the specification limits (T.C. Bayındırlık ve İskan Bakanlığı Karayolları Genel Müdürlüğü, 2006) as presented in Table 4.10.

Table 4.10 Marshall mix design results and specification limits

	Sasobit®	***Rediset®***	***Advera®***	***Specification Limits for Wearing Course***	
Stability (kgf)	1300	1250	1230	**900**	**-**
Voids (%)	4	4	4	**3**	**5**
Flow (mm.)	2.65	2.61	2.4	**2**	**4**
VMA (%)	14.5	14	14.1	**13**	**-**
VFA (%)	70	70	71	**65**	**75**

4.3 Determining the Properties of Recycled Asphalt Pavement

When HMA attains the end of their service life, milled materials already carry substantial value. RAP as the milled materials, can be reused in virgin HMA to decrease the quantity of new material that needs to be used in construction of highway. During service, the blend of aggregates and bitumen undergoes various physical and rheological changes that have to be considered in the design process to ensure that WMA mixtures with RAP perform as well as WMA produced with virgin materials. This section discusses some of the most important characteristics of RAP materials.

The primary steps in the design of recycling included the determination of material properties of RAP and virgin materials, the selection of an appropriate blend percentage of RAP and virgin aggregate to meet gradation, the selection of an appropriate bituminous bitumen blend to satisfy specified viscosity and penetration requirements.

In this part of the study, warm mix recycling tests were performed with the RAP obtained from the road nearby Dokuz Eylül University, Tinaztepe Campus Entrance. Initial experiments include the extraction test that was performed on ten different samples taken from the above mentioned road in order to determine the average bitumen content in the old mix. After determination of the bitumen content, sieve analysis tests were performed on the aggregate that were obtained from extraction test. According to the specifications related with the wearing course, the old aggregates were blended with new aggregates in order to keep gradation within the limits given in the specifications.

4.3.1 The Extraction Method (ASTM D2172)

A centrifuge extractor of 1500 gr. capacity was used in order to determine the content of bitumen in RAP. Centrifuge Method was performed on each of the sample. The steps of the method are given below:

- Approximately 1000 grams re-graded RAP was heated up to 150^{o}C in the oven for grains to be separated easily.
- The sample was placed in the container of the extractor with the centrifuge paper.
- The sample was weighted after cooling with the container and the centrifuge paper.
- The solvent that was about 200 ml. Trichloroethylene was poured on the sample though the fill point where was on the top of the container.
- The assembly was left up to one hour to allow the solvent to take the bitumen into the solution drained from the extension tube.

- The centrifuge process was started and carried out until the drainage from the extension tube was completed.
- The centrifuge process was stopped and a further 200 ml. of Trichloroethylene was added through the fill point, and then the process was restarted. This process should be repeated until the solution is clear.
- The sample with the centrifuge paper were put into 110 ^{o}C oven for the evaporation of remain solvent in the mixture.
- The sample with the centrifuge paper was again weighted after cooling. The difference between the weights gave the bitumen content of sample.

The Extraction Test was performed on the ten different samples to determine the bitumen content based on mentioned test method procedure. The obtained results are presented in Table 4.11.

Table 4.11 Extraction test values

		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample7	Sample 8	Sample 9	Sample 10
A	Cartridge paper, gr.	24.259	24.450	24.154	24.545	24.264	24.005	24.260	24.236	24.323	24.135
B	Container+ Cartridge paper, gr.	1517.759	1517.95	1517.654	1518.045	1517.764	1517.505	1517.760	1517,736	1517.823	1497.635
C	Container+ Cartridge paper+ Material, gr.	2517.759	2517.95	2517.654	2518.045	2517.764	2517.505	2517,760	2517,736	2517.823	2497.635
D	Cartridge paper+ Material(Removed bitumen)	983.3	982.5	983.9	983.5	982.5	982.5	982.3	982.6	983.6	983.74
E=C-B	Weight of the material, gr.	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
F=D-A	Weight of the material(Removed bitumen), gr.	959.041	958.05	959.746	958.955	958.236	958.495	958.04	958.364	959.277	959.605
(E-F)/F*100	Bitumen Percentage	**4.27%**	**4.38%**	**4.20%**	**4.28%**	**4.36%**	**4.33%**	**4.38%**	**4.34%**	**4.25%**	**4.21%**

The average bitumen content:

(4.27+4.38+4.20+4.28+4.36+4.33+4.38+4.34+4.25+4.21)/10 = 4.30%. This value will be used in the calculation of the new bitumen content that will be added in the mixture.

4.3.2 RAP Bitumen Evaluation

The old bitumen had been obtained from the extraction method which was performed on RAP. In order to characterize the properties of the old bitumen, conventional test methods such as: penetration test, softening point test, thin film oven test etc. were performed. These tests were conducted in conformity with the relevant test methods that are presented in Table 4.12.

Table 4.12 Properties of the old bitumen

Test	***Specification***	***Results***
Penetration (25 °C; 0.1 mm)	ASTM D5 EN 1426	23
Softening Point (°C)	ASTM D36 EN 1427	72.9
Penetration Index (PI)		1.45
Viscosity at (135 °C)-Pa.s	ASTM D4402	0.563
Viscosity at (165 °C)-Pa.s	ASTM D4402	0.138
Thin Film Oven Test (TFOT) (163°C; 5 hr)	ASTM D1754 EN 12607-1	-
Change of Mass (%)		0.02
Retained Penetration (%)	ASTM D5 EN 1426	18
Softening Point Diff.after TFOT (°C)	ASTM D36 EN 1427	1.9

Since RAP bitumen reacts and loses some of its components during the aging process, its rheological behavior will naturally differ from virgin materials. During aging process, bitumen is exposed to hot air at high temperatures ranging from 135°C to 165°C, resulting in a significant increase in viscosity. Besides, bitumen loses many of its oil components during construction and service resulting in a high proportion of asphaltenes in the blend, which leads to increased stiffness and viscosity.

4.3.3 RAP Aggregate Gradation

Sieve Analysis Test performed on extracted aggregates (13 kg) which were obtained from the Extraction Test. The aggregates washed separately with water and then put into the 110^{o}C oven for drying. Sieve analysis results are given in Table 4.13 for extracted aggregates. The aggregates were sieved starting with the 19 mm. (3/4 inch) sieve. The other types that were used in this process are as follows:

- 12.5 mm. (1/2 inch)
- 9.5 mm. (3/8 inch)
- 4.75 mm. (No:4)
- 2.00 mm. (No:10)
- 0.425 mm. (No:40)
- 0.180 mm. (No:80)
- 0.075 mm. (No:200)

Table 4.13 Sieve analysis results for extracted aggregates

Sieve No	**Cumulative Weight Passing (gr)**	**% Retained**	**% Pass**
3/4″	13299	0	100
1/2″	13092	1.6	98.4
3/8″	11966	10.1	89.9
No.4	7197.5	45.9	54.1
No.10	4016	69.8	30.2
No.40	1792.5	86.5	13.5
No.80	1173	91.18	8.82
No.200	775	94.17	5.83

The mix gradation (10%, 20%, %30, %40 and %50 of the RAP and 90%, 80%, 70%, 60% and %50 of new aggregate) must meet the requirements of the specifications related to the wearing course construction. Table 4.14 presents the details related to mix gradation and the limits of the specifications.

Table 4.14 Mix gradation and specifications

Sieve Size/No.	Specification Limits	Passing (%)	Retained (%)	Cumulative Retained (%)	Cumulative Retained (gr.)	Differences (gr.)	Reclaimed Asphalt Pavement (RAP) and Virgin Aggregates Ratio									
							%10 RAP Agg.	%90 Virgin Agg.	%20 RAP Agg.	%80 Virgin Agg.	%30 RAP Agg.	%70 Virgin Agg.	%40 RAP Agg.	%60 Virgin Agg.	%50 RAP Agg.	%50 Virgin Agg.
3/4'	100	100				0	0	0	0	0	0	0	0	0	0	0
1/2'	83-100	92	8	8	92	92	9.2	82.8	18.4	73.6	27.6	64.4	36.8	55.2	46	46
3/8'	70-90	73	19	27	310.5	218.5	21.85	196.65	43.7	174.8	65.55	152.95	87.4	131.1	109.3	109.25
No.4	40-55	44.2	28.8	55.8	641.7	331.2	33.12	298.08	66.2	264.96	99.36	231.84	132	198.72	165.6	165.6
No.10	25-38	31	13.2	69	793.5	151.8	15.18	136.62	30.4	121.44	45.54	106.26	60.7	91.08	75.9	75.9
No.40	10-20	12	19	88	1012	218.5	21.85	196.65	43.7	174.8	65.55	152.95	87.4	131.1	109.3	109.25
No.80	6-15	8	4	92	1058	46	4.6	41.4	9.2	36.8	13.8	32.2	18.4	27.6	23	23
No.200	4-10	5.3	2.7	94.7	1089	31	3.1	27.9	6.2	24.8	9.3	21.7	12.4	18.6	15.5	15.5
Filler	-	-	5.3	100	1150	61	6.1	54.9	12.2	48.8	18.3	42.7	24.4	36.6	30.5	30.5

4.3.4 Calculation of Additional Bitumen in the Mix

Based on the information given in Bituminous Mixtures Laboratory Handbook, published by General Directorate of the State of Highways, the bitumen content needed for the mix gradation of RAP and the new aggregates can be calculated by the following formulas:

$$Pr = Pc - (Pa * Pp)$$

Where;

Pr: Percent of bitumen to be added in the mix including RAP

Pa: Percent of aged bitumen in the mix determined by Marshall test

Pc: Percent of total bitumen in the mix

Pp: Percentage of RAP in the mix

Table 4.15 illustrates the detailed calculation of the percentage of the bitumen to be added in the mix based on RAP content for each of the additive.

