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THE EFFECT OF THE USE OF POLYFIBERS ON ASPHALT MIXTURE PROPERTIES

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IN
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The Effect of The Use of Polyfibers on Asphalt Mixture Properties

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Supervisor
Assist. Prof. Dr. Okan ŞİRİN

by

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ABSTRACT

THE EFFECT OF THE USE OF POLYFIBERS ON ASPHALT MIXTURE PROPERTIES

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In this thesis, the effect of the use of polyfibers on asphalt mixture properties was studied. Polyfiber (polypropylene fiber-PPF) with the length of 19 mm was utilized in the experimental studies with the ratio of PPF in asphalt mixtures specified as 0.3 %, 0.6 % and 1 % by the total weight of the mixture. Marshall mix design method was used to determine the optimum asphalt contents for conventional mixture and modified mixtures. Marshall specimens were prepared with a similar aggregate gradation of binder layer Type 1 as described in the manual of the General Directorate of Highways of Turkey. 50/70 penetration bitumen was used in all the experiments at 143 ˚C mixing temperature. Bulk specific gravity, voids analysis, stability, and flow tests were conducted on these specimens. According to the test results obtained from the laboratory studies, some improvements (such as stability and flow) on properties of modified asphalt mixtures were observed due to the inclusion of polyfiber.

Keywords: Polyfiber, Marshall mix design method, Stability, Flow.

ÖZET

POLİFİBER KULLANIMININ ASFALT KARIŞIMI ÖZELLİKLERİ ÜZERİNE ETKİSİ

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Bu tezde, polifiber kullanımının asphalt karışımı özellikleri üzerindeki etkisi çalışılmıştır. Deneysel çalışmada, 19 mm uzunluğundaki polifiber (polipropilen lifler-PPF), toplam karışım ağırlığının % 0.3'ü, % 0.6'sı ve % 1'i olarak belirlenen oranlarda asfalt karışımı üzerinde uygulanmıştır. Katkılı ve katkısız karışımlardaki en uygun asfalt oranının bulunması için Marshall karışım dizaynı metodu kullanılmıştır. Marshall numuneleri, Yollar Fenni Şartnamesi'nde belirtildiği gibi, binder tabakası Tip 1'in agrega gradasyonu temel alınarak hazırlanmıştır. Bütün deneylerde 50/70 penetrasyonlu bitüm, 143 ˚C karışım sıcaklığında kullanılmıştır. Hacim özgül ağırlığı ve boşluk analizleri ile stabilite ve akma testleri bu numuneler üzerinde uygulanmıştır. Laboratuar çalışmalarından elde edilen test sonuçlarına göre, polifiber ilavesiyle katkılı asfalt karışımlarının özellikleri üzerinde bazı iyileşmeler (stabilite ve akma gibi) gözlenmiştir.

Anahtar Kelimeler: Polifiber, Marshall karışım dizaynı metodu, Stabilite, Akma.

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LIST OF SYMBOLS

Abbreviations:

AC	Asphalt content
AP	Amorphous polialfaolefin
AR	Asphalt rubber
CB	Carbon black
CRM	Crumb rubber modifier
EVA	Ethylene vinyl acetate
FTIR	Fourier transform infrared
GTR	Ground tire rubber
HDPE	High density polyethylene
HMA	Hot mix asphalt
HPP	Homopolymer polypropylene
ICP	Impact copolymer
KC	Kaolinite clay
LAST	Laboratory asphalt stability test
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
MDPE	Medium density polyethylene
MFR	Melt flow rate
MQ	Marshall quotient
MWD	Molecular weight distribution
PAV	Pressure aging vessel
PE	Polyolefin
PMA	Polymer modified asphalt
PP	Polypropylene
PPF	Polyfiber (Polypropylene fiber)
RCP	Random copolymer

SBR	Styrene-butadiene rubber
SBS	Styrene–butadiene–styrene
SE	Cellulosed fiber
SEBS	Styrene-etylene-butylene-styrene
SIS	Styrene-isoprene-styrene
SMA	Stone matrix asphalt
SSD	Saturated surface dry
VFA	Voids filled with asphalt
VMA	Voids in the mineral aggregate
ZDBC	Zinc dibutyl dithiocarbamate
ZDDP	Zinc dialkyl dithiophosphate

Symbols:

G_b	Asphalt binder specific gravity
G_{mb}	Bulk specific gravity of the compacted mixture
G_{mm}	Maximum theoretical specific gravity of the mixture
G_{sa}	Apparent specific gravity of the aggregate
G_{sb}	Bulk specific gravity of the aggregate
G_{se}	Effective specific gravity of the aggregate
P_b	Asphalt content by weight of mix
V_a	Air voids
W_D	Dry weight
W_{SSD}	Saturated surface dry weight
W_{sub}	Weight submerged in water

CHAPTER 1

INTRODUCTION

1.1 General

Asphalt materials have been known and used in building and road construction since ancient times. They find wide usage in the construction industry. The use of asphalt as a cementing agent in pavements is the most common of its applications.

The asphalt pavements have been used firstly as a road construction in the last period of 1860s. After this application, the usage of asphalt pavements improved with new methods such as Marshall mix design method and Hveem mix design method. Improvements of these methods made the asphalt pavements more applicable and usable. The improvement of asphalt pavements industry have continued with additives and modifiers to improve the properties of asphalt pavements.

The specialized asphalt modifiers of the last two decades have improved asphalt performance, and made possible designs such as open-graded friction courses and thin-lift overlays. And today modifiers make it possible to improve lower-performing performance-graded asphalt binders. Modified asphalt binders are typically used in high stress applications to improve cracking and rutting resistance performance of asphalt concrete. They have been used in intersections with stop-and-go traffic, high-volume truck routes, and high-volume interstates. Modifiers have also been used in extreme climate conditions to reduce aging in desert climates and to help produce binders for extreme low-temperature applications.[1]

In this thesis, the effects of polyfibers on asphalt mixtures were analyzed. Polyfibers, which is a kind of fiber asphalt modifier, includes 100% pure polypropylene fibers, was used as an asphalt modifier. Polyfiber (polypropylene fiber-PPF) length was chosen as 19 mm and the ranging of PPF in asphalt mixtures specified as 0.3 %, 0.6 % and 1 % by the total weight of the mixture. Marshall mix design method was used to determine the optimum asphalt contents. Marshall specimens were prepared in the laboratory using at 143 ˚C mixing and compaction temperature and, stability and flow tests were conducted on these specimens.

1.2 Objectives of The Study

The main objectives of this study are briefly explained below.

- The research into the effect of the use of polypropylene fibers on asphalt mixture properties

- The research into the feasibility of polypropylene fibers as asphalt modifier

- The evaluation and determination of the optimum ratio of polypropylene fibers on asphalt mixture properties

1.3 Outline of the Thesis

Chapter 1-Introduction: Aim and objectives of the thesis are introduced.

Chapter 2-Literature survey: A literature survey for asphalt modifiers according to their types is summarized and the effects of these modifiers are briefly explained.

Chapter 3-Polypropylene and polypropylene fibers: Polypropylene with types and properties and polypropylene fibers with manufacturing process are briefly described.

Chapter 4-Marshall method of asphalt mix design: The procedure of Marshall mix design method and the determination of optimum asphalt content are indicated.

Chapter 5-Laboratory test results and discussion: Materials, mixtures, test results of these mixtures and discussion of these results are presented.

Chapter 6-Conclusions and recommendations: Conclusion of the thesis and recommendation for future studies are given.

CHAPTER 2

LITERATURE SURVEY

2.1 General Classification of Modifiers Used In Hot Mix Asphalt Mixtures

Modifier means that additive material on asphalt concrete, which is improved the properties and performance of asphalt concrete. There are several types of modifiers for several properties improvement on asphalt concrete such as rideability, rutting, cracking, patching, skid resistance and stability. The use of modifiers to improve the performance of asphalt/aggregate mixtures has been employed in the highway industry from almost the first use of hot mix asphalt. Modifiers take many different forms.

Asphalt modifiers can be classified as follows:

1. Fillers
2. Extenders
3. Polymers
    - Rubbers
    - Plastics
4. Fibers
5. Oxidants and Antioxidants
6. Hydrocarbons
7. Antistripping Agents
8. Waste Materials [1,2]

The effect of the use of modifiers on asphalt mixtures are briefly discussed below.

2.1.1 Fillers

Mineral fillers include mineral dust from the crushing and screening of aggregates (including baghouse fines), lime, portland cement and fly ash. Other materials such as carbon black and sulfur have been used primarily to modify asphalt binder properties but they do have a role of filler. [1]

Conductivity of asphalt concrete containing conductive fillers was investigated by Wu et al. [3]. Carbon black, graphite and carbon fibre were employed to design and prepare electrically conductive asphalt mixtures containing single filler or mixed fillers of conductive powder plus carbon fibre. The effects of filler type, filler content and mixed fillers on the resistivity of asphalt concrete were investigated. Experimental results showed that the insulating-conductive percolation transition of the resistivity under the function of filler content appears in the single-filler composites and the percolation threshold is approximately 12%, 10%, and 5% by volume percentage of the binder phase for carbon black, graphite and carbon fibre respectively. The combination function of mixed fillers had appreciable advantages over single powder filler, but no obvious advantages over simple fiber in the conductivity improvement at the same total filler content.

Asi and Assa'ad [4] studied to find the effect of fly ash on asphalt mixes. The effect of fly ash, according to the specimens without fly ash and with 10 %, 50 % and 100 % replacement of the mineral filler by fly ash were discussed. Test results were showed that, in general, the addition of fly ash improved both strength, and water sensitivity of the asphalt concrete mixes. Replacing 10% of the mineral filler by fly ash proved to be the most effective percentage in improving the mechanical properties of all the prepared samples.

2.1.2 Extenders

The concept of extending asphalt binder became prominent after the 1973 oil embargo. It appeared at that time that the price of asphalt cement would continue to increase and that asphalt cement might become scarce. The Federal Highway

Administration (FHWA) promoted the investigation of extending asphalt binders by partially substituting with sulfur and lignin. [1]

Sulfur is an abundant, non-metallic chemical element. It is a yellow, crystalline solid at room temperature. Sulfur has been used to modify hot mix asphalt (HMA) base, binder and surface courses. Lignin has not been used as an asphalt extender in commercial HMA production. However, it has been evaluated in the laboratory as a potential substitute or extender of asphalt cement. [1,5]

The high-temperature storage stability of styrene–butadiene–styrene triblock copolymer (SBS) modified asphalt with the addition of elemental sulfur was studied by Wen et al. [6]. The dynamic mechanical properties of SBS-modified asphalts before and after adding sulfur were characterized by using dynamic shear rheometry. Also, storage stability test and viscosity test were done. According to the all of the experimental results, it was found that the addition of sulfur to SBS modified asphalt resulted in the formation of a chemically vulcanized SBS network structure in the modified binders, and the high temperature performance of the binders was improved and their temperature susceptibility was reduced to a great extent. The rheological properties of SBS modified asphalts depended strongly on the sulfur level. Increasing sulfur levels led to increasing crosslinking density in the modified binders, and consequently the rheological properties of SBS-modified asphalt was improved. The morphology of SBS-modified asphalts, which was characterized by optical microscopy, showed that the compatibility and storage stability of SBS modified asphalt were improved by the addition of sulfur.

2.1.3 Polymers

Plastic and rubber materials are both referred to as polymers. Simply stated, a “polymer” is a very large molecule made by chemically reacting many (poly) smaller molecules (monomers) to one another in long chains or clusters. The sequence and chemical structure of the monomers determine the physical properties of the resulting polymer.[1]

2.1.3.1 Rubbers

Numerous rubber materials (or elastomers) are available for modifying asphalt cement binder. Rubber materials are very complex in nature and may not impart their properties as a neat polymer when blended with asphalt cement. Moreover, their properties may be diluted or even changed when the modifier is used in hot mix asphalt (HMA). Each modifier may react differently with different asphalt cements. Whether a particular combination will yield improvements in the desired property is very difficult to predict. It becomes necessary to test the modified asphalt binder. [1]

Al-Dubabe et al. [7] studied about polymer modification of Arab asphalt. According to this study, the most promising polymer types and concentrations were found such as styrene-butadiene-styrene (SBS) at 3 % for asphalt from Ras Tamura Refinery and Riyadh Refinery; styrene-butadiene-styrene at 3 % for asphalt from BAPCO Refinery, by total weight of the blend.

Engineering properties of polymer modified asphalt (PMA) mixtures were studied by Khattak and Baladi [8]. The elastic, fatigue, tensile and permanent deformation properties of styrene-butadiene-styrene (SBS) and styrene-etylene-butylene-styrene (SEBS) polymer modified asphalt were investigated at 60 ˚C, 25 ˚C and -5 ˚C. It was found that, the SBS and SEBS polymer systems considerably increase the indirect tensile strength and fracture toughness of asphalt mixtures at 25 ˚C and 60 ˚C. Fatigue life of PMA mixtures was considerably higher than the straight and processed asphalt mixtures. The SBS polymer system appeared to increase the asphalt concrete mixture’s resistance to low temperature cracking.

Raad et al. [9] studied about crumb rubber modifiers. In this study, the influence of field aging on the fatigue performance of asphalt concrete and asphalt-rubber concrete were investigated and the results were discussed. Results indicated that field aging reduced the beam fatigue resistance of conventional asphalt concrete dense-graded mix and to a lesser extent, asphalt-rubber hot mix gap-graded. Aging effects on beam fatigue life were more severe at –2 ˚C than at 22 ˚C. The influence of aging on predicted pavement fatigue life depended not only on the stiffness of the mix and its fatigue properties but also on the stiffness or layer moduli of the pavement components. Longer fatigue life predictions were obtained for asphalt-rubber hot mix gap-graded than conventional asphalt concrete dense-graded mix, for both aged and unaged conditions. Aging of the conventional asphalt concrete dense-graded mix could be detrimental to pavement fatigue. In comparison, aging of asphalt-rubber hot mix gap-graded showed increased fatigue life performance.

Fatigue and permanent deformation models for polymer-modified asphalt mixtures were studied by Khattak and Baladi [10]. In this study, SBS, SEBS Kraton, SBR Latex, Elvaloy AM and crumb rubbers were used as modifiers. Tensile and compressive strain, resilient modulus, fatigue life and permanent deformation of modified asphalts were analyzed and discussed. It was found that the rheological and engineering properties of polymer modified asphalt (PMA) mixtures largely depended on the polymer type and content. The improvements in the fatigue lives and resistance to permanent deformation were mainly due to the improvements in the rheological properties of the binders. The addition of polymer increased the laboratory fatigue life of asphalt mixtures and decreased their rut potential. Fatigue life and permanent deformation models were developed. These models showed that the laboratory fatigue life and permanent deformation were strongly related to the rheological properties of binders and the engineering properties of the PMA mixtures.

Crumb rubber modifier was studied by Kim, Loh, Zhai and Bahia [11]. According to this study, modifier ratios were 8 % and 12 %, and the effect of these ratios for viscosity, failure stress and failure strain were analyzed and discussed. The results indicate that the concentration and size of crumb rubber influence viscosity significantly. The rubber size had a significant effect on the volume of residue collected. It was found that both fatigue and strain dependencies were highly sensitive to asphalt binder type, rubber size and rubber content. The failure properties of crumb rubber modifier measured that the failure stress and strain reduced with increasing rubber size and concentration.