Table 4.15 Calculation of the percentage of the bitumen to be added in the mix based on RAP content for each of the additive

ADDITIVES	RAP Content (%)	Pc (%)	Pa (%)	Pp (%)	Pr (%)
	10			0.1	**3.87**
	20			0.2	**3.44**
SASOBIT®	30	4.3		0.3	**3.01**
	40			0.4	**2.58**
	50			0.5	**2.15**
	10			0.1	**4.10**
	20			0.2	**3.67**
REDISET®	30	4.53	4.3	0.3	**3.24**
	40			0.4	**2.81**
	50			0.5	**2.38**
	10			0.1	**4.07**
	20			0.2	**3.64**
ADVERA®	30	4.50		0.3	**3.21**
	40			0.4	**2.78**
	50			0.5	**2.35**

4.4 Determination of Marshall Parameters with WMA Additives with Different Contents of RAP

Marshall Test E Machine (ASTM D1559) was used for determination of Marshall Parameters with WMA additives. The steps related to mix design were given in section 4.2. In the following part, Marshall Specimens will be prepared by mixing 10%, 20%, 30%, 40% and 50% of reclaimed asphalt pavement and 90%, 80%, 70%, 60% and 50% of new aggregate together with bitumen produced with WMA additives. Table 4.16 presents a summary of the design parameters used in experiments.

Table 4.16 A summary of the design parameters used in experiments

Bitumen Type	B 50/70
Aggregate	Limestone
WMA Additives and Contents	Sasobit® (3%); Rediset® (2%); Advera® (5%)
RAP Contents (%)	10, 20, 30, 40, 50

4.4.1 WMA Additives with Different Content of RAP

After determining the contents of the bitumen to be added with respect to the values given in section 4.3.4, the asphalt concrete samples including WMA additives and different percentages of RAP were prepared taken into the mixing and compaction temperatures into consideration. The mechanical properties of different RAP percentages with Sasobit®, Rediset® and Advera® in terms of stability, flow and air voids are presented in Table 4.17, 4.18, 4.19 and Figure 4.6, Figure 4.7, Figure 4.8 respectively.

Table 4.17 Marshall mix design for RAP with Sasobit®

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**
10%	4.3	4.1	61.18	61.22	61.20	**61.2**	1181.5	694.5	1185.5	491.0	2.406	2.5114	4.19	14.55	71.2	2.11	1196	1.062	1270
10%	4.3	4.1	62.46	62.00	61.68	**62.0**	1190.5	699.0	1194.0	495.0	2.405	2.5114	4.24	14.60	71.0	2.31	1235	1.038	1282
10%	4.3	4.1	61.62	61.54	61.48	**61.5**	1190.0	699.5	1193.0	493.5	2.411	2.5114	3.99	14.37	72.3	2.34	1211	1.053	1275
Avg.											**2.408**		**4.14**	**14.51**	**71.5**	**2.30**			**1276**
20%	4.3	4.1	62.80	63.06	63.02	**63.0**	1190.5	697.5	1193.0	495.5	2.403	2.5114	4.33	14.68	70.5	2.20	1260	1.013	1276
20%	4.3	4.1	62.90	62.98	63.04	**63.0**	1185.5	695.5	1188.0	492.5	2.407	2.5114	4.15	14.52	71.4	2.12	1279	1.013	1296
20%	4.3	4.1	63.24	63.30	63.14	**63.2**	1183.0	691.0	1185.0	494.0	2.395	2.5114	4.65	14.96	68.9	2.36	1285	1.008	1295
Avg.											**2.401**		**4.38**	**14.72**	**70.3**	**2.20**			**1289**
30%	4.3	4.1	63.68	63.88	64.02	**63.9**	1190.0	692.0	1192.0	500.0	2.380	2.5114	5.23	15.49	66.2	1.75	1292	0.99	1279
30%	4.3	4.1	63.24	63.06	63.00	**63.1**	1192.5	696.0	1193.5	497.5	2.397	2.5114	4.56	14.88	69.4	1.71	1283	1.01	1296
30%	4.3	4.1	63.44	63.40	63.26	**63.4**	1192.5	694.0	1193.0	499.0	2.390	2.5114	4.84	15.14	68.0	2.46	1296	1.003	1300
Avg.											**2.389**		**4.88**	**15.17**	**67.9**	**2.00**			**1292**
40%	4.3	4.1	65.00	64.62	64.84	**64.8**	1195.5	697.2	1198.2	501.0	2.386	2.5114	4.99	15.26	67.3	1.50	1532	0.968	1483
40%	4.3	4.1	64.72	64.92	65.12	**64.9**	1194.1	695.7	1197.3	501.6	2.381	2.5114	5.21	15.47	66.3	1.32	1542	0.966	1490
40%	4.3	4.1	65.22	65.24	65.44	**65.3**	1194.0	695.1	1197.8	502.7	2.375	2.5114	5.43	15.66	65.3	1.31	1516	0.956	1449
Avg.											**2.381**		**5.21**	**15.46**	**66.3**	**1.40**			**1474**
50%	4.3	4.1	62.40	63.24	63.38	**63.0**	1191.2	695.2	1195.5	500.3	2.381	2.5114	5.20	15.45	66.4	1.37	2080	1.013	2107
50%	4.3	4.1	63.58	62.98	63.22	**63.3**	1192.8	693.7	1197.8	504.1	2.366	2.5114	5.78	15.98	63.8	1.44	1947	1.005	1957
50%	4.3	4.1	63.42	63.36	63.38	**63.4**	1193.3	688.3	1200.0	511.7	2.332	2.5114	7.14	17.19	58.4	1.45	1839	1.003	1845
Avg.											**2.360**		**6.04**	**16.21**	**62.9**	**1.40**			**1969**

Table 4.18 Marshall mix design for RAP with Rediset®

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**	**Stability (kgf)**	**Correlation fact.**	**Corr. Stability (kgf)**
	Wa	**Wb**	**1**	**2**	**3**	**Avg.**	**A**	**C**	**B**	**V**	**Dp**	**Dt**	**Vh**	**(%)**	**%**	**mm**	**kgf**		**kgf**
10%	4.5	4.3	61.52	60.96	60.82	**61.1**	1186.5	701.4	1188.4	487.0	2.436	2.5278	3.62	13.68	73.6	2.51	1192	1.065	1269
10%	4.5	4.3	61.76	61.68	61.88	**61.8**	1196.0	710.9	1198.0	487.1	2.455	2.5278	2.86	13.00	78.0	2.48	1198	1.043	1250
10%	4.5	4.3	61.46	61.58	61.84	**61.6**	1192.3	707.2	1194.7	487.5	2.446	2.5278	3.24	13.34	75.7	2.49	1194	1.049	1253
Avg.											**2.446**		**3.24**	**13.34**	**75.7**	**2.49**			**1257**
20%	4.5	4.3	62.38	62.46	62.50	**62.4**	1194.1	704.0	1195.8	491.8	2.428	2.5278	3.95	13.97	71.8	1.53	1312	1.028	1349
20%	4.5	4.3	62.00	62.56	62.22	**62.3**	1199.5	709.4	1201.2	491.8	2.439	2.5278	3.51	13.58	74.1	1.79	1264	1.03	1302
20%	4.5	4.3	61.90	62.28	61.38	**61.9**	1195.6	705.6	1197.3	491.7	2.432	2.5278	3.81	13.84	72.5	2.08	1242	1.04	1292
Avg.											**2.433**		**3.75**	**13.80**	**72.8**	**1.80**			**1314**
30%	4.5	4.3	62.44	62.60	62.72	**62.6**	1204.3	701.1	1207.3	506.2	2.379	2.5278	5.88	15.70	62.6	1.56	1323	1.023	1353
30%	4.5	4.3	61.88	61.98	61.92	**61.9**	1198.6	704.2	1200.0	495.8	2.418	2.5278	4.36	14.34	69.6	1.61	1307	1.04	1359
30%	4.5	4.3	61.68	61.80	63.12	**62.2**	1195.2	701.3	1197.6	496.3	2.408	2.5278	4.73	14.67	67.8	1.68	1296	1.033	1339
Avg.											**2.402**		**4.99**	**14.91**	**66.6**	**1.62**			**1350**
40%	4.5	4.3	64.30	64.42	64.28	**64.3**	1185.1	676.9	1190.8	513.9	2.306	2.5278	8.77	18.29	52.1	1.48	1394	0.98	1366
40%	4.5	4.3	64.60	64.48	64.82	**64.6**	1185.8	675.6	1191.1	515.5	2.300	2.5278	8.99	18.50	51.3	1.65	1393	0.973	1355
40%	4.5	4.3	64.82	64.68	64.66	**64.7**	1183.1	679.0	1187.4	508.4	2.327	2.5278	7.94	17.55	54.8	1.45	1385	0.97	1343
Avg.											**2.311**		**8.57**	**18.11**	**52.7**	**1.53**			**1355**
50%	4.5	4.3	66.00	66.18	65.98	**66.1**	1184.6	678.0	1202.0	524.0	2.261	2.5278	10.57	19.90	46.9	1.40	1433	0.941	1348
50%	4.5	4.3	66.12	66.38	66.26	**66.3**	1184.1	679.1	1202.3	523.2	2.263	2.5278	10.47	19.81	47.2	1.60	1452	0.938	1362
50%	4.5	4.3	66.70	66.74	66.68	**66.7**	1185.5	679.5	1203.7	524.2	2.262	2.5278	10.53	19.87	47.0	1.32	1455	0.93	1353
Avg.											**2.262**		**10.52**	**19.86**	**47.0**	**1.44**			**1355**

Table 4.19 Marshall mix design for RAP with Advera®

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**	**Stability (kgf)**	**Correlation fact.**	**Corr. Stability (kgf)**
	Wa	**Wb**	**1**	**2**	**3**	**Avg.**	**A**	**C**	**B**	**V**	**Dp**	**Dt**	**Vh**	**(%)**	**%**	**mm**	**kgf**		**kgf**
10%	4.5	4.3	62.16	62.18	62.20	**62.2**	1194.6	705.5	1195.6	490.1	2.437	2.5330	3.77	13.61	72.3	2.47	1133	1.033	1170
10%	4.5	4.3	62.28	62.42	62.26	**62.3**	1193.8	704.5	1195.4	490.9	2.432	2.5330	3.99	13.81	71.1	2.52	1119	1.03	1153
10%	4.5	4.3	62.08	62.30	62.16	**62.2**	1194.7	705.6	1196.2	490.6	2.435	2.5330	3.86	13.69	71.8	2.45	1126	1.033	1163
Avg.											**2.435**		**3.88**	**13.70**	**71.7**	**2.50**			**1162**
20%	4.5	4.3	63.20	62.76	62.70	**62.9**	1202.9	706.2	1203.4	497.2	2.419	2.5330	4.49	14.25	68.5	2.02	1236	1.015	1255
20%	4.5	4.3	62.58	62.42	62.52	**62.5**	1198.0	702.3	1200.9	498.6	2.403	2.5330	5.14	14.84	65.4	2.11	1216	1.025	1246
20%	4.5	4.3	62.78	62.68	62.64	**62.7**	1201.3	705.5	1203.9	498.4	2.410	2.5330	4.84	14.57	66.8	2.08	1224	1.02	1248
Avg.											**2.411**		**4.82**	**14.56**	**66.9**	**2.07**			**1250**
30%	4.5	4.3	63.28	63.30	63.36	**63.3**	1203.4	705.4	1205.3	499.9	2.407	2.5330	4.96	14.68	66.2	1.56	1303	1.005	1310
30%	4.5	4.3	63.60	63.62	63.72	**63.6**	1200.2	703.9	1203.3	499.4	2.403	2.5330	5.12	14.82	65.5	1.62	1312	0.998	1309
30%	4.5	4.3	63.50	63.54	63.62	**63.6**	1206.7	706.6	1208.7	502.1	2.403	2.5330	5.12	14.82	65.5	1.90	1326	0.998	1323
Avg.											**2.405**		**5.07**	**14.77**	**65.7**	**1.70**			**1314**
40%	4.5	4.3	63.62	63.68	63.62	**63.6**	1202.5	705.5	1205.7	500.2	2.404	2.5330	5.09	14.80	65.6	1.64	1457	0.998	1454
40%	4.5	4.3	63.40	63.00	63.26	**63.2**	1200.0	703.5	1203.2	499.7	2.401	2.5330	5.19	14.89	65.1	1.56	1446	1.005	1453
40%	4.5	4.3	64.08	63.96	64.02	**64.0**	1203.5	705.5	1207.9	502.4	2.396	2.5330	5.43	15.10	64.1	1.72	1448	0.988	1431
Avg.											**2.400**		**5.24**	**14.93**	**64.9**	**1.60**			**1446**
50%	4.5	4.3	64.42	64.40	64.42	**64.4**	1203.0	703.5	1206.2	502.7	2.393	2.5330	5.52	15.18	63.6	1.42	1586	0.978	1551
50%	4.5	4.3	64.54	64.48	64.52	**64.5**	1200.5	701.5	1203.8	502.3	2.390	2.5330	5.65	15.29	63.1	1.66	1590	0.975	1550
50%	4.5	4.3	64.76	64.52	64.54	**64.6**	1200.0	700.5	1203.1	502.6	2.388	2.5330	5.74	15.38	62.7	1.52	1578	0.973	1535
Avg.											**2.390**		**5.64**	**15.29**	**63.1**	**1.50**			**1546**

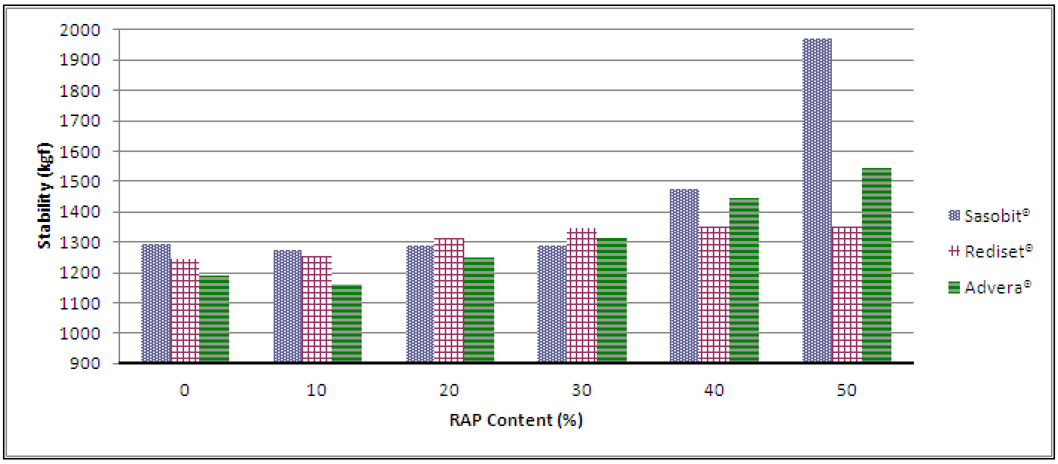

Figure 4.6 Marshall stability values for RAP and control samples

As illustrated in Figure 4.6, all recycled asphalt mixtures involving all WMA additives provide adequate stability (min. 900 kg. related to wearing course specification). The stability values increases with increase of RAP content for the mixtures prepared with Sasobit® and Advera® additive. However, no significant variation is observed on the stability values above 30% RAP content addition for the mixtures involving Rediset® additive.

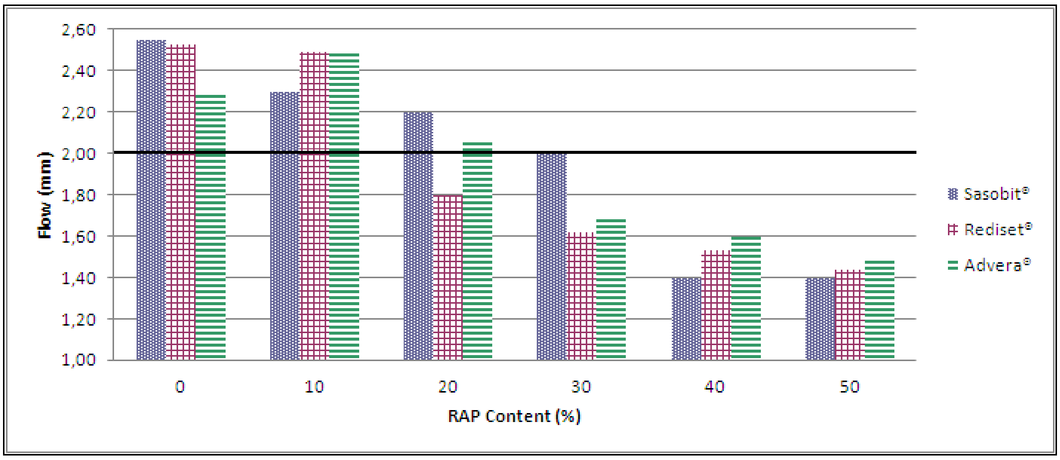

Figure 4.7 Flow values for RAP and control samples

As presented in Figure 4.7; the flow values decrease with increasing RAP content for the mixtures prepared with all WMA additives. As the flow values are indicator of deformation characteristic, the flow values less than the specification limits (2 mm.) is not favorable since it implies that the mix is very stiff and brittle. As depicted in Figure. 4.7, based on the lower limitation of flow values, the percentages of RAP addition are determined as 30%, 10% and 20% for the specimens prepared with Sasobit®, Rediset® and Advera® respectively.