Chipps et al. [12] studied about field tests and economic analysis of high-cure crumb rubber modified asphalt. According to this study, modifier ratios were 8 % - 17.6 %, and the effect of these ratios for viscosity, durability, life-cycle cost and superpave performance grades were analyzed and discussed. These results showed that the life-cycle cost of high-cure crumb-rubber modified asphalt compared very favorably to conventional asphalt binders. A high-cure crumb-rubber binder at 16 % rubber in a dense graded mix would need to last just 16 % longer than the comparable conventional mix in order to have an equal capitalized cost, the breakeven point. At the same time, oxidative hardening rates at road aging conditions were reduced some 50 % or more by the high-cure rubber. Consequently, achieving the required extended life was believed to be well within reach for dense-graded mixes, even for a high-rubber content binder.

The characterization of the low-temperature behavior of modified asphalt concretes were analyzed by Fortier and Vinson [13]. Rubber powder was used as rubber modifier. The results about asphalt cement influence, aging influence, modifier influence and low-temperature behavior were discussed. The results of binder tests showed an improvement in the low temperature viscoelastic properties of modified asphalt cement may not provide a clear picture of the low-temperature performance of a modified asphalt concrete mixture. Failure of modified asphalt concrete mixtures without any apparent fracture was commonly shown.

Raad and Saboundjian [14] studied about rubber modified pavements. Crumb rubber modifier, about 3-4 % in mix, was used for modification. Fatigue behavior of the modified asphalt was analyzed and discussed. According to the tests results, the dynamic flexure stiffness of the conventional mix was higher than the rubberized mixes for the range of temperatures considered. Both rubberized mixes, PlusRide and asphalt-rubber, exhibited essentially equal stiffness variation with temperature. When compared to the conventional mix, the rubberized mixes seemed to have the ability to dissipate more energy before 50% reduction in flexural stiffness. At 20 ˚C, asphalt-rubber and conventional mixes exhibited essentially similar fatigue resistance, whereas PlusRide had the least fatigue life. However, at 0 ˚C the fatigue resistance of PlusRide and asphalt-rubber exceeded that of the conventional mix. The fatigue resistance of asphalt-rubber in this case was the highest.

Raad et al. [15] studied about low-temperature cracking performance of pavements modified with styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR) and crumb rubber modifier (CRM) in relation to thermal crack initiation and progression over time. Thermal stress restrained specimen test and, indirect tensile creep and strength test were done and the test results were discussed. It was found that the use of polymer modifiers improved the low-temperature cracking performance. The degree of improvement depends on type of modifier, climate and pavement age.

Anderson et al. [16] studied about modified asphalt binders. Polyethylene, ethylene vinyl acetate, SB-reacted, gilsonite and SBS were used as modifiers with the ratios of 5 %, 4 %, 4.3 %, 10 %, 4 %, respectively. Dynamic shear rheometer test, bending beam rheometer test, direct tension test, indirect tensile creep and strength test and shear frequency sweep test were done. According to the tests results, using mixtures containing plastomer-modified asphalt binders showed moderate signs of brittle distress, similar to that seen in the Gilsonite modified section. Performance tests showed that the highest modulus values were seen for the Gilsonite modified binder and mixture, followed by the plastomer modified binders and mixtures.

Johnson and Freeman [17] studied about the effect of ethylene vinyl acetate (EVA) and styrene-butadiene-styrene (SBS) on asphalt concrete. Rutting performances of the modified asphalt binders with different modifier ratios were analyzed and the results were discussed. The ruts in the unmodified pavement exceeded the value assigned as failure (13 mm). The polymer-modified pavements demonstrated adequate resistance to rutting.

Stastna, Liu and Zanzotto [18] studied about rheological characteristics of selected polymer modified asphalts. The changes in molecular mechanisms after the addition of polymer into asphalt were investigated. Styrene-butadiene-styrene (SBS), styrene-isoprene-styrene (SIS) and ethylene vinyl acetate (EVA) were used as modifiers. According to the tests results, polymer modified asphalts, the blend of 5% SBS (radial) with the base asphalt 200/300 pen exhibited behavior somewhat similar to that of high molecular weight polymers. The 5% blends of the base asphalt with linear SBS and EVA exhibit much weaker similarity with the behavior of polymers. The studied blends of SIS and the base asphalt do not show any presence of the rubbery plateau. However, their thermal properties at high temperatures are different from the ones of the base asphalt for all of the studied blends.

Bahia, Rangel and Yang [19] studied about modified binders in the pressure aging vessel (PAV) procedure. In this study, modifier types were SBD, SBR, SBSR, SBRH, PE, NEAT, NEAT PE and HLIME. The rheological properties were evaluated using the dynamic shear rheometer. The results showed that within the same generic type of modifier there are important differences in response to PAV aging. The standard deviation of the change in critical temperatures ranged between 2 and 5 °C. The analysis of possible separation did not show any significant difference.

Bahia and Zhai [20] studied about stability of modified binders using the Laboratory Asphalt Stability Test (LAST) procedure. In this study, SBS, SB Diblock, SBR, PE, NEAT and EMA were used as asphalt binder modifiers. The potential for separation and the potential for degradation of modifiers in asphalt during high temperature storage were measured. The results collected in this study indicates that storage stability of the modified binders was influenced by modifier type, source of base asphalt, testing temperature, agitation speed and also by rheological parameter measured. A number of modified binders have been found to be stable under static and high agitation conditions. Other binders have been found to require minimal agitation to remain stable for extended time periods. SBS and SBR modified binders have been found to be stable under static and high agitation conditions. Other binders have been found to require minimal agitation to remain stable for extended time periods. When SBS, SB Diblock, and SBR are mixed with asphalt, the modified binders showed much higher separation rates and separation ratios than the same modifiers mixed with asphalt.

Critical properties of modified asphalt binders were studied by Bahia, Zhai and Turner [21]. SBS, SBR, PE, EMA, EVA, ethylene terpoly, gilsonite, oxidized and vacuum distilled were selected as asphalt modifiers for the project. Dynemic shear rheometer, bending beam rheometer, flash point and strain dependency tests were done. According to the tests results, polymeric modifiers showed higher mass loss than processed and other modification. All of the modified binders gave similarly high shear and bending rates. Modified binders, although showed higher viscosity values, were still workable because of their shear tinning behavior.

Wong and Wong [22] investigated the effects of different sizes of crumb rubber modifier (CRM) on high temperature susceptibility of wearing coarse mixtures. Some tests about rutting resistance on CRM and conventional mixtures. The results showed that all the CRMs have overall contributed to better performance of both binders and mixtures at high temperatures. In addition, among these three CRM sizes, mixtures modified with 0.15 mm CRM exhibited the best effect on the dense-graded mixture whereas mixtures modified with 0.60 mm CRM exhibited the best effect on the open-graded mixture of porous asphalt.

The effect of long-term aging on rheological properties of polymer modified asphalt binders was studied by Ruan et al. [23]. Modifiers included diblock poly (styrene-butadiene) rubber, triblock poly (styrene-butadiene-styrene), and tire rubber. Polymer modification resulted in increased asphalt complex modulus at high temperatures, decreased asphalt complex modulus at low temperatures, broadened relaxation spectra, and improved ductility. Oxidative aging decreased asphalt temperature susceptibility, damaged the polymer network in binders, further broadened the relaxation spectrum, and diminished polymer effectiveness in improving asphalt ductility.

The viscosity of polymer modified asphalts was studied by Stastna et al. [24]. Styrene-butadiene-styrene (SBS) and ethylene vinyl acetate (EVA) were used as asphalt modifiers. The tests about viscosity to determine the viscosity functions on modified asphalts were done. According to the tests results, the strongest effect, from the studied polymers, on the low-shear-rate region of the steady-shear viscosity had the linear SBS.

The change in the properties of the styrene-butadiene block copolymers (SBS) modified asphalt under different ageing conditions has been studied by Cortizo et al. [25]. The rolling thin film oven test, pressure ageing vessel procedure and thermal degradation were done. The tests results showed that the physical and rheological properties of asphalt are improved by means of SBS copolymer modification as evidenced by both conventional and rotational viscosimetric properties.

The performance of polymer-modified asphalt mixtures and specially designed reinforcement techniques against reflection cracking for the typical asphalt pavement overlays were evaluated by Kim et al. [26]. In this study, the asphalt was modified using carbon black (CB), a low-density polyethylene (LDPE) and a styrene-butadiene-styrene (SBS). Cracking resistance tests were done and the results were discussed. All of the modifiying and reinforcing materials used in this study showed a significant effect on improving resistance against crack propagation.

Properties of styrene-butadiene-styrene (SBS) copolymer/kaolinite clay (KC) compound and asphalt modified with the compound were studied by Ouyang et al. [27]. Modified asphalts with different ratios of SBS/KC were analyzed according to stability test, rheological test, swelling test and density test. The results of these tests were discussed. The SBS/KC ratio in the compounds had a great effect on the high temperature storage stability. The modified asphalts were very stable at high temperature when the SBS/KC ratio was around 3. The maximum KC content in the modified asphalts was 2%, and the KC content had slight influence on the mechanical properties of the modified asphalts. The KC could improve the rheological properties of the modified asphalt to some extent.

2.1.3.2 Plastics

Numerous plastic materials (plastomers) are available for modifying asphalt cement binder. The handling, storage and use of plastic polymers is very similar to that for rubber polymers. [1]

Hınıslıoğlu and Ağar [28] studied about high density polyethylene (HDPE) as bitumen modifier in asphalt concrete mix. In this study, HMA were prepared by mixing the HDPE in 4 %, 6 % and 8 %. According to these ratios, stability, flow and Marshall Quotient at 145 ˚C, 155 ˚C and 165 ˚C with 5-15 and 30 minutes of mixing time were analyzed. HDPE-modified asphalt concrete results in a considerable increase in the Marshall Stability (strength) value and a Marshall Quotient value (resistance to deformation). Four percent HDPE, 165 ˚C of mixing temperature and 30 minute of mixing time were determined as optimum conditions for Marshall

Stability, flow and Marshall Quotient (MQ). MQ increased 50% compared to control mix.

Tayfur et al. [29] studied about amorphous polialfaolefin (AP), polyolefin (PE), and stiren-butadien-stiren copolymer (SBS) with mixing ratios of 6 %, 0.6 % and 5 %, respectively. In this study, the effects of modifiers about indirect tensile strength, stability, stiffness modulus, and resistance to the permanent deformation rates were analyzed. The tests results showed that SBS mixtures were found as the most resistance mixtures in view of the rutting. Additives performed different performance levels but showed more resistance to permanent deformation according to the conventional mixtures.

Al-Abdul Wahhab et al. [30] studied about linear low-density polyethylene (LLDPE), medium density polyethylene (MDPE), high density polyethylene (with two type, HDPE-1 and HDPE-2), asphalt modifiers. This study showed LLDPE, MDPE, HDPE-1 and HDPE-2 were satisfying the performance requirements with percentage of 3 %, 2 %, 2 % and 2 %, respectively. Polymers were satisfying the storage stability requirements based on the measured shear loss modulus after 72 hours while LLDPE showed great disintegration. MDPE, HDPE-1 and HDPE-2 showed significant increase in resilient modulus at both high and low temperatures. The results showed significant improvement in both fatigue behavior and rutting resistance of all the polymer types mixes compared with the control mix.

Polymer modification of Arab asphalt was studied by Al-Dubabe et al. [7]. According to this study, the most promising polymer types and concentrations were found such as linear low-density polyethylene at 3 %, polypropylene at 1.5 % for asphalt from Riyadh Refinery; polypropylene at 1.5 % for asphalt from BAPCO Refinery; linear low-density polyethylene at 3 %, polypropylene at 1.5% for asphalt from Al-Ahmadi Refinery, by total weight of the blend.

The characterization of the low-temperature behavior of modified asphalt concretes were analyzed by Fortier and Vinson [13]. Latex polymer, ethylene acrylate copolymer and elastomer were used as modifiers. The results about asphalt cement influence, aging influence, modifier influence and low-temperature behavior were discussed. The tests results showed that the modifiers improved the low-temperature performance of unaged asphalt concrete mixtures.

Messersmith, Jones and Wells [31] studied about polymer modified asphalt in Alabama. Plastomer wax, reactive elastic plastomer and elastomer polymer were used as modifier. Rutting, separation and ductility tests were done and the test results were analyzed and discussed. Force ductility testing indicated that all polymer-modified asphalt tested was more elastic than an unmodified mixture, and the elastomer-modified asphalt was the most elastic. Separation testing indicated that the elastomer-modified asphalt was more prone to separation during storage than the other modified asphalts. Laboratory rut testing indicated that the reactive plastomer modified asphalt provided more resistance to rutting than the other modified asphalts.

2.1.4 Fibers

The use of natural fibers such as asbestos has been well known for many years. However, manufactured and/or synthetic fibers have been promoted to replace asbestos. [1]

Fibers are most commonly used as reinforcement or stiffener in the manufacture of roofing and industrial water-proofing membrane systems. They have the potential of reinforcing and improving the tensile strength and cohesion of HMA mixtures. [1]

Tayfur et al. [29] studied about cellulosed fiber (SE) and cellulosed fiber mixed with bitumen (BE) with mixing ratios of 0.4 % and 0.6 %, respectively. In this study, the effects of modifiers about indirect tensile strength, stability, stiffness modulus and resistance to the permanent deformation rates were analyzed and discussed. The indirect tensile strengths of the modified mixtures were higher than the control mix. This indicates that the mixtures containing additives have higher values of tensile strength at failure indirect tensile strength under static loading. Modified mixtures reveal more resistance to the permanent deformation. BE mixtures have lower flow value.

Concrete pavement crack and seat performance and fiber modified overlay were studied by Huang and White [32]. Performance evaluation of cracking and seating techniques and fiber modified asphalt overlay were done. Polypropylene fibers were used for modification with 2.6 kg/Mg and 3.0 kg/Mg. The tests results showed that cracked and seated sections with 2.6 kg/Mg fiber had smaller maximum deflection, larger percent decrease of deflection and less reflective cracks than sections with 3.0 kg/Mg fiber. It appeared that 2.6 kg/Mg fiber content was favorable over 3.0 kg/Mg on cracked and seated sections.

The characterization of the low-temperature behavior of modified asphalt concretes were analyzed by Fortier and Vinson [13]. A blend of polypropylene and Kevlar fibers, 38 mm in length, were used as modifiers. The results about asphalt cement influence, aging influence, modifier influence and low-temperature behavior were discussed. The tests results showed that the modifiers were decreased the fracture strength and produced a warmer fracture temperature.

Effects of fibers on hot-mix asphalt performance were studied by White, Huang and Montgomery [33]. Polypropylene fibers, 10 mm in length, were used as modifiers and its content changed between 1.7 kg/ton and 3.0 kg/ton. Fatigue tests, rutting performance tests and field performance tests were done, and the tests results were analyzed. Results of fatigue tests indicated that fiber increased the fatigue life of overlay mixture. Wheel track tests of samples at approximately the same air voids indicated that asphalt-fiber mixture performed better than the control mixture. The sections with fiber in both base and binder had less cracks than those with fiber only in the base. Asphalt-fiber mixtures appeared to perform well in under severe conditions.

Anderson et al. [16] also studied about modified asphalt binders. One of the modifier, were used in this study, was polyester fibers with the ratio of 6.3 %. Dynamic shear rheometer test, bending beam rheometer test, direct tension test, indirect tensile creep and strength test and shear frequency sweep test were conducted. The tests results showed that polyester fibers improved the strength capability and rutting performance of asphalt binders.