Therefore, it can be concluded that the 30% RAP content with Sasobit®, 10% RAP content with Rediset® and 20% RAP content with Advera® can be accepted as an optimum RAP content based on the specification limits of flow and stability values.

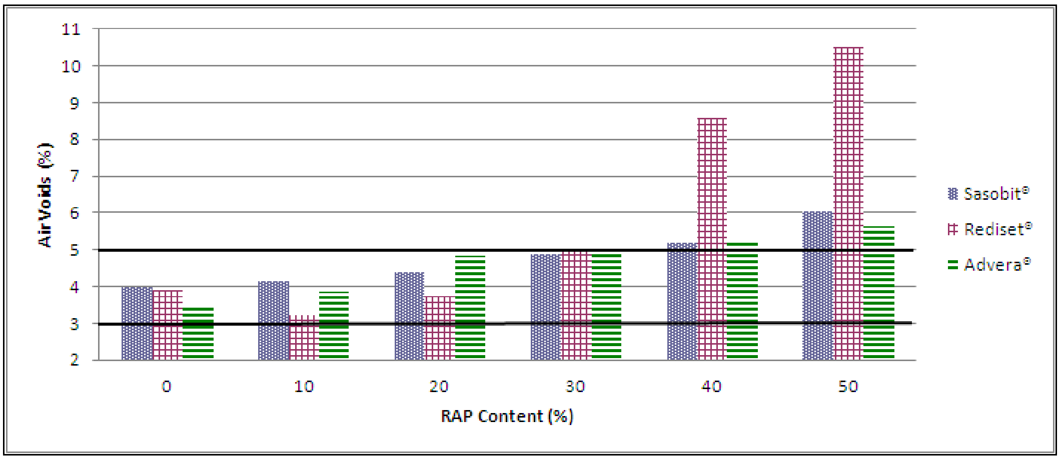

Figure 4.8 Air void values for RAP and control samples

As illustrated in Figure 4.8, as RAP contents increase, the voids increase as well for all specimens involving WMA additives. Besides, the concluded optimum RAP contents for each WMA additive satisfies the specification limits of air voids value (3%-5%).

4.5 Indirect Tensile Properties of Samples with Optimum RAP Content

The indirect tensile strength test is used to determine the tensile properties of the asphalt concrete which can be further related to the cracking properties of the pavement.

Indirect Tensile Strength (ITS) was performed by loading (at a constant rate of 50 mm. per minute) a cylindrical specimen with a single or repeated compressive load which acted parallel and along the vertical diametric plane in accordance with ASTM D6931-07.

The IDT strength of bituminous mixtures was conducted by loading a cylindrical specimen across its vertical diametric plane at a specified rate of deformation and test temperature. The peak load at failure was recorded and used to calculate the IDT strength of the specimen. The procedures of method is given below:

- Mineral filler and aggregates are heated in an oven to a temperature of 150°C.
- The bitumen is heated in a pouring to temperature of 145–150 °C.
- Aggregates and bitumen are mixed with a mixer.
- The temperature of the prepared mixture should be in the mixing temperature interval.
- Compaction hammer as well as the compaction molds are cleaned and heated to compaction temperatures.
- The filter paper is inserted into the bottom of the mold to prevent adhesion between the mixture and the mold.
- The warm mix is introduced into the mold. Seventy five blows are used for compaction depending on the amount of the tire inflation pressure used for the traffic design.
- After the specimens have been removed from the mold they are allowed to cool to the room temperature.
- Average specimen heights and diameters (101.6 mm=4 in.) are determined for each specimen.
- Place the specimen in a plastic bag and then place the specimen in a 25 °C water bath for 2 hours.
- Remove the specimen from the water bath and plastic bag.
- Ensure that the loading strips are parallel and centered on the vertical diametric plane. Diagram of an IDT strength loading fixture is illustrated in Figure 4.6.

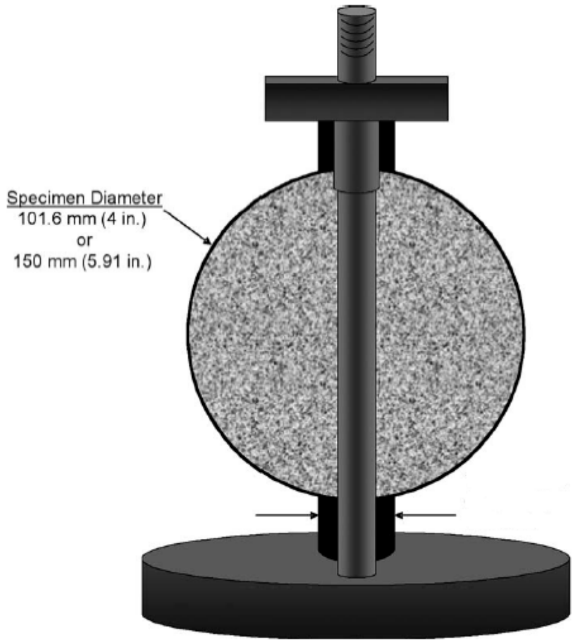

Figure 4.6 Diagram of an IDT strength loading fixture

- Apply a vertical compressive ramp load until the maximum load is reached. The recommended rate is 50 mm./min.
- Consequently, record the maximum load.
- Calculate the tensile strength using the following equation:

$$S_t = 2P/\pi*t*D$$

Where;

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

P = Applied load, kg.

D = Diameter of specimen, cm.

t = Thickness of specimen, cm.

4.5.1 Indirect Tensile Properties of Control Samples

According to the explanations given in part 4.5, Indirect Tensile Strength was tested on the specimens that contain three different WMA additives (Sasobit® at a dose 3% by weight of the bitumen, Rediset® at a dose 2% by weight of the bitumen and Advera® at a dose 5% by weight of the bitumen) in order to show results of control samples. Indirect Tensile Strength test results of control samples are presented in Table 4.20.

Table 4.20 ITS results of control samples

Additive	Bitumen Content (%)	Specimen No.	Specimen Thickness (cm)				Diameter	Load	Load	ITS
			1	2	3	Ave.	(mm)	(kgf)	(N)	(kPa)
SASOBIT ®	**4,30%**	**1**	62,3	61,5	61,4	**61,7**	101,6	1148	11258,03	1142,57
		2	61,3	61,1	61,1	**61,2**	101,6	1156	11336,49	1161,06
		Average								**1151,82**
REDISET ®	**4,53%**	**1**	61,0	61,1	60,8	**61,0**	101,6	1112	10904,99	1120,90
		2	61,0	61,2	61,3	**61,2**	101,6	1130	11081,51	1134,95
		Average								**1127,92**
ADVERA ®	**4,49%**	**1**	61,6	61,3	61,4	**61,4**	101,6	1096	10748,09	1096,26
		2	61,4	61,3	61,4	**61,4**	101,6	1104	10826,54	1105,46
		Average								**1100,86**

4.5.2 Indirect Tensile Properties of Samples with Optimum RAP Content

After Indirect Tensile Strength test results of control samples had been obtained, samples with optimum RAP contents were prepared according to procedures of method given in part 4.5.

Indirect Tensile properties of samples with 30% optimum RAP for Sasobit® additive, 10% optimum RAP for Rediset® and 20% optimum RAP for Advera® are given in Table 4.21. Besides, ITS ratio and the comparison of control mix along with RAP content are presented in Table 4.22 and Figure 4.9.