Durability of geogrid-reinforced asphalt concrete was investigated by Komatsu et al. [34]. Geogrids constructed from high-modulus and high strength polyoxymethylene fibers were prepared and used to reinforce asphalt concrete. Wheel tracking test and crack resistance test were done. The geogrid-reinforced asphalt concrete showed remarkable increases in the durability in comparison with the control mix.

2.1.5 Oxidants and Antioxidants

Sometimes it is desirable to increase the stiffness of HMA mixtures for improved strength. This may be appropriate for low stability mixes such as sand-asphalt. One approach is to use harder asphalt cement at the beginning. However, this approach may reduce the long term performance. The other approach is to use oxidation catalysts which stiffen the asphalt cement binder after the HMA is placed on the pavement. [1]

Asphalt cements undergo oxidative hardening during HMA production and construction, and subsequently during service. Antioxidant additives consisting of lead or other compounds are available to minimize oxidative hardening of asphalt cements, thereby increasing the durability of HMA mixtures. [1]

The aging resistance of styrene-butadiene-styrene (SBS) tri-block copolymer modified asphalt by addition of antioxidants was studied by Ouyang et al. [35]. Zinc dialkyl dithiophosphate (ZDDP) and Zinc dibutyl dithiocarbamate (ZDBC) were used as antioxidants. Fourier Transform Infrared (FTIR) analysis and viscosity test were conducted on modified asphalt specimens. The tests results showed that antioxidants, ZDDP or ZDBC modified PMA (modified asphalt) were resistant to the formation of carbonyl to some extent, indicating the improvement of aging resistance of the PMA by the addition of the antioxidants. ZDDP and ZDBC as antioxidants could retard the oxidation of the PMA through the inhibition of peroxides and radical scavenging. Furthermore, ZDDP in a liquid state at room temperature acted as plasticiser, giving rise to a good aging resistance of PMA.

2.1.6 Hydrocarbons

It may not always be possible to obtain an asphalt cement of desired properties (such as viscosity, penetration and ductility) for a particular project. However, modification of the available asphalt cement is possible by adding either softer or harder hydrocarbon materials such as recycling and rejuvenating oils. [1]

Ahmedzade et al. [36] studied about Tall oil pitch (TOP), styrene-butadiene-styrene (SBS) and TOP+SBS in variant quantities. In this study, stability, flow, compression strength, fatigue life and deformation of modified asphalts were analyzed with different TOP and SBS combination ratios. The results of investigation indicated that asphalt mixture modified by 8 % TOP + 6 % SBS gave the best results in the tests that were carried out in this study, so that, this modification increases physical and mechanical properties of asphalt binder.

2.1.7 Antistripping Agents

Separation and removal of asphalt binder from aggregate surface due primarily to the action of moisture and/or moisture vapor is generally termed “stripping.” Antistripping agents are used to minimize or eliminate stripping of asphalt cement from aggregate in HMA mixtures. Both liquid antistripping additives and lime additives are used to resist stripping. [1]

Antistripping agents and acid were studied by Bishara et al. [37]. In this study, the effects of acid and antistripping agents on asphalt concrete were analyzed and discussed with different ratios and temperatures. It was found that modification with acid (phosphoric acid) hardened asphalt and extended its upper limit of application. The gain in high temperature increases with the amount of acid used.

Critical properties of modified asphalt binders were studied by Bahia, Zhai and Turner [21]. Hydrated lime, polyamines and amidoamines were selected as asphalt modifiers for the project. Dynemic shear rheometer, bending beam rheometer, flash point and strain dependency tests were done and, the tests results were analyzed and discussed. All of the modified binders gave similarly high shear and bending rates.

Modified binders, although showed higher viscosity values, were still workable because of their shear tinning behavior.

2.1.8 Waste Materials

Numerous waste materials result from manufacturing operations, service industries, sewage treatment plants, households and mining [1,38]. Legislation has been enacted by several states in recent years to either mandate the use of some waste materials or to examine the feasibility of such usage. The hot mix asphalt industry has been pressured in recent years to incorporate a wide variety of waste materials (such as roofing shingles, scrap rubber from tires and waste glass) into HMA pavements.

Solaimanian et al. [39] studied the performance characteristics of asphalt binders and mixtures modified by waste toner. Waste toner was used for modification with 5 %, 10 % and 16 % by mass of toner-binder blend. The effect of waste toner about viscosity, complex modulus, stiffness and creep rate were analyzed and discussed with different modifier ratios. The results indicated that as the amount of waste toner in the blend increases, the stiffness and the viscosity of the modified binder increase. The mixture analysis also indicated higher strength and stability for toner-modified asphalt concrete compared with unmodified mixtures.

Choubane et al. [40] studied about asphalt-rubber mixes. According to the project, ground tire rubber (GTR) was used as asphalt modifier. Some tests were done on asphalt-rubber surface mixes about rideability, rutting, cracking, patching and skid resistance. The results showed that the addition of rubber drastically improved the crack resistance of surface mixtures.

Al-Dubabe et al. [7] studied about polymer modification of Arab asphalt. According to this study, the most promising polymer types and concentrations were found such as crumb rubber tires at 10 % for asphalt from Ras Tamura Refinery and Riyadh Refinery; crumb rubber tires at 5% for asphalt from Al-Ahmadi Refinery, by total weight of the blend.

Thermo-rheological behavior and storage stability of ground tire rubber-modified bitumens were evaluated by Navarro et al. [41]. Crumb rubber tires were used as modifier. In this project, dynamic oscillatory tests, shear rate sweep tests and static storage tests were done. The results of these tests showed that the addition of ground tire rubber to bitumen increased both the linear viscoelastic moduli and viscosity, at high in-service temperatures, and reduced the storage and loss moduli, at low temperatures.

The effect of different types and levels of waste toners on asphalt binders were studied by Yıldırım et al. [42]. In this project, magnetic and non-magnetic waste toners were used as asphalt modifiers. Superpave binder performance tests, including dynamic shear rheometer (DSR), and rotational viscometer (RV) for high and intermediate temperatures, and bending beam rheometer (BBR) for low temperatures were used to evaluate binder properties for different levels of toner modification. Test results indicated that the stiffness of the blend increased at all temperatures as the percentage of the toner content present increased.

The feasibility using asphalt rubber (AR), produced by blending ground tire rubber (GTR) with asphalt, as a binder for stone matrix asphalt (SMA) was investigated by Chiu and Lu [43]. Two different sizes of GTR produced in Taiwan were used with different mixing ratios. The tests performed were moisture susceptibility and rutting resistance tests. The results of this study showed that it was not feasible to produce a suitable SMA mixture using an asphalt rubber made by blending with 30% coarse GTR with a maximum size of 0.85 mm. However, SMA mixtures meeting typical volumetric requirements for SMA could be produced using an asphalt rubber containing 20% of a fine GTR with a maximum size of 0.6 mm. Rutting resistance of AR–SMA mixtures was better than that of the conventional SMA mixtures.

The feasibility of utilizing waste tire and carpet fibers in stone matrix asphalt (SMA) was researched by Putman and Amirkhanian [44]. Optimum asphalt contents with different ratios of waste fibers were found and some tests were done about stability and tensile strength. Experimental results showed that no significant difference in permanent deformation or moisture susceptibility was found in mixtures containing waste fibers compared to cellulose or polyester. Also, the tire, carpet, and polyester fibers significantly improved the toughness of the mixtures compared to the cellulose fibers.

2.2 Conclusion on Literature Review

The results of the literature survey can be summarized in Table 2.1. In this table, general purpose or use of asphalt modifiers and generic examples of asphalt modifiers according to the modifier types are explained briefly. [1]

Table 2.1 Summary of Literature Survey [1]

Type	General Purpose or Use	Generic Examples
Filler	• Fill voids and therefore reduce optimum asphalt content • Meet aggregate gradation specifications • Increase stability • Improve the asphalt cement-aggregate bond	• Mineral filler: ○ crusher fines ○ lime ○ portland cement ○ fly ash • Carbon black
Extender	• Substituted for a portion of asphalt cement (typically between 20 – 35 % by weight of total asphalt binder) to decrease the amount of asphalt cement required	• Sulfur • Lignin
Rubber	• Increase HMA stiffness at high service temperatures • Increase HMA elasticity at medium service temperatures to resist fatigue cracking • Decrease HMA stiffness at low temperatures to resist thermal cracking	• Natural latex • Synthetic latex (e.g., Polychloroprene latex) • Block copolymer (e.g., Styrene-butadiene-styrene (SBS)) • Reclaimed rubber (e.g., crumb rubber)
Plastic		• Polyethylene/ polypropylene • Ethylene acrylate copolymer • Ethyl-vinyl-acetate (EVA) • Polyvinyl chloride (PVC) • Ethylene propylene or EPDM • Polyolefins
Fiber	• Improving tensile strength of HMA mixtures • Improving cohesion of HMA mixtures • Permit higher asphalt content without significant increase in draindown	• Natural: ○ Asbestos ○ Rock wool • Manufactured: ○ Polypropylene ○ Polyester ○ Fiberglass ○ Mineral ○ Cellulose

Table 2.1 Summary of Literature Survey (continued) [1]

Type	**General Purpose or Use**	**Generic Examples**
Oxidant	• Increase HMA stiffness after the HMA is placed	• Manganese salts
Antioxidant	• Increase the durability of HMA mixtures by retarding their oxidation	• Lead compounds • Carbon • Calcium salts
Hydrocarbon	• Restore aged asphalt cements to current specifications • Increase HMA stiffness in general	• Recycling and rejuvenating oils • Hard and natural asphalts
Antistripping Agents	• Minimize stripping of asphalt cement from aggregates	• Amines • Lime
Waste Materials	• Replace aggregate or asphalt volume with a cheaper waste product	• Roofing shingles • Recycled tires • Glass

CHAPTER 3

POLYPROPYLENE AND POLYPROPYLENE FIBERS

3.1 Polypropylene

Polypropylene (PP) is a thermoplastic material that is produced by polymerizing propylene molecules, which are the monomer units, into very long polymer molecule or chains. There are a number of different ways to link the monomers together, but PP as a commercially used material in its most widely used form is made with catalysts that produce crystallizable polymer chains. These give rise to a product that is a semicrystalline solid with good physical, mechanical, and thermal properties. Another form of PP, produced in much lower volumes as a byproduct of semicrystalline PP production and having very poor mechanical and thermal properties, is a soft, tacky material used in adhesives, sealants, and caulk products. The above two products are often referred to as "isotactic" (crystallizable) PP (i-PP) and "atactic" (noncrystallizable) PP (a-PP), respectively. [45]

As is typical with most thermoplastic materials, the main properties of PP in the melt state are derived from the average length of the polymer chains and the breadth of the distribution of the polymer chain lengths in a given product. In the solid state, the main properties of the PP material reflect the type and amount of crystalline and amorphous regions formed from the polymer chains. [45]

Semicrystalline PP is a thermoplastic material containing both crystalline and amorphous phases. The relative amount of each phase depends on structural and stereochemical characteristics of the polymer chains and the conditions under which the resin is converted to final products such as fibers, films, and various other geometric shapes during fabrication by extrusion, thermoforming, or molding. [45]

Polypropylene has excellent and desirable physical, mechanical, and thermal properties when used in room-temperature applications. It is relatively stiff and has a high melting point, low density, and relatively good resistance to impact. These properties can be varied in a relatively simple manner by altering the chain regularity (tacticity) content and distribution, the average chain lengths, the incorporation of a comonomer such as ethylene into the polymer chains, and the incorporation of an impact modifier into the resin formulation. [45]

3.1.1 Types of Polypropylene

Polypropylene containing only propylene monomer in the semicrystalline solid form is referred to as homopolymer PP (HPP), and we use this to mean the i-PP form. Polypropylene containing ethylene as a comonomer in the PP chains at levels in about the 1-8% range is referred to as random copolymer (RCP). HPP containing a commixed RCP phase that has an ethylene content of 45-65% is referred to as an impact copolymer (ICP). [45]

3.1.1.1 Homopolymer

Homopolymer PP is the most widely used polypropylene material in the HPP, RCP, and ICP family of products. It is made in several different reactor design using catalysts that link the monomers together in a stereospecific manner, resulting in polymer chains that are crystallizable. Whether they crystallize and to what extent depends on the conditions under which the entangled mass of polymer chains transitions from the melt to the solid state or how a heat-softened solid PP material is strained during a further fabrication procedure like fiber drawing. [45]

Homopolymer PP is a two-phase system because it contains both crystalline and noncrystalline regions. The noncrystalline, or amorphous, regions are composed of both isotactic PP and atactic PP. The isotactic PP in the amorphous regions is crystallizable, and it will crystallize slowly over time up to the limit that entanglement will allow. The extent of crystallization after the initial fabrication step of converting PP pellets or powder to a molded article will slowly increase over time, as will the stiffness. A widely accepted model of HPP morphology likens the solid structure to a system consisting of pieces of stiff cardboard linked together by strands of softer material. In the areas represented by flat pieces of cardboard, PP polymer chains weave up and down into close-packed arrays called crystallites ("little crystals"), which are called lamella by morphologists. The soft strands linking the pieces of stiff cardboard are polymer chains that exit one crystallite, enter another, and then begin weaving up and down in another crystallite. The crystallizability of the chains is one factor that determines how thick the crystallites will be, and the thickness of the crystallites determines how much heat energy is required to melt them (the melting temperature). A typical HPP has an array of crystallites from thick ones to very thin ones, and these manifest themselves as an array of melting points. [45]

Homopolymer PP is marketed mainly by melt flow rate (MFR) and additive formulation into fiber, film, sheet, and injection molding applications. Melt flow rate is an indicator of the weight-average molecular weight as measured by the ASTM or ISO MFR test method. [45]

3.1.1.2 Random Copolymer

Random copolymers are ethylene/propylene copolymers that are made in a single reactor by copolymerizing propylene and small amounts of ethylene (usually 7% and lower). The copolymerized ethylene changes the properties of the polymer chains significantly and results in thermoplastic products that are sold into markets in which slightly better impact properties, improved clarity, decreased haze, decreased melting point, or enhanced flexibility are required. The ethylene monomer in the PP chain manifests itself as a defect in the chain regularity, thus inhibiting the chain's crystallizability. As the ethylene content increases, the crystallite thickness gradually decreases, and this manifests itself in a lower melting point. The amount of ethylene incorporated into the chain is usually dictated by the balance between thermal, optical, and mechanical properties. [45]

3.1.1.3 Impact Copolymer

Impact copolymers are physical mixtures of HPP and RCP, with the overall mixture having ethylene contents on the order of 6-15% wt%. These are sold into markets where enhanced impact resistance is needed at low temperatures, especially freezer temperature and below. [45]

The RCP part of the mixture is designed to have ethylene contents on the order of 40-65% ethylene and is termed the rubber phase. The rubber phase can be mechanically blended into the ICP by mixing rubber and HPP in an extruder, or it can be polymerized in situ in a two-reactor system. The HPP is made in the limit reactor and the HPP with active catalyst still in it is conveyed to a second reactor where a mixture of ethylene and propylene monomer is polymerized in the voids and interstices of the HPP polymer powder particle. The amount of rubber phase that is blended into the HPP by mechanical or reactor methods is determined by the level of impact resistance needed. The impact resistance of the ICP product is determined not only by its rubber content but also by the size, shape, and distribution of the rubber particles throughout the ICP product. Reactor products usually give better impact resistance at a given rubber level for this reason. [45]