Table 4.21 ITS results of optimum RAP content

Additive	RAP Content (%)	Specimen No.	Specimen Thickness (cm)				Diameter	Load	Load	ITS
			1	**2**	**3**	**Ave.**	**(mm)**	**(kgf)**	**(N)**	**(kPa)**
SASOBIT ®	**30**	**1**	62,6	62,6	62,7	**62,6**	101,6	1325	12993,81	1300,20
		2	63,1	63,3	63,1	**63,2**	101,6	1336	13101,68	1299,10
		3	63,4	63,6	63,3	**63,5**	101,6	1345	13189,94	1302,49
		Average								**1300,60**
REDISET ®	**10**	**1**	61,4	61,4	61,4	**61,4**	101,6	1217	11934,69	1217,95
		2	62,0	61,9	61,9	**61,9**	101,6	1230	12062,18	1220,36
		3	61,5	61,5	61,5	**61,5**	101,6	1302	12768,26	1301,46
		Average								**1246,59**
ADVERA ®	**20**	**1**	63,1	62,9	62,8	**62,9**	101,6	1257	12326,96	1227,85
		2	63,1	63,0	63,1	**63,1**	101,6	1232	12081,79	1200,50
		3	63,0	63,0	63,0	**63,0**	101,6	1248	12238,70	1217,25
		Average								**1215,20**

Table 4.22 ITS ratio and comparison of control mix along with RAP content

Additive	Bitumen Content (%)	ITS Results of Control Samples (kPa)	RAP Content (%)	ITS Results of RAP Content (kPa)	ITS Ratio
SASOBIT®	4,30	1151,82	30	1300,60	1,129
REDISET®	4,53	1127,92	10	1246,59	1,105
ADVERA®	4,49	1100,86	20	1215,20	1,104

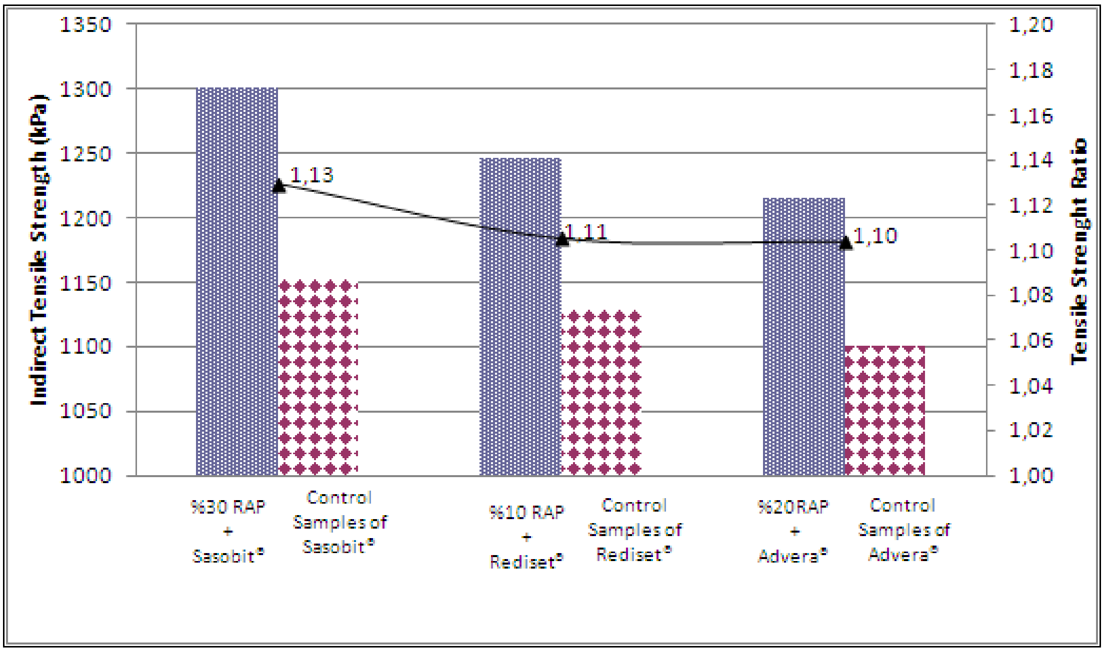

Figure 4.9 ITS results of control samples and optimum RAP contents for each WMA additives

In this study, the indirect tensile strengths of all optimum percentage of RAP with WMA additives are higher than the control mix. This indicates that the mixtures containing RAP have higher values of tensile strength at failure indirect tensile strength under static loading. This would further imply that WMA mixtures with RAP appear to be capable of withstanding larger tensile strains prior to cracking. Based on the ITS ratio, 30% optimum RAP for Sasobit® additive have the most increase in tensile strength over the control mix.

CHAPTER FIVE
COST-BENEFIT ANALYSIS

Different techniques of producing Warm Mix Asphalt promise various energy savings for production. This mostly depends on how much the production temperature is lowered and what kind of WMA additive is used compared with Hot Mix Asphalt. The economical benefit from energy savings should be discussed together with the cost as higher energy prices promise greater savings.

The cost analysis calculations are carried out in three steps:

- Calculation of benefits.
- Calculation of cost.
- Determination of final cost.

Cost-benefit analysis was performed to inspect the advantages and disadvantages of Recycled Asphalt Pavement in terms of economy. For this purpose a highway section (1 km. in length, 10 m. in width and 5 cm. in thickness) is chosen. Transportation distance constitutes main part of the analysis. Therefore, the place of refinery and plant must be determined for exact analysis. For all cases, the refinery is chosen as Aliağa Refinery and the plant site is chosen as Ege Asfalt located in Pınarbaşı/İZMİR. The distance between the two locations is approximately 65 km. Chosen location is the center of İzmir region (Konak), the distance from Konak where RAP is taken to Ege Asfalt plant is approximately 20 km. The distance from Ege Asfalt plant to construction site is designated as M.

5.1 Case Study for Hot Mix Asphalt

The unit costs related to the benefits and costs of Hot Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 65.77 TL/ton. includes;

- The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 =60.3778 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank:

F = K * (0.0007 * M + 0.01)
In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.
M=The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

4.88% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

F_3 = 8.0475 TL/ton * 0.0488 ton = 0.392718 TL/ton

- The cost of bituminous mixture transportation from plant to construction site:

F_4 = K * (0.0007 * M + 0.01)
F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45) TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):

$F = K * (0.0007 * M + 0.01)$

$F = 145 * (0.0007 * 65 + 0.01) = 8.0475$ TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

$F_5 = 8.0475 * 0.0042 = 0.0338$ TL/ton

- Heating of the bitumen:

1 tone bituminous mixture includes 0.0488 tone bitumen,

The heating cost of 0.0488 tone bitumen;

$F_6 = 26.74$TL/ton $* 0.0488 = 1.304912$ TL/ton

Costs in the case of Hot Mix Asphalt:

$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6$

$\Sigma C = 65.77+60.3778+0.392718+0.1015*M+1.45+0.0338+1.304912$

$\Sigma C = (129.329,230+0.1015*M)$ TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = **(155.195,076+121.8*M) TL**

5.2 Case Study for Warm Mix Asphalt with Sasobit® Additive

The unit costs related to the benefits and costs of Warm Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 65.77 TL/ton.

- The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 = 53.202 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank:

F = K * (0.0007 * M + 0.01)
In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.
M=The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

4.3% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

F_3 = 8.0475 TL/ton * 0.043 ton = 0.3460425 TL/ton

- The cost of bituminous mixture transportation from plant to construction site :

F_4 = K * (0.0007 * M + 0.01)
F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45) TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):

F = K * (0.0007 * M + 0.01)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

F_5 = 8.0475 * 0.0042 = 0.0338 TL/ton

- Heating of the bitumen:

1 tone bituminous mixture includes 0.043 tone bitumen,

The heating cost of 0.043 tone bitumen

F_6 = 24.074TL/ton * 0.043 = 1.0352 TL/ton

- Cost of Sasobit® additive at a dose 3% by weight of the bitumen:

Price of Sasobit® is 2300 €/ton;

Cost of Sasobit® additive F_7 =7.02 TL/ton (for 1 tone bituminous mixture)

Costs in the case of Warm Mix asphalt with Sasobit® additive:

$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6+F_7$

ΣC = 65.77+53.202+0.3460425+0.1015*M+1.45+0.0338+1.0352+7.02

ΣC = (128.857,043+0.1015*M) TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = (**154.628,451+121.8*M) TL**

5.3 Case Study for Warm Mix Asphalt with Rediset® Additive

The unit costs related to the benefits and costs of Warm Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 65.77 TL/ton.

- The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 = 56.047 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank:

F = K * (0.0007 * M + 0.01)
In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.
M=The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

4.53% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

F_3 = 8.0475 TL/ton * 0.0453 ton = 0.3646 TL/ton

- The cost of bituminous mixture transportation from plant to construction site:

F_4 = K * (0.0007 * M + 0.01)
F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45) TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):

$F = K * (0.0007 * M + 0.01)$

$F = 145 * (0.0007 * 65 + 0.01) = 8.0475$ TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

$F_5 = 8.0475 * 0.0042 = 0.0338$ TL/ton

- Heating of the bitumen:

1 tone bituminous mixture includes 0.0453 tone bitumen,

The heating cost of 0.0453 tone bitumen

$F_6 = 24.4908$TL/ton $* 0.0453 = 1.109$ TL/ton

- Cost of Rediset® additive at a dose 2% by weight of the bitumen:

Price of Rediset ® is 2300 €/ton;

Cost of Rediset ® additive $F_7 = 4.93$ TL/ton (for 1 tone bituminous mixture)

Costs in the case of Warm Mix asphalt with Rediset® additive:

$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6+F_7$

$\Sigma C = 65.77+56.047+0.3646+0.1015*M+1.45+0.0338+1.109+4.93$

ΣC = (129.704,400+0.1015*M) TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = **(155.645,280+121.8*M) TL**

5.4 Case Study for Warm Mix Asphalt with Advera® Additive

The unit costs related to the benefits and costs of Warm Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 65.77 TL/ton.