As the rubber content of the ICP product is increased, so is the impact resistance, but this is at the expense of the stiffness (flexural modulus) of the product. Consequently, polymer scientists often describe a product as having a certain impact-stiffness balance. The stiffness of the ICP product is dictated by the stiffness of the HPP phase and the volume of rubber at a given rubber size distribution in the product. The impact resistance is dictated by the amount and distribution of the rubber phase in the ICP product. [45]

3.1.2 Tacticity

The solid-state characteristics of PP occur because the propylene monomer is asymmetrical in shape. It differs from the ethylene monomer in that it has a methyl group attached to one of the olefinic carbons. This asymmetrical nature of the propylene monomer thus creates several possibilities for linking them together into polymer chains that are not possible with the symmetrical ethylene monomer, and gives rise to what are known as structural isomers and stereochemical isomers in the PP chain. [45]

In structural isomerism, polymer scientists refer to the olefinic carbon with the methyl group on it as the "head" (h) and the other olefinic carbon as the "tail" (t) of the monomer. The most common method of polymerization uses catalysts that link the monomers together in the "head-to-tail" fashion. Occasionally there is a "mistake" made and the monomers form a "head-to-head" or a "tail-to-tail" linkage, but these tend to be rare. [45]

Stereochemical isomerism is possible in PP because propylene monomers can link together such that the methyl groups can be situated in one spatial arrangement or another in the polymer. If the methyl groups are all on one side of the chain, they are referred to as being in the "isotactic" arrangement, and if they are on alternate sides of the chain, they are referred to as being in the "syndiotactic" arrangement. Each chain has a regular and repeating symmetrical arrangement of methyl groups that form different unit cell crystal types in the solid state. A random arrangement of methyl groups along the chain provides little or no symmetry, and a polymer with this type of arrangement is known as "atactic" polypropylene. Chain structures of atactic polypropylene, syndiotactic polypropylene and isotactic polypropylene are presented in Figure 3.1. [45, 46]

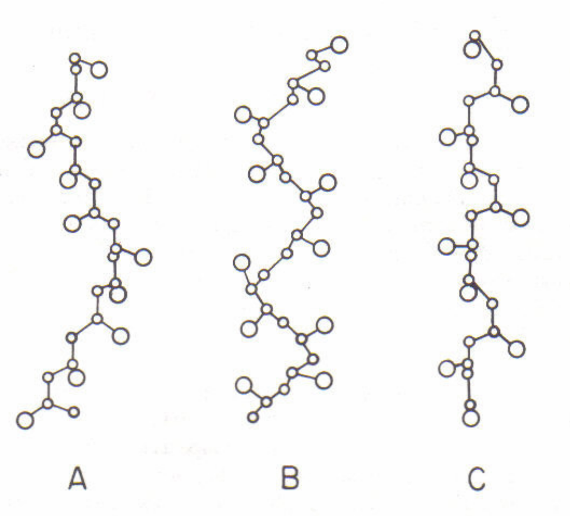

Figure 3.1 Molecular Configuration for Various Polypropylene Structures: (A) Atactic (B) Syndiotactic (C) Isotactic [46]

When polymer scientists discuss the stereochemical features of PP, they usually discuss it in terms of "tacticity" or "percent tacticity" of polypropylene, and in the marketplace the term "polypropylene" is generally used to refer to a material that has high tacticity, meaning high isotactic content. The high-tacticity PP materials have desirable physical, mechanical and thermal properties in the solid state. Atactic material is a soft, sticky, gummy material that is mainly used in sealants, caulks, and other applications where stickiness is desirable. Syndiotactic PP, not a large-volume commercial material, is far less crystalline than isotactic PP. [45]

3.1.3 Mechanical Properties

The mechanical properties of most interest to the PP product design engineer are its stiffness, strength, and impact resistance. Stiffness is measured as the flexural modulus, determined in a flexural test, and impact resistance by a number of different impact tests, with the historical favorite being the Izod impact at ambient and at subambient temperatures. These mechanical properties are mostly used to predict the properties of molded articles. Strength is usually defined by the stress at the yield point rather than by the strength at break, but breaking strength is usually specified for fiber or film materials under tensile stress. [45]

To understand the use and comparison of mechanical property data, one must remember that mechanical properties are not measured on the resins themselves but instead on specimens fabricated from the resin, and it is from the physics governing the fabrication and mechanical testing procedures that the mechanical properties are derived. Because there are so many variables that can affect mechanical properties, consensus testing organizations like ASTM and ISO were formed to bring some uniformity and consistency to specimen preparation and mechanical testing. Because the ASTM and ISO fabrication and testing methods allow some freedom within their guidelines, when one is asked what the mechanical properties of a material are, the first answer should be to ask by what tests, what specimens, and under what conditions. The latter includes such factors as the exact specimen type, age of specimen, how the specimen was conditioned, testing speed, testing temperature, data acquisition procedure, and method of calculation. [45]

Flexural modulus or stiffness typically increases as the level of crystallinity increases in a PP product, but it also depends on the type of crystal morphology. Thus, stiffness generally decreases as the crystallizability (tacticity) decreases or, in random copolymers, as the ethylene content increases because this tends to decrease crystallizability. [45]

3.1.4 Rheology

Rheology is the science that studies the deformation and flow of matter, and in PP there is interest in both viscosity and elasticity of the melt state and the solid state. The rheological properties of PP are important because of the broad range of processing techniques to which PP is subjected, including fiber and film extrusion, thermoforming, and injection molding. The viscosity of PP is of most importance in the melt state because it relates to how easily a PP product can be extruded or injection molded. In fiber extrusion, melt elasticity is important to processability of a PP product because it relates to how easily a material can be drawn into a fiber. In contrast to PP, most engineering resins are used mainly in injection molding operations. [45]

The viscosity of a PP product is related to its average molecular weight, and a good estimation of it at low shear rates can be obtained from the MFR test. This is only a single point test, and more information about the viscosity at different strain rates is needed to completely understand and characterize the processability of a product. The strain rate dependence of melt viscosity in PP is related to its molecular weight distribution, which is commonly described by the ratio of the average molecular weight to average-number molecular weight averages. As the molecular weight distribution (MWD) of PP gets broader, it shear thins (becomes less viscous) more than a narrower MWD PP at the same strain rate. [45]

As indicated above, the rheological properties in the melt are related to the MWD, In PP these are controlled mainly by the process used, although with Ziegler-Natta catalysts there is a small effect due the catalyst. Typical MWDs are in the 5-6 range. The MWD can be made more narrow by using postreactor polymer chain shortening. This may be accomplished by adding a peroxide in the extrusion compounding manufacturing step, in which stabilizers and other additives are normally incorporated into the PP reactor product before pelletization. These controlled rheology (CR) resins have higher MFR and reduced MWD than the unmodified reactor product. In the CR process, also known as visbreaking (for viscosity breaking), the longer higher molecular weight molecules are preferentially (statistics) broken. [45]

The MWD can be made broader by using a two-reactor configuration that produces different melt flow rates in each reactor. Recently, metallocene PP catalysts have shown the ability to produce PPs with very narrow molecular weight distributions, on the order of 2-3. These resins have a great deal of value in fiber extrusion applications where less shear sensitivity of the viscosity is important. [45]

3.1.5 Morphology

Homopolymer PP exists as a two- and possibly a three-phase system of crystalline and amorphous phases with the amorphous phase comprising a crystallizable isotactic portion and a noncrystallizable atactic portion. The noncrystallizable, gummy, atactic PP phase has small amounts of a low molecular weight oily material at a level of 1% and lower. The latter has been characterized in some products as having some structural inversions of propylene monomers and some branches other than methyl. Typical levels of crystallinity in extruded PP pellets are in the 60 -70% range. One way to describe the morphology of PP is to consider it an assemblage of crystallites that act as physical cross-links in an amorphous matrix. [45]

In the crystalline phase, the alpha or monoclinic phase is the dominant crystal form of PP with a melting point of about 160 ˚C. The beta or hexagonal phase is less common and less stable. The latter has a melting point of about 145 ˚C. Typical levels of beta crystallites are less than 5% in injection-molded parts. [45]

3.1.6 Polypropylene Applications

PP should really be considered a group of polymers, not just a single polymer. Because the properties of PPs cover a substantial range, the applications of PP are quite diverse. This, of course, belies the usual classification of PP as a commodity resin. [45]

Organizing a discussion on applications is challenging because the question arises as to whether similarity of uses or similarity of the fabricated products or similarity of the fabrication techniques should be used as the criterion for arranging information.

The applications of polypropylene can be summarized as follows:

1. Fibers and fabrics
2. Strapping
3. Film
4. Sheet / thermoforming
5. Injection molding
6. Blow molding
7. Automotive [45]

3.2 Polypropylene Fibers

One of the latest members of the rapidly growing thermoplastic polymer family which appears capable of successfully competing with the currently saturated textile and chemical markets is polypropylene fiber (PPF). [46]

The low costs of propylene monomer and the polymerization process give propylene a cost advantage over similar products. In addition, polypropylene fibers, because of their structural uniqueness, exhibit outstanding physical properties relative to other commercial fibers. The density of polypropylene is the lowest of any fiber available; supertenacity polypropylene fibers have been prepared that exceed the strength of all commercial fibers — including the much more expensive nylons. Polypropylene fibers also excel in other important physical properties, such as toughness, resilience, permeability, chemical resistance, and abrasion resistance. [46]

3.2.1 Fiber Manufacture Operations

Three basic methods of preparation of synthetic fibers are used commercially:

1. Wet spinning
2. Dry spinning
3. Melt spinning

In each process a viscous fluid is extruded through a multiholed die or spinneret, forming a fine-diameter fiber. Polypropylene fibers are prepared via the melt spinning technique, which essentially is comprised of two manufacturing stages:

1. Extrusion of a fiber
2. The subsequent thermal and mechanical stretching of the fiber

A diagram of a typical equipment line arrangement is shown in Figure 3.2. [46]

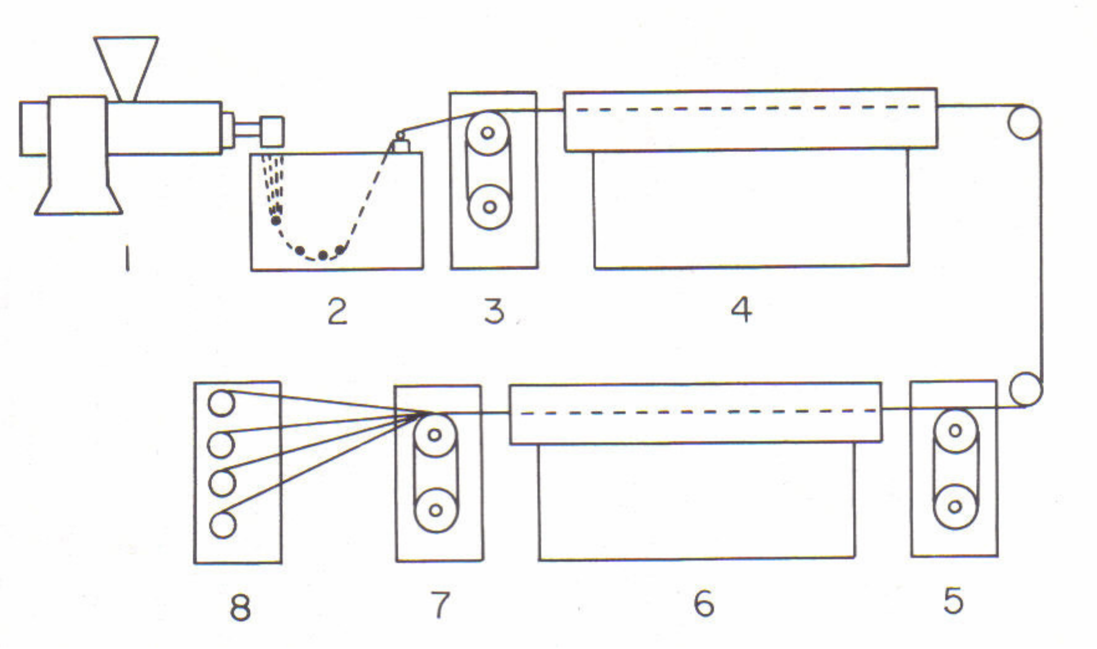

Figure 3.2 Typical Line Diagram For The Extrusion of Polypropylene Mono-filaments: (1) Extruder, (2) Quench Tank, (3) Pull-Out Rolls (4) Draw Oven, (5) Draw Rolls, (6) Relax Oven, (7) Relax Rolls, (8) Wind-Up. [46]

3.2.1.1 Extrusion

The melting of the resin, sometimes termed as “plasticating” is accomplished with a conventional thermoplastic extruder equipped with a polyethylene-type metering screw having a minimum 4:1 compression ratio and a metering zone no less than four flights in length. An extruder barrel with a length-to-diameter ratio of 24:1 is preferred since polypropylene requires higher extrusion temperatures than most other thermoplastic resins. [46]

A wire cloth screen pack in the head of the extruder is positioned to prevent foreign particles from impregnating the extruded fibers. Since highly oriented fibers, such as polypropylene, are sensitive to contamination breakage, this screening is expedient. A pressure control valve is generally installed after the screen pack (immediately upstream of the die) to compensate for variations in polymer throughputs at a given screw speed, which may result from varying polymer melt viscosity or barrel temperature profiles. This pressure control is best obtained at the 90° bend of the polymer flow it ream inherent in monofilament die heads; the die head is essentially the transition section of the extrusion line which conveys the extruded melt to the die. [46]

The die containing the capillaries through which the molten polymer is forced into fibers is mounted to the downstream side of the die head. The melt temperature and pressure are monitored at the entrance to the die by thermocouples and pressure gauges, or, preferably, pressure transducers. The extrusion die is the most important single part of the monofilament operation and requires careful design, machining, and maintenance. Filament irregularities which can be attributed to deficiencies at the die include (1) end-to-end fiber diameter variation, (2) surface flaws, (3) flow pulsation and attendant diameter variations in the fiber produced, and (4) excessive fiber waviness in the quench bath. [46]

3.2.1.2 Draw-Down, Quenching And Drying

Between the die exit and the pull-out rolls (first Godet station), the extruded fibers are predrawn, water-quenched, separated into an orderly arrangement, and dried of adhering surface moisture. [46]

The predraw, or draw-down, is a decrease in fiber diameter which occurs as the molten polymer emerges from the die; the diameter of this unoriented fiber is approximately 50% of the die hole diameter. The operational variables controlling the uniformity of draw-down are polymer throughput and filament velocity just prior to the quench bath. Upon solidification of the fiber in the quench bath, draw-down is complete. [46]

Fast quenching retards crystal growth and results in an amorphous fiber composed of a large number of small crystallites; this type of fiber excels in toughness and flexibility. Quenching at higher bath temperatures promotes crystal growth, resulting in a more crystalline fiber which exhibits superior strength and rigidity. [46]

The quenched fibers are drawn around an adjustable guide assembly located in the quench bath and over another set of guide bars positioned at the exit of the bath, which serves to maintain an orderly arrangement of the fibers. An air jet is directed at the "tow" to surface-dry the fibers, upon their exit from the bath. Removal of this moisture is of prime importance as uneven heating will result in the fiber orientation section. [46]

3.2.1.3 Orientation, Relaxation And Wind-Up

The fibers then pass into the orientation, or draw, stages, which impart thermal and mechanical treatments to the fibers. Initially the temperature of the fibers is raised by an orientation oven in preparation of the all-important stretching of the fibers. This step is the most single important operation in the manufacture of fibers relative to the properties exhibited by the fibers. The stretching of the fibers is effected by high-speed draw rolls driven by powerful motors; the ratio of the speed of the pull rolls and the draw rolls is the draw ratio. The higher the draw ratio, the more orientation imparted to the fibers. [46]

In order to minimize shrinkage, by relieving residual stresses, the fibers are then permitted to relax and become heat-set by passing through another oven. The heat-set temperature must be higher than the end use of the fibers in order to be effective in preventing shrinkage. The last set of rolls which pulls the fibers through the relax oven is driven at a speed slightly lower than that of the draw rolls. The individual fibers in the tow are then wound upon a spindle in the wind-up station. This wind-up unit is generally synchronized with the speed of the other rolls to maintain uniform winding. [46]

CHAPTER 4

MARSHALL METHOD OF ASPHALT MIX DESIGN

4.1 General

The Marshall design method was formulated by a highway engineer, Bruce Marshall, but was developed and perfected by the U.S. Army Corps of Engineers. It was developed chiefly as a method for designing airfield pavements but has been used successfully for highway pavements as well. The Marshall method is applicable to hot-mix pavements using penetration-grade asphalt cements and having a maximum aggregate size of 25.4 mm or less. [1]

Test specimens for the Marshall method are 6.35 cm high by 10.2 cm in diameter and are prepared by heating, mixing, and compacting the asphalt-aggregate mixture in a prescribed manner. Specimens are analyzed for density and voids and tested for stability and flow. Stability is defined as load resistance at 60˚C under test conditions, and flow as the total strain at maximum load. [47]

The general steps in proportioning an asphalt concrete include the following:

1. Select an aggregate gradation which meets requirements and which can be practically produced.

2. Determine the blend percentages which will meet the job gradation, and determine the probable gradation ranges for the individual materials so that fluctuations in the job mix can be predicted.

3. Prepare test specimens using the aggregate gradation and a range of asphalt contents.

4. Analyze the test specimens for bulk specific gravity, voids, and stability.

5. Select the optimum asphalt content from the test data. [1]

4.2 Preparation of Test Specimens

In determining the optimum asphalt content for a particular blend or gradation of aggregates by the Marshall method, a series of test specimens is prepared for a range of different asphalt contents so that the test data curves show a well-defined "optimum" value. Tests should be scheduled on the basis of 0,5 percent increments of asphalt contents, with at least two asphalt contents above "optimum" and at least two asphalt contents below “optimum”. To establish asphalt contents for use in these laboratory tests, the optimum asphalt content must first be estimated. [47]

To provide adequate data, triplicate test specimens are usually prepared for each asphalt content used. Thus, a hot-mix design study using five different asphalt contents will normally require at least 15 test specimens. Each test specimen will usually require approximately 1200 g of aggregate. [47]

The equipment required for the preparation of test specimens is as follows:

- Oven and hot plate; electric, for heating aggregates, asphalt, and equipment as required
- Scoop; for handling hot aggregates
- Cans; pouring, 2.5 lt size, for heating and dispensing asphalt, cement
- Thermometer; armored, +10 to +250°C
- Balance; 20 kg capacity, sensitive to 1 g, for weighing aggregates and asphalt as shown in Figure 4.1.

Figure 4.1 Balance

- Boiling water bath; consisting of hot plate and bucket for water for heating compaction hammer and mold
- Compaction pedestal; consisting of a wooden post, capped with a 25 mm steel plate and attached to a rigid floor slab
- Mixer; commercial bread dough mixer, equipped with two metal mixing bowl- and two wire stirrers. An example of mixer is seen in Figure 4.2.

Figure 4.2 Mixer

- Compaction mold; consisting of a base plate, forming mold and collar extension. The forming mold has an inside diameter of 10.2 cm and a height of approximately 7.6 cm; the base plat and collar extension are designed to be interchangeable will either end of forming mold as seen in Figure 4.3.

Figure 4.3 Compaction Mold

- Compaction hammer; consisting of a flat, circular tamping fan and equipped with a 4.5 kg weight constructed to obtain a specified 45 cm height of drop. Also a Marshall compaction machine can be used as shown in Figure 4.4.
- Mold holder; consisting of spring tension device designed to hold compaction mold in place on compaction pedestal
- Extrusion jack; consisting of hydraulic jack and loading frame for extruding compacted specimens from mold
- Gloves, welder's; for handling hot equipment
- Marking crayons; for identifying test specimens [47,48]

Figure 4.4 Marshall Compaction Machine

After equipments is prepared, the procedure goes on as follows;

1. Number of Specimens; Prepare at least three and preferably five specimens for each combination of aggregates and asphalt content.

2. Preparation of Aggregates; Dry aggregates to constant weight at 105 to 110 °C and separate the aggregates by dry sieving into the desired size fraction.

3. Preparation of Mold and Hammer; Thoroughly clean the specimen mold assembly and the face of the compaction hammer, and heat them in a boiling-water bath or on the hot plate to a temperature between 90 and 150°C. Place a piece of filter-paper toweling cut to size in the bottom of the mold before the mixture is placed in the mold.

4. Preparation of Mixtures; Weigh into separate pans for each test specimen the amount of each size fraction required to produce a batch which will result in a compacted specimen. This will normally be about 1200 g. It is generally desirable to prepare a trial specimen prior to preparing the aggregate batches. Place the pans in the oven or on the hot plate, and heat to a temperature approximately 10 °C above the mixing temperature. If a hot plate is used, provision should be made for dead space, baffle plates, or a sand bath beneath the pans and the hot plate to prevent local overheating. Charge the mixing bowl with heated aggregates, and dry-mix thoroughly. Form a crater in the dry blended aggregate, and weigh the required amount of asphalt cement into the mixture in accordance with the accumulative batch weights. At this point the temperature of the aggregate and asphalt shall be within the limits of the mixing temperature. Asphalt should not be held at mixing temperatures for more than 1 hr before using. Mix the aggregate and asphalt cement, preferably with a mixer, as quickly and thoroughly as possible to yield a mixture having a uniform distribution of asphalt throughout.

5. Compaction of Specimens; Place the entire batch in the mold; spade the mixture vigorously with a heated spatula or trowel fifteen times around the perimeter and ten times over the interior. Remove the collar, and smooth the surface to a slightly rounded shape. Temperature of the mixture immediately prior to compaction shall be within the limits of the compaction temperature, otherwise, it shall be discarded. In no case shall the mixture be reheated.

6. Replace the collar; place the mold assembly on the compaction pedestal in the mold holder. Apply 35, 50, or 75 blows, as specified according to the design traffic category, with the compaction hammer, using a free fall of 45 cm. Hold the axis of the compaction hammer perpendicular to the base of the mold assembly during compaction. Remove the base plate and collar, and reverse and reassemble tin-mold. Apply the same number of compaction blows to the face of the reversed specimen. After compaction, remove the base plate and allow the specimen to cool in air until no deformation will result when removing it from the mold. When more rapid cooling is desired, table fans may be used. Remove the specimen from the mold by means of an extrusion jack or other compression device, then plan on a smooth, level

surface until ready for testing. Normally specimens are allowed to cool overnight. [1]

4.3 Procedure For Testing Specimens

In the Marshall method each compacted test specimen is subjected to the following tests and analysis in the order listed:

1. Specific gravity determinations
2. Voids analysis
3. Stability and flow test [47,48]

4.3.1 Specific Gravity Determinations

4.3.1.1 Bulk Specific Gravity of the Compacted Asphalt Mixture (G_{mb})

The ratio of the mass in air of a unit volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the mass in air (of equal density) of an equal volume of gas-free distilled water at a stated temperature. This value is used to determine weight per unit volume of the compacted mixture. It is very important to measure G_{mb} as accurately as possible. Since it is used to convert weight measurements to volumes, any small errors in G_{mb} will be reflected in significant volume errors, which may go undetected.

G_{mb} can be found by the following equation.

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}} \tag{4.1}$$

G_{mb} = Bulk specific gravity of the compacted mixture
W_D = Dry weight
W_{SSD} = Saturated surface dry (SSD) weight
W_{sub} = Weight submerged in water [1]

4.3.1.2 Theoretical Maximum Specific Gravity of Bituminous Paving Mixture (G_{mm})

The ratio of the mass of a given volume of voidless (Va = 0) HMA at a stated temperature (usually 25 ^{o}C) to a mass of an equal volume of gas-free distilled water at the same temperature. It is also called Rice Specific Gravity (after James Rice who developed the test procedure). Multiplying G_{mm} by the unit weight of water gives Theoretical Maximum Density (TMD).

G_{mm} can be found by the following equation.

$$G_{mm} = \frac{1}{\frac{1-P_b}{G_{se}} + \frac{P_b}{G_b}} \tag{4.2}$$

G_{mm} = Maximum theoretical specific gravity of the mixture
P_b = Asphalt content by weight of mix (percent)
G_{se} = Effective specific gravity of the aggregate (It is the average of bulk specific gravity (G_{sb}) and apparent specific gravity (G_{sa}) of the aggregate)
G_b = Asphalt binder specific gravity [1]

4.3.2 Voids Analysis

4.3.2.1 Air Voids (V_a)

The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture. The amount of air voids in a mixture is extremely important and closely related to stability and durability.

V_a can be found by the following equation.

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100 \tag{4.3}$$

V_a = Air voids

G_{mm} = Maximum theoretical specific gravity of the mixture

G_{mb} = Bulk specific gravity of the compacted mixture [1]

4.3.2.2 Voids in The Mineral Aggregate (VMA)

The volume of intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of the total volume of the specimen. When VMA is too low, there is not enough room in the mixture to add sufficient asphalt binder to adequately coat the individual aggregate particles. Also, mixes with a low VMA are more sensitive to small changes in asphalt binder content. Excessive VMA will cause an unacceptably low mixture stability.

VMA can be calculated by the following equation.

$$VMA = \left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right) \times 100 \qquad (4.4)$$

VMA = Voids in the mineral aggregate

G_{mb} = Bulk specific gravity of the compacted mixture

P_b = Asphalt content by weight of mix (percent)

G_{sb} = Bulk specific gravity of the aggregate [1]

4.3.2.3 Voids Filled With Asphalt (VFA)

The portion of the voids in the mineral aggregate that contain asphalt binder. This represents the volume of the effective asphalt content. It can also be described as the percent of the volume of the VMA that is filled with asphalt cement. VFA is inversely related to air voids; as air voids decrease, the VFA increases.

VFA can be calculated by the following equation.

$$VFA = \frac{VMA - V_a}{VMA} \quad 100 \qquad (4.5)$$

VFA = Voids filled with asphalt
VMA = Voids in the mineral aggregate
V_a = Air voids[1]

4.3.3 Stability And Flow Test

The equipment required for the testing of the 10.2 cm diameter by 6.35 cm height specimens is as follows:

- Marshall testing machine; an electrically powered (220-volt) testing device. It is designed to apply loads to test specimens through semicircular testing heads at a constant rate of strain of 5 cm per min. It is equipped with a calibrated proving ring for determining the applied testing load, a Marshall stability testing head for use in testing the specimen, and a Marshall flow meter for determining the amount of strain at the maximum load for test. A universal testing machine equipped with suitable load and deformation-indicating devices can be used instead of the Marshall testing frame. A typical Marshall testing machine is shown in Figure 4.5.

- Water bath, at least 15 cm deep and thermostatically controlled to 60˚C ± 1˚C. The tank should have a perforated false bottom or be equipped with a shelf for suspending specimens at least 5 cm above the bottom of the bath. A water bath is shown in Figure 4.6.

Figure 4.5 Marshall Testing Machine

Figure 4.6 Water Bath

After the bulk specific gravity of the test specimen has been determined, the stability and flow tests are performed as follows:

1) "Zero" the flow meter by inserting a 10.2 cm diameter metal cylinder in the testing head, placing the flow meter over the guide rod and adjusting the flow meter to read zero.

2) Immerse the specimen in a water bath at 60˚C ± 1˚C for 30 to 40 minute before test.

3) Thoroughly clean the inside surfaces of the testing head. Lubricate the guide rods with a thin film of oil so that the upper test, head will slide freely without binding. If a proving ring is used to measure the applied load, check to see that the dial indicator is firmly fixed and "zeroed" for the "no-load" position.

4) With testing apparatus in readiness, remove the test specimen from the water bath and carefully dry the surface. Place the specimen in the lower testing head and center; then fit the upper testing head into position and center the complete assembly in the loading device. Place the flow meter over the marked guide rod.

5) Apply the testing load to the specimen at a constant rate of deformation, 5 cm per min, until failure occurs. The point of failure is defined by the maximum load reading obtained. The total number of pounds required to produce failure of the specimen at 60 °C shall be recorded as its Marshall stability value.

6) While the stability test is in progress, hold the flow meter firmly in position over the guide rod and remove as the load begins to decrease; take a reading and record. The stability value so obtained is corrected for height. The correlation ratios according to the thickness of specimens are given in Table 4.1.

7) The entire procedure, both stability and flow tests, starting with the removal of the specimen from the water bath, shall be completed within a period of 30 sec. [47,48]

Table 4.1 Marshall Stability Correlation Ratios [49]

Marshall Stability Correlation Ratios			
Thickness of Specimen (mm)	**Correlation Ratio**	**Thickness of Specimen (mm)**	**Correlation Ratio**
50.0	1.470	63.0	1.013
50.5	1.453	63.5	1.000
51.0	1.435	64.0	0.988
51.5	1.418	64.5	0.975
52.0	1.400	65.0	0.962
52.5	1.375	65.5	0.951
53.0	1.337	66.0	0.940
53.5	1.311	66.5	0.930
54.0	1.290	67.0	0.918
54.5	1.274	67.5	0.906
55.0	1.265	68.0	0.894
55.5	1.250	68.5	0.885
56.0	1.231	69.0	0.875
56.5	1.214	69.5	0.866
57.0	1.194	70.0	0.856
57.5	1.178	70.5	0.847
58.0	1.161	71.0	0.836
58.5	1.146	71.5	0.829
59.0	1.130	72.0	0.822
59.5	1.114	72.5	0.815
60.0	1.097	73.0	0.809
60.5	1.082	73.5	0.800
61.0	1.067	74.0	0.792
61.5	1.053	74.5	0.782
62.0	1.038	75.0	0.775
62.5	1.026	75.5	0.769

4.4 Determination of Optimum Asphalt Content

The optimum asphalt content of the asphalt paving mix is determined from six separate smooth curves, which are drawn with percent of asphalt on x-axis and the following on y-axis ;

- Bulk specific gravity
- Air voids
- VMA
- VFA
- Stability
- Flow

After that, the optimum asphalt content can be determined according to the following equation.

$$B_0 = \frac{B_1 + B_2 + B_3}{3} \tag{4.6}$$

B_0 = Optimum asphalt content
B_1 = % asphalt content at maximum bulk specific gravity
B_2 = % asphalt content at maximum stability
B_3= % asphalt content at specified percent air voids in the total mix [1]

4.5 Evaluation And Adjustment of Mix Design

The overall objective of the mix design is to determine an optimum blend of different components that will satisfy the requirements of the given specifications as seen in Table 4.2. This mixture should have:

1. Adequate amount of asphalt to ensure a durable pavement.
2. Adequate mix stability to prevent unacceptable distortion and displacement when traffic load is applied.