- The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 = 55.676 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank

$F = K * (0.0007 * M + 0.01)$

In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.

M= The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

$F = 145 * (0.0007 * 65 + 0.01) = 8.0475$ TL/ton

4.5% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

$F_3 = 8.0475$ TL/ton * 0.045 ton = 0.3621 TL/ton

- The cost of bituminous mixture transportation from plant to construction site:

$F_4 = K * (0.0007 * M + 0.01)$

$F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45)$ TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):

F = K * (0.0007 * M + 0.01)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

F_5 = 8.0475 * 0.0042 = 0.0338 TL/ton

- Heating of the bitumen:

1 tone bituminous mixture includes 0.045 tone bitumen,

The heating cost of 0.045 tone bitumen

F_6 = 25.074TL/ton * 0.045 = 1.12833 TL/ton

- Cost of Advera® additive at a dose 5% by weight of the bitumen:

Price of Advera ® is 600 €/ton;

Cost of Advera ® additive F_7 = 3.19 TL/ton (for 1 tone bituminous mixture)

Costs in the case of Warm Mix asphalt with Advera® additive:

$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6+F_7$

ΣC = 65.77+55.676+0.3621+0.1015*M+1.45+0.0338+1.12833+3.19

ΣC = (127.610,230+0.1015*M) TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = **(153.132,276+121.8*M) TL**

5.5 Case Study for 30% RAP Content with Sasobit® Additive

The unit costs related to the benefits and costs of Warm Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 46.039 TL/ton. (70% virgin aggregate was used.)

- The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 = 37.24 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank:

$F = K * (0.0007 * M + 0.01)$

In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.

M= The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

$F = 145 * (0.0007 * 65 + 0.01) = 8.0475$ TL/ton

3.01% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

$F_3 = 8.0475$ TL/ton * 0.0301 ton = 0.242 TL/ton

- The cost of bituminous mixture transportation from plant to construction site:

$F_4 = K * (0.0007 * M + 0.01)$

$F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45)$ TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):

F = K * (0.0007 * M + 0.01)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

F_5 = 8.0475 * 0.0042 = 0.0338 TL/ton

- Heating of the bitumen:

1 tone bituminous mixture includes 0.043 tone bitumen,

The heating cost of the additional 0.0301 tone bitumen

F_6 = 24.074TL/ton * 0.0301 = 0.7246 TL/ton

- Cost of Sasobit® additive at a dose 3% by weight of the bitumen:

Price of Sasobit® is 2300 €/ton;

Cost of Sasobit® additive F_7 =4.914 TL/ton (for 1 tone bituminous mixture)

- Cost of RAP excavation = F_8 = 5.469 TL/ton

- The transportation costs from the place the RAP material has been extracted and to plant where the material have some treatment to be reused as an asphalt pavement (M=20 km.):

F = K * (0.0007 * M + 0.01)

F = 145 * (0.0007 * 20 + 0.01) = 3.48 TL/ton

%30 RAP was used; F_9 = 0.3 * 3.48 TL/ton = 1.044 TL/ton

Costs in the case of 30% RAP Content with Sasobit® Additive:

$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8+F_9$

$\Sigma C = 46.039+37.24+0.242+0.1015*M+1.45+0.0338+0.7246+4.914+5.469+1.044$

ΣC = (97.156,400+0.1015*M) TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = **(116.587,680+121.8*M) TL**

5.6 Case Study for 10% RAP Content with Rediset® Additive

The unit costs related to the benefits and costs of Warm Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 59.193 TL/ton. (90% virgin aggregate was used.)

- The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 = 50.727 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank:

$F = K * (0.0007 * M + 0.01)$

In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.

M= The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

4.1% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

F_3 = 8.0475 TL/ton * 0.041 ton = 0.3299 TL/ton

- The cost of bituminous mixture transportation from plant to construction site:

F_4 = K * (0.0007 * M + 0.01)

F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45) TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):
-

F = K * (0.0007 * M + 0.01)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

F_5 = 8.0475 * 0.0042 = 0.0338 TL/ton

- Heating of the bitumen

1 tone bituminous mixture includes 0.0453 tone bitumen,

The heating cost of the additional 0.041 tone bitumen

F_6 = 24.4908TL/ton * 0.041 = 1.00412 TL/ton

- Cost of Rediset® additive at a dose 2% by weight of the bitumen

Price of Rediset® is 2300 €/ton;

Cost of Rediset® additive F_7 =4.462 TL/ton (for 1 tone bituminous mixture)

- Cost of RAP excavation = F_8 = 1.823 TL/ton

- The transportation costs from the place the RAP material has been extracted and to plant where the material have some treatment to be reused as an asphalt pavement (M= 20 km.):

$F = K * (0.0007 * M + 0.01)$
$F = 145 * (0.0007 * 20 + 0.01) = 3.48$ TL/ton

%10 RAP was used; $F_9 = 0.1 * 3.48$ TL/ton = 0.348 TL/ton

Costs in the case of 10% RAP Content with Rediset® Additive:
$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8+F_9$
=59.193+50.727+0.3299+0.1015*M+1.45+0.0338+1.00412+4.462+1.823+0.348

ΣC = (119.370,820+0.1015*M) TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = **(143.244,984+121.8*M) TL**

5.7 Case Study for 20% RAP Content with Advera® Additive

The unit costs related to the benefits and costs of Warm Mix Asphalt are taken from The Unit Price List of the Directorate of the General Directorate of State Highways.

The following are the units costs of the year 2011 for 1 tone bituminous mixture:

- Total aggregate cost = F_1 = 52.616 TL/ton. (80% virgin aggregate was used.)

-The preparation of the aggregate between 1 inch and 3/4 inch
- The preparation of the aggregate between 5/8 inch and 1/2 inch
- The preparation of the aggregate between 3/8 inch and 1/4 inch

- Total bitumen cost = F_2 = 45.0359 TL/ton

- The cost of bitumen transportation from the place of delivery to storage tank

F = K * (0.0007 * M + 0.01)
In this formula:

K=The coefficient which is determined by General Directorate of State Highways. The value of this coefficient is 145.
M= The distance of transportation from Aliağa Refinery to Ege Asfalt (65 km.)

F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

3.64% optimum bitumen content is determined for the chosen highway section. The cost of bitumen transportation for 1 tone bituminous mixture from refinery to plant:

F_3 = 8.0475 TL/ton * 0.0364 ton = 0.293 TL/ton

- The cost of bituminous mixture transportation from plant to construction site:

F_4 = K * (0.0007 * M + 0.01)
F_4 = 145 * (0.0007 * M + 0.01) = (0.1015*M+1.45) TL/ton

- The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt (M = 65 km.):

-

F = K * (0.0007 * M + 0.01)
F = 145 * (0.0007 * 65 + 0.01) = 8.0475 TL/ton

0.5 lt. bituminous adhesive agent should be used for each square meter. 0.0042 tone bituminous adhesive agent is needed to transport for 1 tone asphalt mixture.

F_5 = 8.0475 * 0.0042 = 0.0338 TL/ton

- Heating of the bitumen

1 tone bituminous mixture includes 0.045 tone bitumen,

The heating cost of the additional 0.0364 tone bitumen

F_6 = 25.074TL/ton * 0.0364 = 0.9127 TL/ton

- Cost of Advera® additive at a dose 5% by weight of the bitumen

Price of Advera® is 600 €/ton;

Cost of Advera® additive F_7 = 2.584 TL/ton (for 1 tone bituminous mixture)

- Cost of RAP excavation = F_8 = 3.646 TL/ton

- The transportation costs from the place the RAP material has been extracted and to plant where the material have some treatment to be reused as an asphalt pavement (M=20 km.)

F = K * (0.0007 * M + 0.01)

F = 145 * (0.0007 * 20 + 0.01) = 3.48 TL/ton

%20 RAP was used; F_9 = 0.2 * 3.48 TL/ton = 0.696 TL/ton

Costs in the case of 20% RAP Content with Advera® Additive:

$\Sigma C = F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8+F_9$

ΣC=

= 52.616+45.0359+0.293+0.1015*M+1.45+0.0338+0.9127+2.584+3.646+0.696

ΣC = (107.267,400+0.1015*M) TL/ton (Cost of 1 tone bituminous mixture)

Cost of bituminous mixture for 1 km. highway = **(128.720,880+121.8*M) TL**

The calculation of cost analysis conducted on HMA, WMA and an optimum RAP content in terms of M (distance from plant to construction site) is presented in Table 5.1 and Figure 5.1.

An initial comparison was made between hot mix and warm mix asphalt. For all M values, Sasobit® reduces the final cost. However, the similar conclusion cannot be made for Rediset® additive.