3. Adequate voids in the total compacted mixture to permit a small amount of compaction when traffic load is applied without bleeding and loss of stability.
4. Adequate workability to facilitate placement of the mix without segregation.

The selected mix design is normally the most economical one which will satisfactorily meet all the established criteria. The mix showing the higher stability is normally selected, provided that economic considerations are equal. Mixes with abnormally high values of Marshall stability and abnormally low flow values are often less desirable because pavements of such mixes tend to be more rigid or brittle and may crack under heavy volumes of traffic. This is particularly true where base and subgrade deflections are such as to permit from moderate to relatively high deflections of the pavement. [48]

Table 4.2 Marshall Mix Design Criteria [49]

Mix Criteria	**Light Traffic**		**Medium Traffic**		**Heavy Traffic**	
	Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Compaction (number of blows on each end of the sample)	35		50		75	
Stability (minimum)	3336 N (750 lbs.)		5338 N (1200 lbs.)		8006 N (1800 lbs.)	
Flow (0.25 mm (0.01 inch))	8	18	8	16	8	14
Percent Air Voids	3	5	3	5	3	5
Percent Voids Filled With Asphalt (VFA)	70	80	65	78	65	75
Percent Voids in Mineral Aggregate (VMA)	See Table 4.3					

Table 4.3 Minimum VMA Requirement for Asphalt Samples [49]

Nominal Maximum Particle Size		**Minimum VMA Design Air Voids Percent**		
mm.	**in.**	**3.0**	**4.0**	**5.0**
1.18	No. 16	21.5	22.5	23.5
2.36	No. 8	19.0	20.0	21.0
4.75	No. 4	16.0	17.0	18.0
9.5	3/8	14.0	15.0	16.0
12.5	1/2	13.0	14.0	15.0
19.0	3/4	12.0	13.0	14.0
25.0	1.0	11.0	12.0	13.0
37.5	1.5	10.0	11.0	12.0
50	2.0	9.5	10.5	11.5
63	2.5	9.0	10.0	11.0

CHAPTER 5

LABORATORY TEST RESULTS AND DISCUSSION

5.1 General

Marshall specimens were prepared in laboratory conditions and, stability and flow tests were done on these specimens which were prepared with a similar aggregate gradation of binder layer Type 1 according to General Directorate of Highways of Turkey [50].

Medium Traffic was taken into consideration while preparing the specimens and the mixing temperature was chosen as 143 ˚C due to the nature of the modifier.

In this study, the tests were separated into four groups according to the modifier ratio of the mixture. Table 5.1 shows the classification of these four tests.

Table 5.1 Test Classification

Test No	**Modifier Ratio By Weight of the Mixture**
Test 1	0 %
Test 2	0.3 %
Test 3	0.6 %
Test 4	1 %

5.2 Materials

The materials, which are used to preparation of marshall specimens such as aggregate, bitumen (asphalt cement) and polypropylene fiber (modifier) are briefly explained.

5.2.1 Aggregate

The aggregates used for preparing marshall specimens were brought from a private quarry which is known as Güngörler Quarry. The aggregate type is crashed limestone. They were come as four size groups which are 0-5 mm, 5-10 mm, 10-20 mm and 20-35 mm. The physical properties of aggregates used in experiments were analyzed according to ASTM C 127 [51] and ASTM C 128 [52] and these tests results are shown in Table 5.2.

Table 5.2 The Physical Properties of Aggregates

Property	Test Value
Bulk Specific Gravity (g/cm^3)	2.664
Apparent Specific Gravity (g/cm^3)	2.691
Effective Specific Gravity (g/cm^3)	2.678
Water Absorption (%)	0.85

Binder layer and Type 1 were chosen as mix gradation according to General Directorate of Highways of Turkey. The midpoints of the limits were defined as aggregate combination which is shown in Table 5.3 and Figure 5.1.

The total quantity of aggregate was selected as 1200 gr and the quantities of aggregates retained on each sieve were calculated according to the mixture gradation. The aggregate combination was prepared as shown in Figure 5.2.

Table 5.3 Aggregate Combination of Asphalt Mixtures

Sieve Size	Type 1		Mixture (% passing)	Quantity (Retained on each sieve, gr)
	Min. (% passing)	Max. (% passing)		
22,4 mm	100	100	100	0
20,0 mm	82	100	91	108
14,0 mm	68	87	77,5	162
10,0 mm	60	79	69,5	96
5,0 mm	46	65	55,5	168
2,0 mm	34	51	42,5	156
0,425 mm	17	29	23	234
0,150 mm	9	18	13,5	114
0,075 mm	2	7	4,5	108
Pan	0	0	0	54

Total	1200 gr

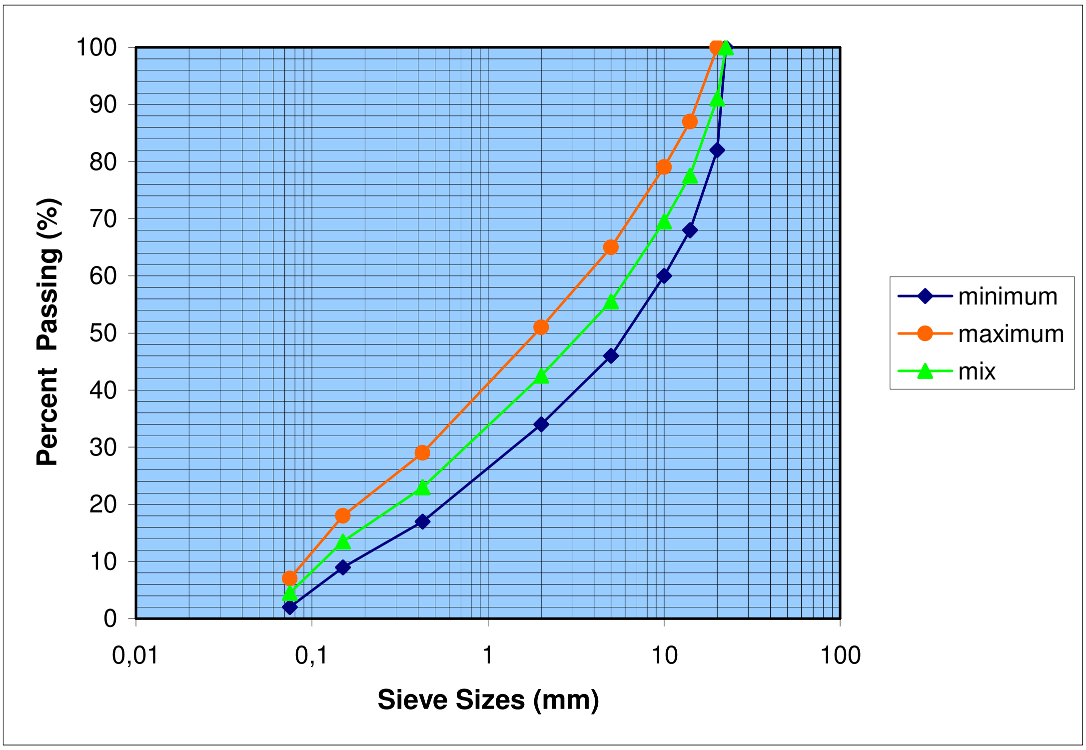

Figure 5.1 Gradation of Mix

Figure 5.2 The Aggregate Combination

5.2.2 Bitumen

The bitumen (asphalt cement) used for preparing marshall specimens were come from Gaziantep Şehitkamil Municipality Asphalt Plant. A 50/70 penetration bitumen was used in all experiments. Specific gravity, penetration, softening point and ductility tests were done on bitumen according to ASTM D 70 [53], ASTM D 5 [54], ASTM D 36 [55] and ASTM D 113 [56], respectively. The physical properties of bitumen are given in Table 5.4.

Table 5.4 The Physical Properties of Bitumen

Property	Test Value
Specific Gravity at 25 ˚C (g/cm^3)	1.034
Specific Gravity at 25 ˚C with 0.3 % PPF (g/cm^3)	0.940
Specific Gravity at 25 ˚C with 0.6 % PPF (g/cm^3)	0.875
Specific Gravity at 25 ˚C with 1.0 % PPF (g/cm^3)	0.828
Penetration at 25 ˚C (1/10 mm)	63
Softening Point (˚C)	52
Ductility at 25 ˚C (cm)	100.5

5.2.3 Polypropylene Fiber

The polypropylene fibers used in the experiments of this study were provided by a polypropylene company called as Polyfibers. Two types of polypropylene fibers were received according to the length, 12 mm and 19 mm. The polypropylene fibers with 19 mm length shown in Figure 5.3 were used as asphalt modifier in this study. The physical properties of polypropylene fibers are shown in Table 5.5 according to Polyfibers Company.

Table 5.5 The Physical Properties of Polypropylene Fibers

Characteristic	Value
Homogeneity (%)	100 % Polypropylene
Color	Transparent
Length (mm)	3-50
Melting temperature (˚C)	160
Specific Gravity (g/cm^3)	0.910
Fire point (˚C)	590
Glass transition temperature (˚C)	-18
Alkali resistance as % of strength retained after treatment in 40 % NaOH solution at 20 ˚C for 1000 h	99.5
Water absorption (%)	0.01-0.02
Moisture retention, at 20 ˚C and 65 % relative humidity	< 0.1 %
Rupture resistance (MPa)	31-41
Elongation (%)	≥ 33
Elongation at rupture (%)	100-600
Tensile strength (MPa)	31-37
Compressive strength (MPa)	37-55
Bending strength (MPa)	41-55
Tensile modulus (MPa)	1137-1551
Bending modulus (73 ˚F, MPa)	1172-1723
Hardness (Rockwell)	R80-R102
Thermal expansion (linear, m/m/˚C)	0.031-0.039

Figure 5.3 Polypropylene Fibers

5.3 Marshall Specimens

Marshall specimens were prepared with 50 blows on each face in laboratory conditions according to ASTM D1559 [57] which is explained in Chapter 4. Four different type of Marshall specimens were prepared according to the polypropylene fiber ratios with 143 ˚C mixing temperature. Quantity of aggregate in the mix was 1200gr.

Bitumen content (asphalt content) was specialized for each test. This content was varied between 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0 percent of aggregate amount according to the test performance. The bitumen contents were used as 3.0, 3.5, 4.0, 4.5, 5.0 and 5.5 % for Test 1; 3.5, 4.0, 4.5, 5.0 and 5.5 % for Test 2 and Test 3; and, 5.0, 5.5, 6.0, 6.5 and 7.0 % for Test 4. Three specimens were prepared for each bitumen content. Therefore, a total of 18 specimens were prepared for Test 1, and 15 specimens were prepared for Test 2, Test 3 and Test 4 for each test group, which means that 63 specimens were analyzed by the total. The specimens are shown in Figure 5.4.

Figure 5.4 Marshall Specimens

5.4 Test Results

Specific gravity determinations, voids analysis, and, stability and flow tests explained in Chapter 4 were applied on the specimens. All of the tests results and graphs are shown the parts called as Test 1, Test 2, Test 3 and Test 4.

5.4.1 Test 1

Table 5.6 Specific Gravity Results of Test 1

Asphalt Content (%)	**Sample No.**	**W_D (g)**	**W_{sub} (g)**	**W_{SSD} (g)**	**G_{mb} (g/cm^3)**	**G_{mb} (g/cm^3) (Avr.)**
3,0	1	1227,8	701,5	1229,2	2,327	2,319
	2	1226,0	699,3	1227,3	2,322	
	3	1219,4	692,7	1221,1	2,308	
3,5	1	1230,8	713,6	1231,8	2,375	2,361
	2	1231,1	709,3	1232,5	2,353	
	3	1232,1	710,5	1233,4	2,356	
4,0	1	1238,6	726,9	1240,3	2,413	2,401
	2	1239,6	722,0	1241,5	2,386	
	3	1240,7	725,9	1241,8	2,405	
4,5	1	1249,4	738,0	1250,7	2,437	2,435
	2	1250,3	738,2	1251,5	2,436	
	3	1249,4	737,7	1251,3	2,433	
5,0	1	1256,4	744,5	1257,1	2,451	2,450
	2	1255,8	744,5	1256,1	2,455	
	3	1255,7	742,6	1256,2	2,445	
5,5	1	1260,5	747,1	1260,9	2,453	2,452
	2	1260,4	746,3	1260,8	2,450	
	3	1261,9	747,7	1262,3	2,452	

Table 5.7 Volumetric Properties of Samples Used in Test 1

Asphalt Content (%)	**G_{mb} (g/cm^3) (Avr.)**	**G_{sb} (g/cm^3)**	**G_{sa} (g/cm^3)**	**G_{se} (g/cm^3)**	**P_b (%)**	**G_b (g/cm^3)**	**G_{mm} (g/cm^3)**	**Va (%)**	**VMA (%)**	**VFA (%)**
3,0	2,319	2,664	2,691	2,678	0,030	1,034	2,556	9,27	15,57	40,48
3,5	2,361	2,664	2,691	2,678	0,035	1,034	2,536	6,90	14,46	52,30
4,0	2,401	2,664	2,691	2,678	0,040	1,034	2,517	4,62	13,47	65,72
4,5	2,435	2,664	2,691	2,678	0,045	1,034	2,499	2,55	12,71	79,95
5,0	2,450	2,664	2,691	2,678	0,050	1,034	2,480	1,22	12,62	90,36
5,5	2,452	2,664	2,691	2,678	0,055	1,034	2,462	0,43	13,03	96,73

Table 5.8 Stability And Flow Results of Test 1

Asphalt Content (%)	Sample No.	Height of sample(cm)	Correlation Ratios	Stability (kg)	Corrected Stability (kg)	Corrected Stability (kg) (Avr.)	Flow (mm)	Flow (mm) (Avr.)
3,0	1	6,45	0.975	1318	1285	1146	3,56	3,73
	2	6,50	0.962	1273	1225		3,81	
	3	6,55	0.951	977	929		3,81	
3,5	1	6,35	1.000	1398	1398	1317	4,32	4,06
	2	6,35	1.000	1341	1341		4,06	
	3	6,40	0.988	1227	1212		3,81	
4,0	1	6,35	1.000	1318	1318	1358	3,81	3,98
	2	6,40	0.988	1364	1348		3,81	
	3	6,35	1.000	1409	1409		4,32	
4,5	1	6,35	1.000	1386	1386	1326	5,08	5,16
	2	6,35	1.000	1409	1409		5,33	
	3	6,35	1.000	1182	1182		5,08	
5,0	1	6,35	1.000	1136	1136	1126	5,84	6,26
	2	6,30	1.013	1068	1082		6,60	
	3	6,35	1.000	1159	1159		6,35	
5,5	1	6,35	1.000	1023	1023	1004	5,84	5,67
	2	6,30	1.013	953	965		5,84	
	3	6,35	1.000	1023	1023		5,33	

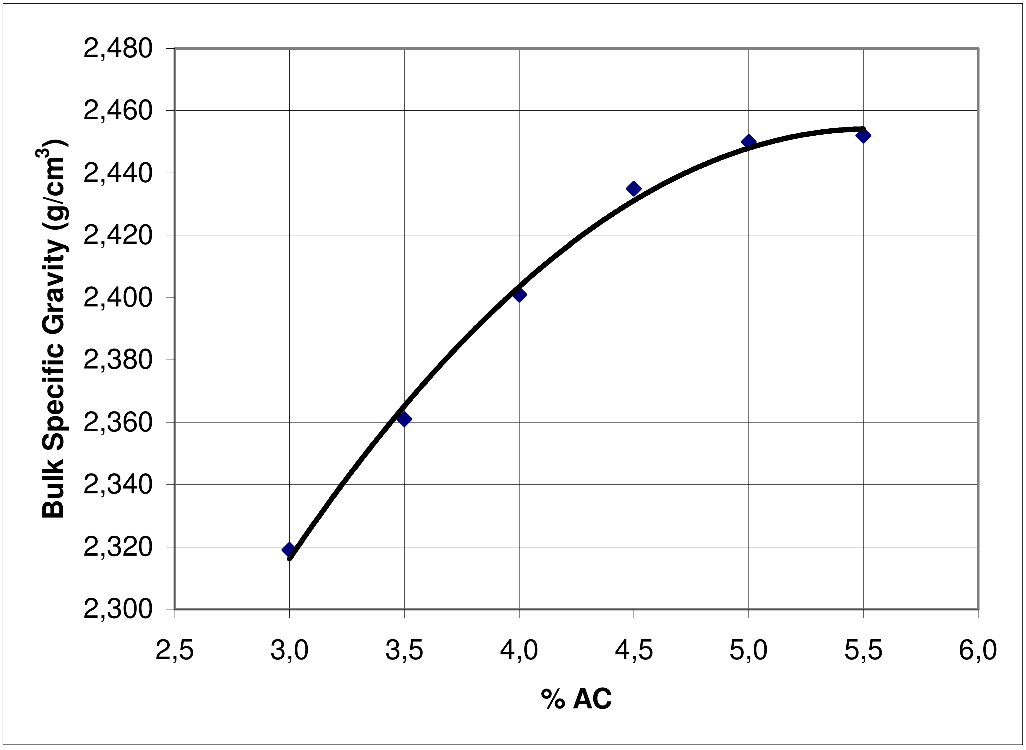

Figure 5.5 Bulk Specific Gravity vs. % AC Graph of Test 1

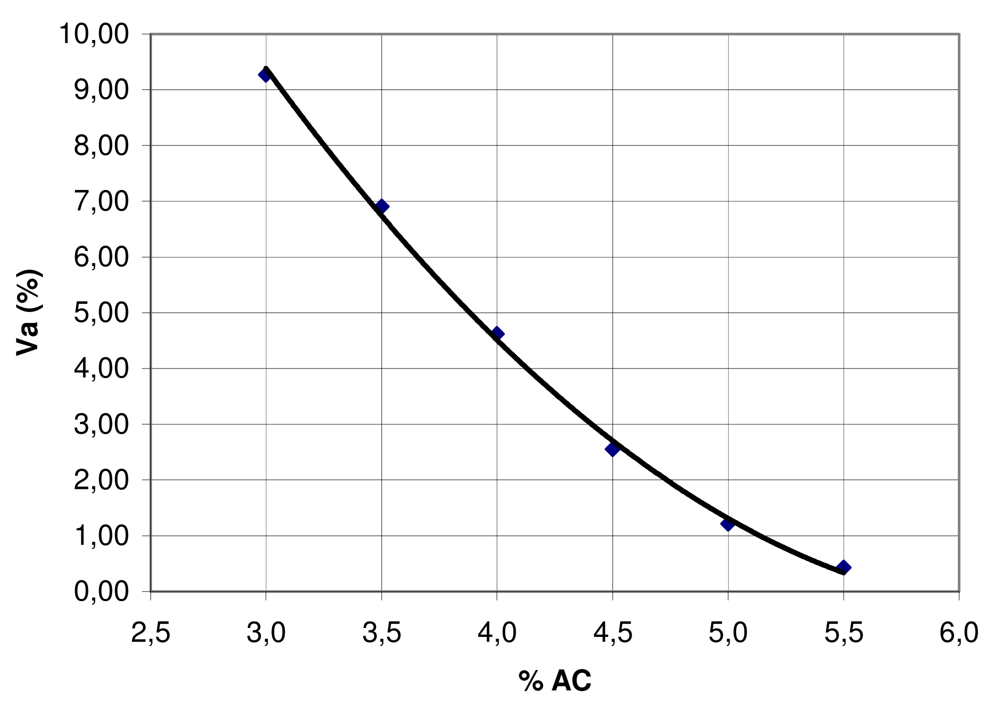

Figure 5.6 Air Voids vs. % AC Graph of Test 1

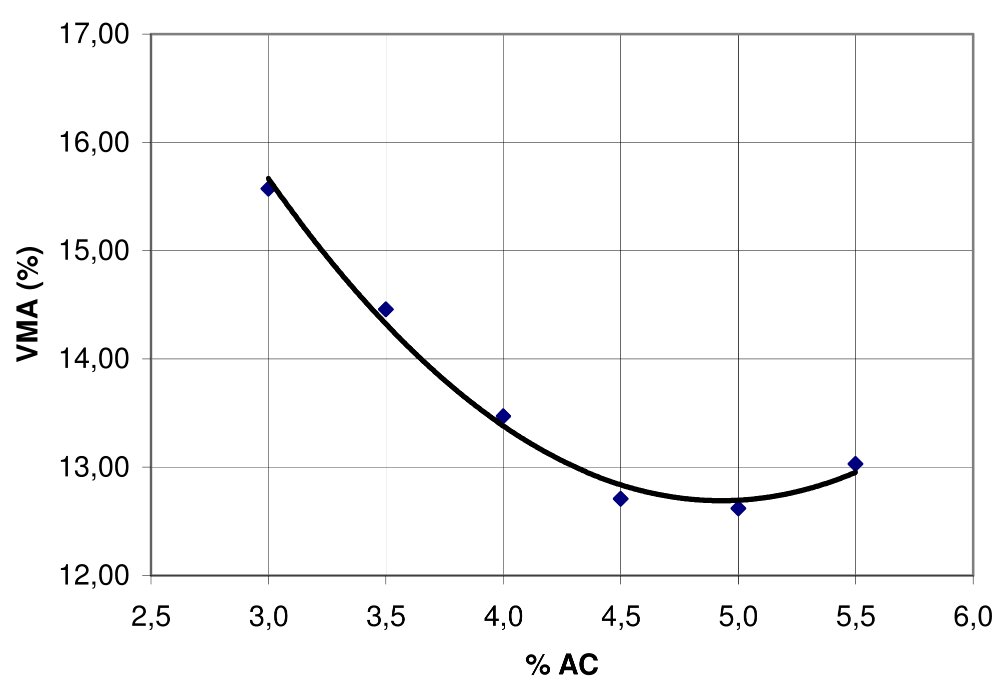

Figure 5.7 Voids in Mineral Aggregate (VMA) vs. % AC Graph of Test 1

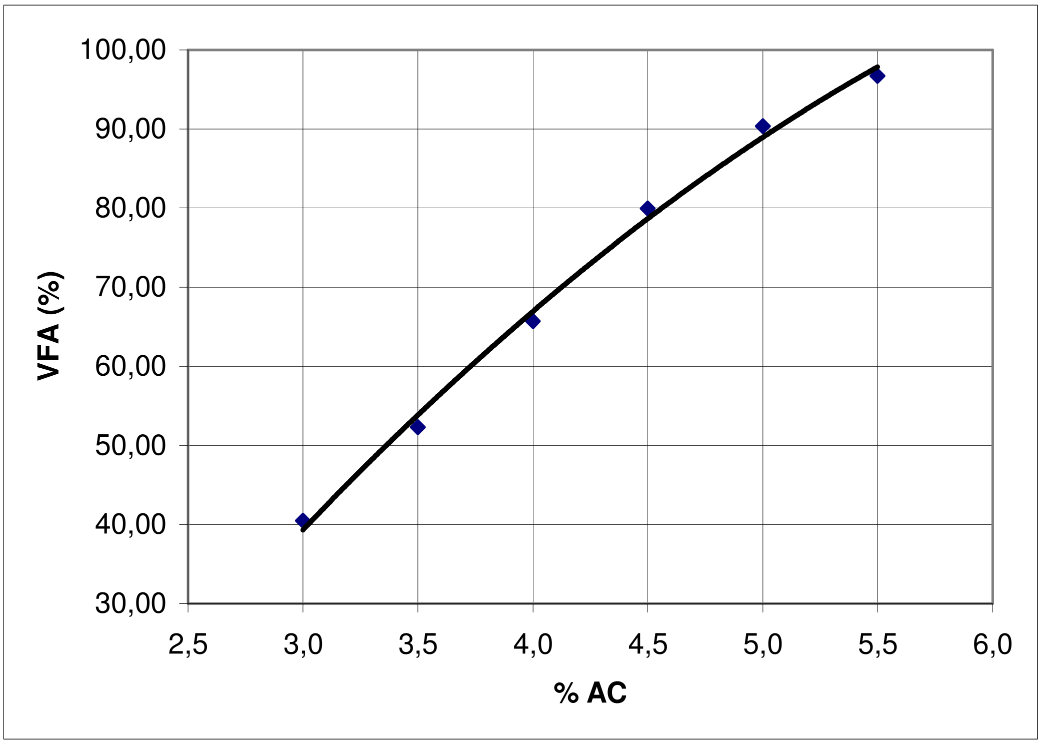

Figure 5.8 Voids Filled with Asphalt (VFA) vs. % AC Graph of Test 1

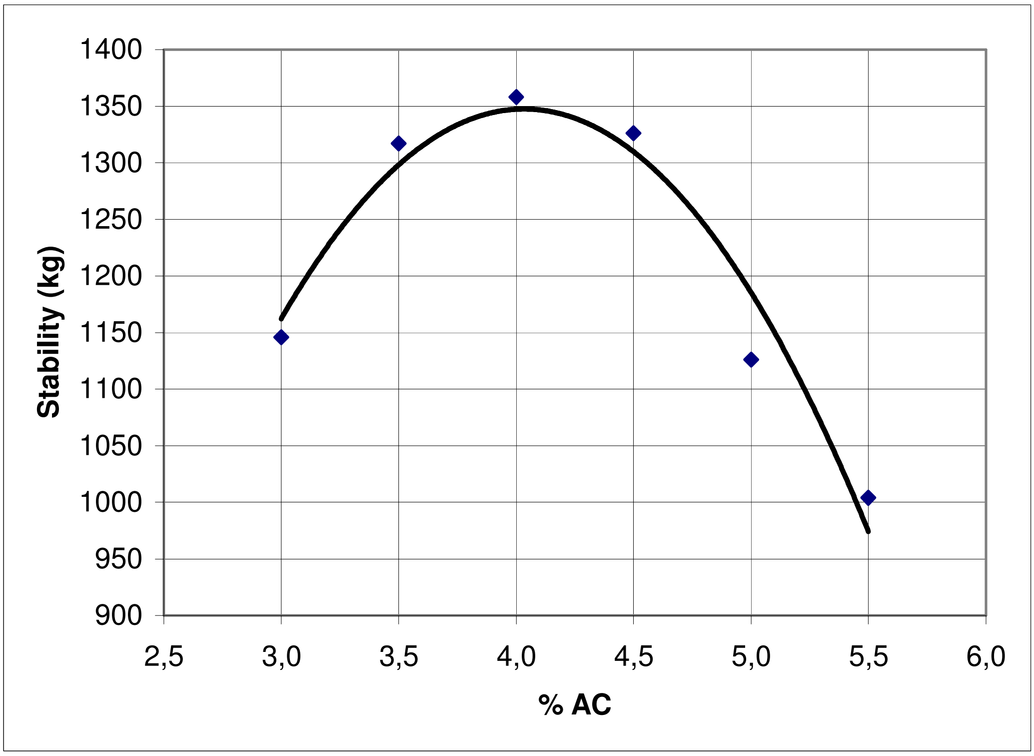

Figure 5.9 Stability vs. % AC Graph of Test 1

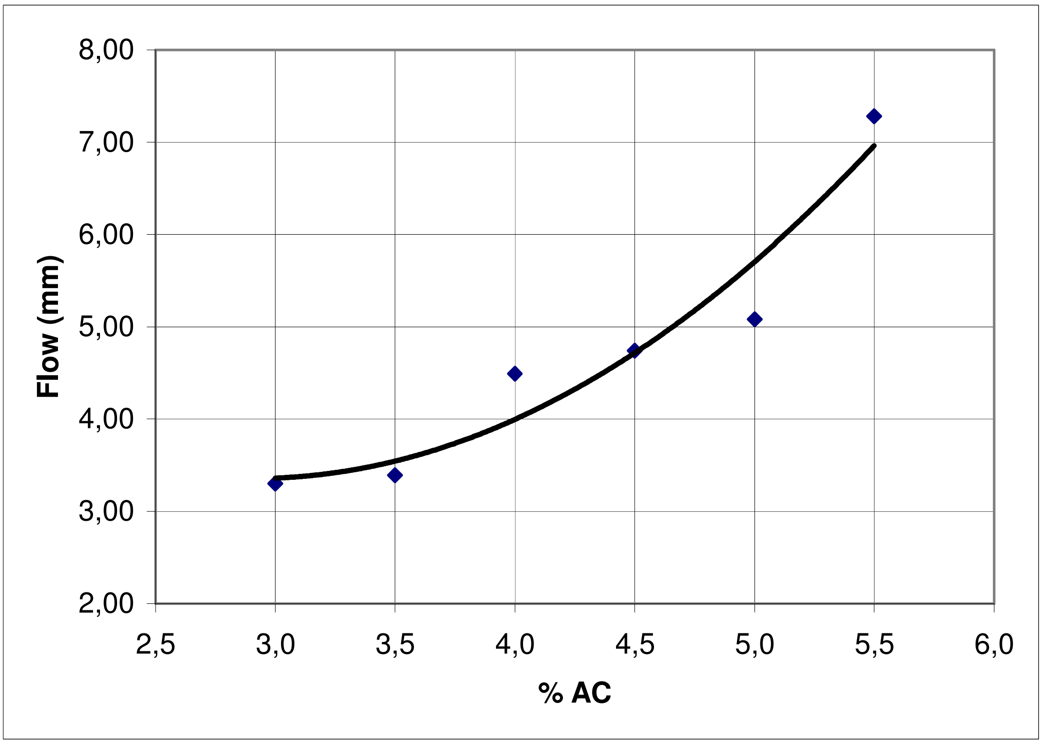

Figure 5.10 Flow vs. % AC Graph of Test 1

According to the test results, the asphalt contents can be found from maximum bulk specific gravity, 4 % air voids and maximum stability which are about 5.4 %, 4.2 % and 4 %, respectively. Therefore, the optimum asphalt content was found as about 4.55 %. The preliminary mix design results according to the optimum asphalt content are briefly shown in Table 5.9.