On the occasion when RAP is taken into consideration, as expected the utilization of RAP decreases the final cost for all cases. Among the RAP additions, it is clearly observed that utilizing of 30% RAP content with Sassobit® additive is the most economic in terms of final cost for all case studies that are calculated for various distances (M=25 km., 50 km. and 75 km.) from plant to construction site.

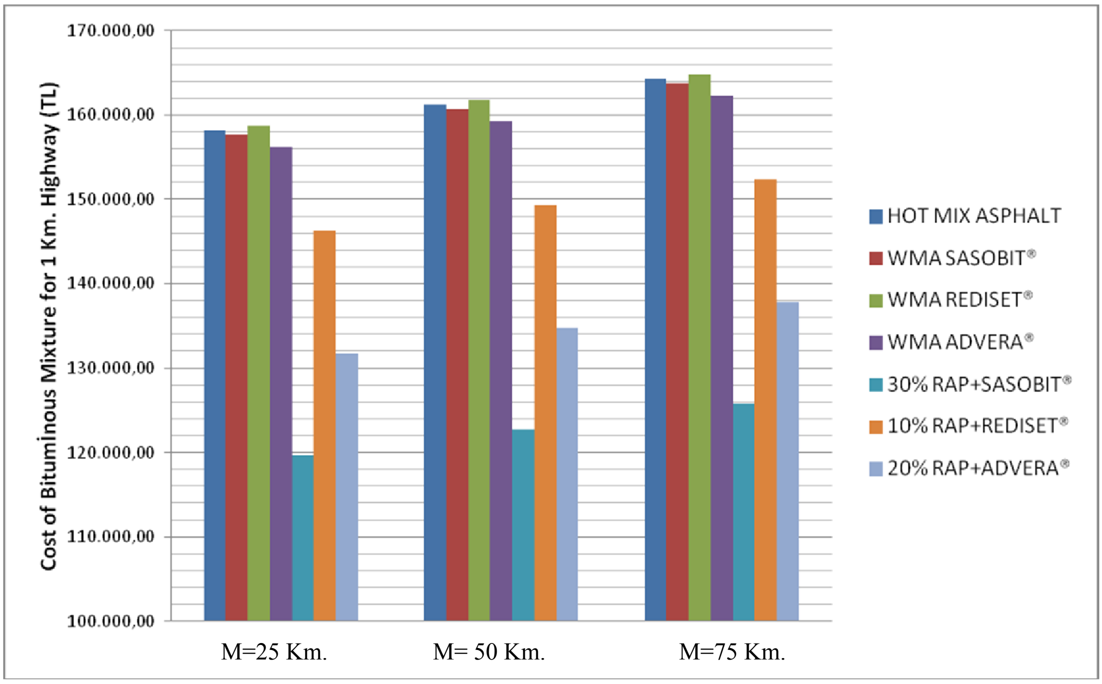

Figure 5.1 Illustration of cost analysis results

The road industry has been seeking to minimize the amount of energy required to product asphalt mixture and to lower asphalt plant emissions, parallel to energy savings and environmental benefits for many years.

Recycling processes save energy. Saved of aggregates reduces necessities of quarrying, transportation and the subsequent processing in recycling methods. Consequently, cost of energy is saved in these processes. Recycled asphalt reduces the demand for new bitumen and saves energy at the refinery. Moreover, electric power consumption significantly decreases because of reduced demand for bitumen.

Emissions from Hot Mix Asphalt are harmful to the environment during the laying and compaction steps. The emissions in Hot Mix Asphalt include nitrogen oxides, carbon monoxide, sulfur dioxide and the other volatile organic components. The WMA additive Sasobit®, and construction temperatures affect on carbon dioxide emissions. This result means that carbon dioxide emission depends on temperature. Thus, decreasing of asphalt mixing or compaction temperatures is a way to decrease amount of carbon dioxide emissions during pavement construction.

Additional important benefit of the Warm Mix Asphalt technology is the reduction of energy consumption required by heating in traditional hot mix asphalt (HMA) to typically found at the production plant. With the decreased production temperature, occurs the additional benefit of reduced emissions at the plant and during lay down. Fuel savings with Warm Mix Asphalt typically range from 20 to 30 %. These rates can be higher than 50% or more in the processes with low energy concrete. The reduced fuel and energy usage gives a reduction of the production of green house gases and reduces the carbon footprint.

Table 5.1 Cost-benefit analysis results

	HOT MIX ASPHALT	WARM MIX ASPHALT			WARM MIX ASPHALT + RAP		
		SASOBIT®	REDISET®	ADVERA®	%30 RAP + SASOBIT®	%10 RAP + REDISET®	%20 RAP + ADVERA®
Total aggregate cost (TL/ton)	65.77	65.77	65.77	65.77	46.039	59.193	52.616
Total bitumen cost (TL/ton)	60.3778	53.202	56.047	55.676	37.24	50.727	45.0359
The cost of bitumen transportation from the place of delivery to storage tank (TL/ton)	0.392718	0.3460425	0.3646	0.3621	0.242	0.3299	0.293
The cost of bituminous mixture transportation from plant to construction site(TL/ton)	0.1015*M+1.45	0.1015*M+1.45	0.1015*M+1.45	0.1015*M+1.45	0.1015*M+1.45	0.1015*M+1.45	0.1015*M+1.45
The cost of bituminous adhesive agent transportation from Aliağa Refinery to Ege Asfalt(TL/ton)	0.0338	0.0338	0.0338	0.0338	0.0338	0.0338	0.0338
Heating of the bitumen (TL/ton)	1.304912	1.0352	1.109	1.12833	0.7246	1.00412	0.9127
Cost of additive (TL/ton)	-	7.02	4.93	3.19	4.914	4.462	2.584
Cost of RAP excavation (TL/ton)	-	-	-	-	5.469	1.823	3.646
Cost of RAP transportation (TL/ton)	-	-	-	-	1.044	0.348	0.696
Cost of 1 tone bituminous mixture (TL)	129.329,230+0.1015*M	128.857,043+0.1015*M	129.704,400+0.1015*M	127.610,230+0.1015*M	97.156,400+0.1015*M	119.370,820+0.1015*M	107.267,400+0.1015*M
Cost of bituminous mixture for 1 km. highway (TL)	**155.195,076+121.8*M**	**154.628,451+121.8*M**	**155.645,280+121.8*M**	**153.132,276+121.8*M**	**116.584,680+121.8*M**	**143.244,984+121.8*M**	**128.720,880+121.8*M**
Case study of bituminous mixture for 1 km. highway (TL), M=25 km.	**158.240,076**	**157.673,451**	**158.690,280**	**156.177,276**	**119.632,680**	**146.289,984**	**131.765,880**
Case study of bituminous mixture for 1 km. highway (TL), M=50 km.	**161.285,076**	**160.718,451**	**161.735,280**	**159.222,276**	**122.677,680**	**149.334,984**	**134.810,880**
Case study of bituminous mixture for 1 km. highway (TL), M=75 km.	**164.330,076**	**163.763,451**	**164.780,280**	**162.267,276**	**125.722,680**	**152.379,984**	**137.855.880**

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

Decreasing asphalt production emissions and lowering compaction emissions in the plant are the most important benefits of utilization of warm mix asphalt. Lowering of mixing and compaction temperatures reduce energy consumption because of saving fuel. The properties of bitumen are improved by means of WMA additive, Sasobit®, Rediset® and Advera®. These results have been reached by the conventional test methods such as penetration, softening point, rotational viscosity, TFOT test results. Besides, the addition of Sasobit®, Rediset® and Advera® help in the reduction of viscosity values which are in return decreases the mixing and compaction temperature leading to the reduction of energy costs as well as emissions.

WMA technology suggests a solution to maintain the available state of technology that enables to utilize more RAP at a relatively lower temperature in HMA mixes. In addition, hot mix asphalt or warm mix asphalt with RAP can exhibit an outstanding performance as well as mixtures which are made of new materials. Marshall Stability values related to RAP mixtures has been found higher than the control mixtures. Based on the utilized aggregate, 30%, 10% and 20% can be accepted as an optimum RAP addition for Sasobit®, Rediset® and Advera® respectively. The other properties of samples including optimum RAP content for each used additive such as flow, air void level, VMA are also within specification limits. The utilization of RAP with WMA gather low flow values with high stability values and hence high MQ values indicating a high stiffness mix with a greater ability to spread the applied load and resist creep deformation. Care must be exercised with very high stiffness mixes due to their lower tensile strain capacity to failure, such mixes are more likely to fail by cracking particularly when laid over foundations which fail to provide adequate support.

Indirect tensile strength (ITS) is a very common performance test used in pavement industry. ITS testing offers a reliable indication of the crack potential for a mixture. ITS was tested on the specimens that contain three different WMA additives (Sasobit® at a dose 3% by weight of the bitumen, Rediset® at a dose 2% by weight of the bitumen and Advera® at a dose 5% by weight of the bitumen) in order to show results of control samples. Sasobit® additive with 30% RAP content has an appreciable increase in tensile strength over the control mix, which may be due to crystallize structure of both Sasobit® aided WMA mixture and RAP materials. Overall, air voids in the Advera® mix has the poorest performance in terms of Indirect Tensile Strength. Air voids in the WMA mixture prepared with Advera® may contribute the lower ITS value and the lower ITS ratio.

The main benefit of the RAP with WMA technology is the ability to reduce final cost compared to HMA and WMA mixtures. The reduction rate is strongly connected with the less need of virgin bitumen, virgin aggregates and less need of heating process that are used in WMA mixtures containing with RAP. Among the RAP additions, it is clearly observed that utilizing of 30% RAP content with Sasobit® additive is the most economic in terms of final cost for all case studies.

The conclusion of the study covers the utilization of three types warm mix asphalt additives with different percentages of RAP materials. More research can be conducted to evaluate the stripping and rutting behavior of the samples including RAP and different types of WMA additives. Besides, to investigate the possibility of thermal cracking, more tests should be completed that evaluates the tensile strength at lower temperatures.

REFERENCES

Al-Rousan, T., Asi, I., Al-Hattamleh, O. & Al-Qablan, H. (2008). Performance of asphalt mixes containing RAP. *Jordan Journal of Civil Engineering,* 2 (3), 218-227.

Austerman, A. J., Mogawer, W. S., & Bonaquist, R. (2009). *Evaluating the effects of warm mix asphalt technology additive dosages on the workability and durability of asphalt mixtures containing recycled asphalt pavement.* Washington, DC: Transportation Research Board 88th Annual Meeting.

Button, J. W., Estakhri, C., & Wimsatt, A. (2007). *A synthesis of warm-mix asphalt.* Texas: Texas Transportation Institute, The Texas A&M University.

Chiu, C., Hsu, T. & Yang, W. (2007). Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resources, Conservation and Recycling ,* 52 (3), 545-556

Chowdhury, A., & Button, J. W. (2008). *A review of warm mix asphalt.* Texas: Texas Transportation Institute, The Texas A&M University.

Croteau, J. M. & Tessier, B. (2008). *Warm mix asphalt paving technologies: A Road Builder's Perspective.* Ottawa: 2008 Annual Conference of the Transportation Association of Canada.

D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., Harman, T., Jamshidi, M., Jones, W., Newcomb, D., Prowell, B., Sines, R., & Yeaton, B. (2008). *Warm-Mix asphalt: European practise.* Washington, DC: American Trade Iniatives.

Dunning, R. & Mendenhall, R. (1978). *Design of recycled asphalt pavements and selection of modifiers, recycling of bitumenous pavements*. *ASTM STP*662, 35-46.

Estakhri, C., Button, J., & Alvarez, A. E. (2010). *Field and laboratory investigation of warm mix asphalt in Texas.* Texas: Texas Transportation Institute, The Texas A&M University.

Gandhi, T. (2008). *Effets of warm mix asphalt additives on asphalt binder and mixture properties.* South Carolina: Clemson University.

Hodo, W., Kvasnak, A., & Brown, E. R. (2009). *Investigation of foamed asphalt (warm mix asphalt) with high reclaimed asphalt pavement (RAP) content for sustainment and rehabilitation of asphalt pavement.* Washington, D.C: Transportation Research Board 88th Annual Meeting.

Huffman, J. (Ed.). (2001). *Basic asphalt recycling manual* (1st ed.). Annapolis, Maryland: Asphalt Recycling & Reclamation Association (ARRA).

Hurley*, G. C., &* Prowell*, B. D.* (2005). *Evaluation of Sasobit® for use in warm mix asphalt.* Auburn: National Center for Asphalt Technology.

Jones, D., Tsai, B. W., & Signore, J. (2010). *Warm-Mix asphalt study:laboratory test results for AkzoNobel Rediset^{TM} WMX.* UC Davis, UC Berkeley: University of California Pavement Research Center (UCPRC).

Kandhal, P. S., & Mallick, R. B. (1997). *Pavement recycling guidelines for state and local governments participant's reference book.* Auburn: National Center for Asphalt Technology, Auburn University.

Kanitpong, K., Nam, K., Martono, W. & Bahia, H. (2008). Evaluation of a warm-mix asphalt additive. *Construction Materials,* 161 (CM1), 1-8.

Kiggundu, B. & Newman, J. (1987). *Asphalt-aggregate interactions in hot recycling.* Albuquerque, New Mexico: New Mexico Engineering Research Institute.

Mallick, R., Bradley, J., & Bradbury, R. (2007). An evaluation of heated reclaimed asphalt pavement (RAP) material and wax modified asphalt for use in recycled hot mix asphalt (HMA). *Journal of the Transportation Research Board, No:1998, 112-122.*

Mallick, R., Kandhal, P., & Bradbury, R. (2008). Using warm mix asphalt technology to incorporate high percentage of reclaimed asphalt pavement (RAP) material in asphalt mixtures. *Journal of Transportation Research Board, No:2051, 71-79.*

Mallick, R., Bergendahl, J. & Pakula, M. (2009). *A laboratory study on CO_2 emission reductions through the use of warm mix asphalt.* Washington, DC: Transportation Research Board 88th Annual Meeting.

Middleton, B. & Forfylow, B. (2008). *An evaluation of warm mix asphalt produced with the double barrel green process.* Calgary, AB: 7th International Conference on Managing Pavement Assets (ICMPA).

Newcomb, D. (2006). *An introduction to warm-mix asphalt.* Lanham, MD: National Asphalt Pavement Association.

O'Sullivan, K., & Wall, P. (2009). *The effect of warm mix asphalt additives on recycled asphalt pavement.* Worcester, Massachusetts: Worcester Polytechnic Institute.

Pakula, M., & Mallick, R. (2007). *CO_2 Emission reductions through the use of warm mix asphalt.* Worcester, Massachusetts: Worcester Polytechnic Institute.

Park, T. (2007). Causes of bleeding in a hot-in-place asphalt pavement. *Construction and Building Materials,* 21 (12), 2023-2030

Romier, A., Audeon, M., David, J., Martineau, Y. & Olard, F. (2007). Low-energy asphalt with performance of hot-mix asphalt. *Journal of the Transportation Research Board,* 1962, 101-112.

Rubio, M. C., Martínez, G., Baena, L. & Moreno, F. (2012). Warm mix asphalt: an overview. *Journal of Cleaner Production,* 24, 76-84.

Santucci, L. (2007). Recycling asphalt pavements: A strategy revisited. *Tech Topics*, 8, 1-12.

Sargand, S., Figueroa, J. L., Edwards, W., & Al-Rawashdeh, A. S. (2009). *Performance assessment of warm mix asphalt (WMA) pavements.* Athens, OH: Ohio Research Institute for Transportation and the Environment (ORITE).

Sengoz, B. (1997). *Hot and cold recycling of bituminous mixtures.* Izmir, Graduate School of Natural and Applies Sciences of Dokuz Eylul University.

Sengoz, B., & Isikyakar, G. (2008). Analysis of styrene-butadiene-styrene polymer modified bitumen using fluorescent microscopy and conventional test methods. *Journal of Hazardous Materials,* 150 (2), 424-432.

T.C. Bayındırlık ve İskan Bakanlığı Karayolları Genel Müdürlüğü (2006). *Karayolu teknik şartnamesi*. Ankara: Karayolları Genel Müdürlüğü.

Tao, M., & Mallick, R. (2009). *An evaluation of the effects of warm mix asphalt additives on workability and mechanical properties of reclaimed asphalt pavement (RAP) material.* Washington, DC: 88th Annual Meeting of Transportation Research Board, National Research Council.

Wasiuddin, N. M., Selvamohan, S., Zaman, M. M. & Guegan, M. L. (2007). Comparative laboratory study of Sasobit and Aspha-Min additives in warm-mix asphalt. *Journal of the Transportation Research Board,* 1998, 82-88.

Wu, S., Cong, P., Yu, J., Luo, X., & Mo, L. (2006). Experimental investigation of related properties of asphalt binders containing various flame retardants. *Fuel*, 85 (9), 1298-1304.

Xiao, F., Punith, V. S., & Amirkhanian, S. N. (2012). Effects of non-foaming WMA additives on asphalt binders at high performance temperatures. *Fuel*, 94, 144-155.

Yu, J., Cong, P., & Wu, S. (2009). Laboratory investigation of the properties of asphalt modified with epoxy resin. *Journal of Applied Polymer Science,* 113 (6), 3557–3563.

Zaumanis, M. & Haritonovs, V. (2010). Research on properties of warm mix asphalt. *Scientific Journal of Riga Technical University Construction Science,* 11, 77-84.

Zaumanis, M. (2010). *Warm mix asphalt investigation.* Kongens.Lyngby: Technical University of Denmark.

Zhang, J. (2010). *Effets of warm mix asphalt additives on asphalt mixture characteristics and pavement performance.* Lincoln, Nebraska: University of Nebraska-Lincoln.