Table 5.9 The Mix Design Results of Test 1

Property	**Evaluation of Asphalt Content**
	4.55 % AC
Bulk Specific Gravity (g/cm^3)	2.435
Air Voids (%)	2.50
VMA (%)	12.80
VFA (%)	79
Stability (kg)	1300
Flow (mm)	4.85

5.4.2 Test 2

Table 5.10 Specific Gravity Results of Test 2

Asphalt Content (%)	Sample No.	W_D (g)	W_{sub} (g)	W_{SSD} (g)	G_{mb} (g/cm^3)	G_{mb} (g/cm^3) (Avr.)
3,5	1	1236,2	693,9	1237,4	2,275	2,271
	2	1235,1	692,0	1236,8	2,267	
	3	1237,8	695,5	1240,2	2,272	
4,0	1	1239,2	706,3	1241,9	2,314	2,309
	2	1243,5	705,9	1245,5	2,304	
	3	1244,1	708,6	1247,5	2,309	
4,5	1	1253,3	723,0	1256,8	2,348	2,369
	2	1254,7	727,5	1256,9	2,370	
	3	1254,0	731,4	1256,3	2,389	
5,0	1	1258,3	735,8	1259,5	2,403	2,399
	2	1259,8	734,9	1260,9	2,395	
	3	1258,6	734,3	1259,0	2,399	
5,5	1	1263,5	740,2	1264,2	2,411	2,408
	2	1265,6	740,4	1266,3	2,407	
	3	1266,8	741,1	1267,4	2,407	

Table 5.11 Volumetric Properties of Samples Used in Test 2

Asphalt Content (%)	**G_{mb} (g/cm^3) (Avr.)**	**G_{sb} (g/cm^3)**	**G_{sa} (g/cm^3)**	**G_{se} (g/cm^3)**	**P_b (%)**	**G_b (g/cm^3)**	**G_{mm} (g/cm^3)**	**Va (%)**	**VMA (%)**	**VFA (%)**
3,5	2,272	2,664	2,691	2,678	0,035	0,940	2,515	9,68	17,72	45,38
4,0	2,309	2,664	2,691	2,678	0,040	0,940	2,493	7,39	16,80	56,00
4,5	2,369	2,664	2,691	2,678	0,045	0,940	2,472	4,16	15,08	72,39
5,0	2,399	2,664	2,691	2,678	0,050	0,940	2,451	2,13	14,46	85,28
5,5	2,408	2,664	2,691	2,678	0,055	0,940	2,430	0,91	14,57	93,74

Table 5.12 Stability And Flow Results of Test 2

Asphalt Content (%)	Sample No.	Height of sample(cm)	Correlation Ratios	Stability (kg)	Corrected Stability (kg)	Corrected Stability (kg) (Avr.)	Flow (mm)	Flow (mm) (Avr.)
3,5	1	6,70	0.918	975	895	896	4,83	4,91
	2	6,70	0.918	953	875		4,83	
	3	6,70	0.918	1000	918		5,08	
4,0	1	6,60	0.940	1205	1133	1057	5,84	5,17
	2	6,60	0.940	1068	1004		4,83	
	3	6,60	0.940	1101	1035		4,83	
4,5	1	6,50	0.962	1068	1027	1193	5,59	5,08
	2	6,50	0.962	1290	1241		4,83	
	3	6,50	0.962	1364	1312		4,83	
5,0	1	6,40	0.988	1523	1505	1459	6,35	6,18
	2	6,40	0.988	1413	1396		6,86	
	3	6,45	0.975	1513	1475		5,33	
5,5	1	6,40	0.988	1296	1280	1173	5,84	5,67
	2	6,45	0.975	1114	1086		5,84	
	3	6,45	0.975	1183	1153		5,33	

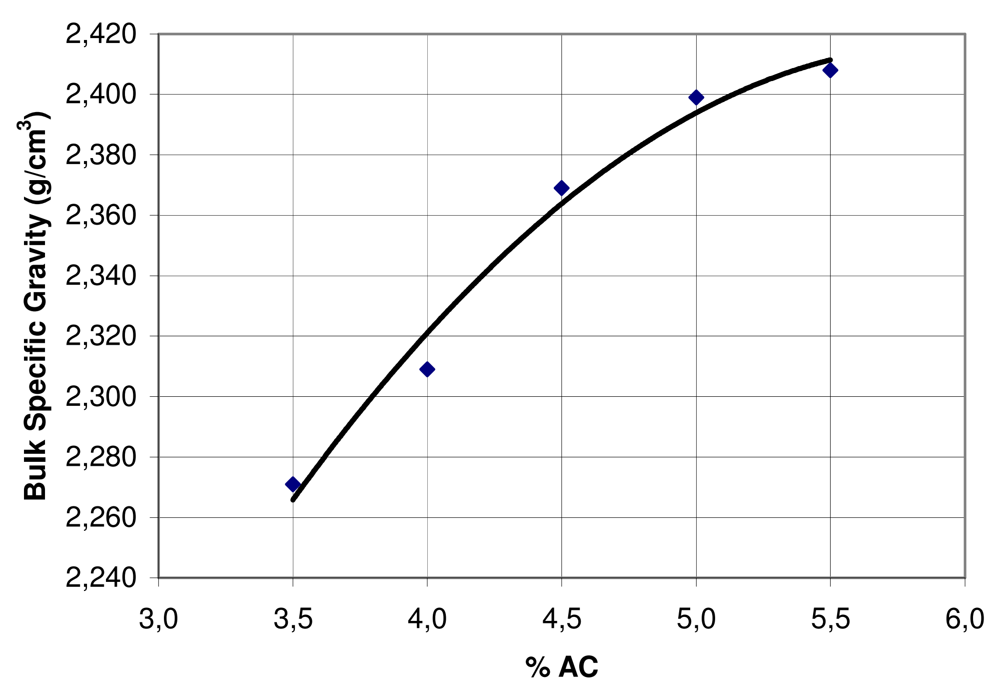

Figure 5.11 Bulk Specific Gravity vs. % AC Graph of Test 2

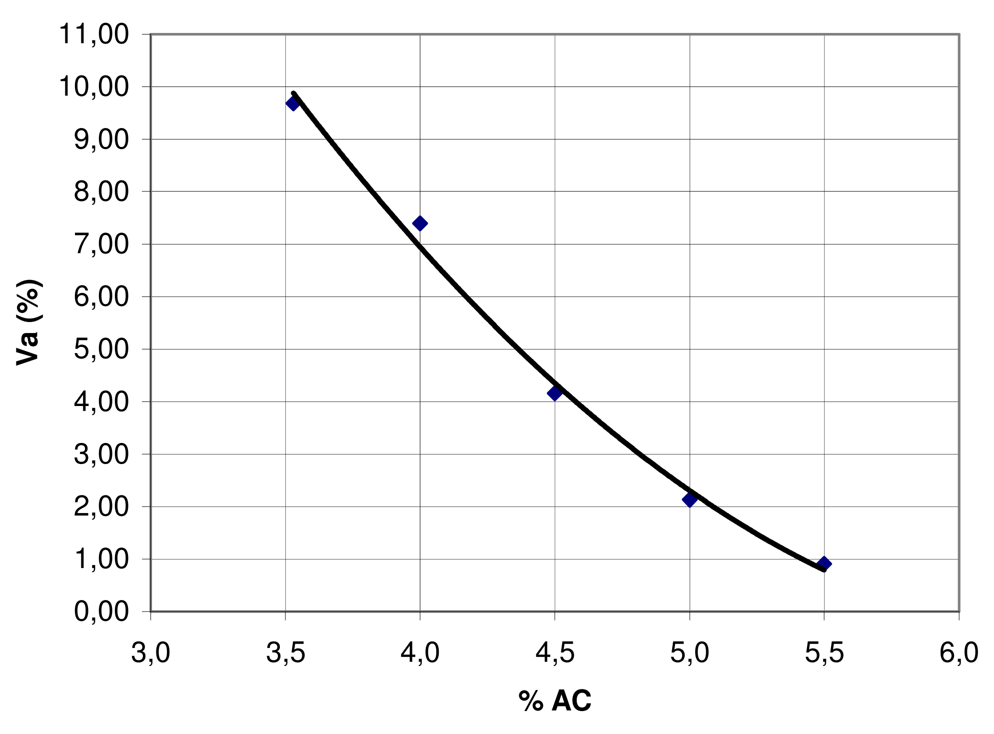

Figure 5.12 Air Voids vs. % AC Graph of Test 2

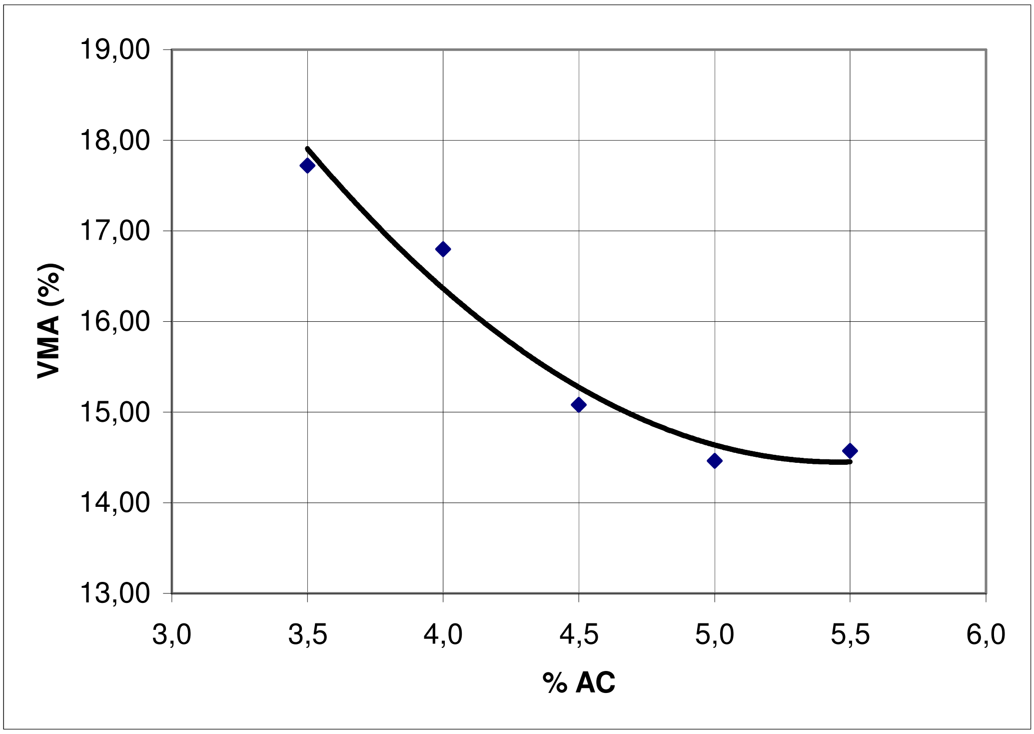

Figure 5.13 Voids in Mineral Aggregate (VMA) vs. % AC Graph of Test 2

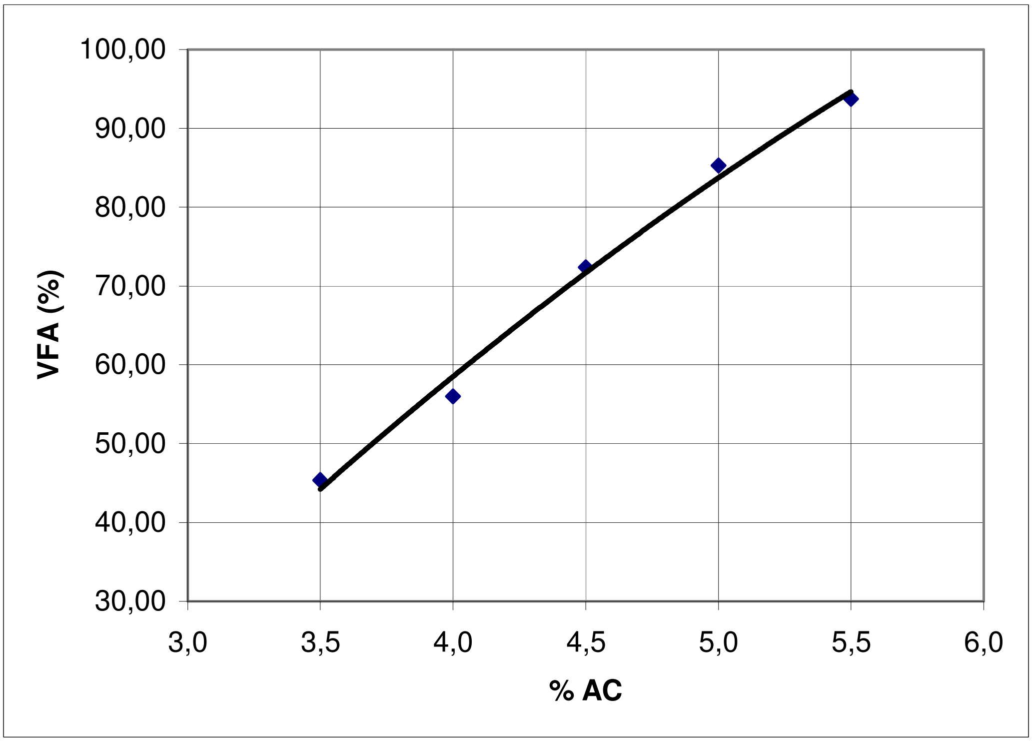

Figure 5.14 Voids Filled with Asphalt (VFA) vs. % AC Graph of Test 2

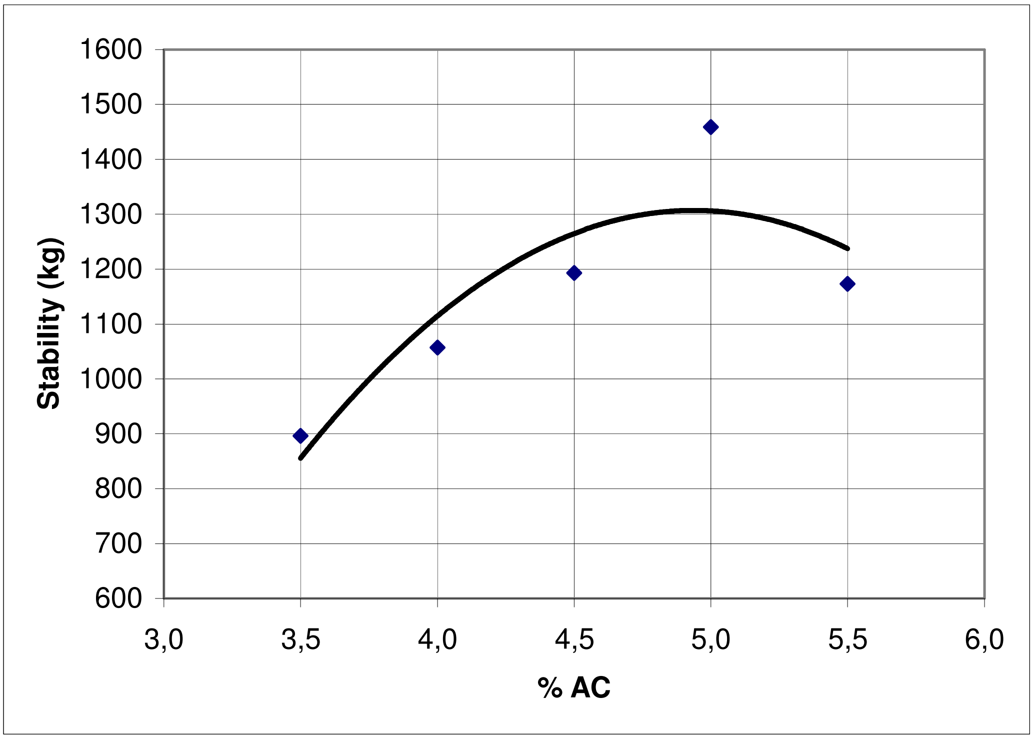

Figure 5.15 Stability vs. % AC Graph of Test 2

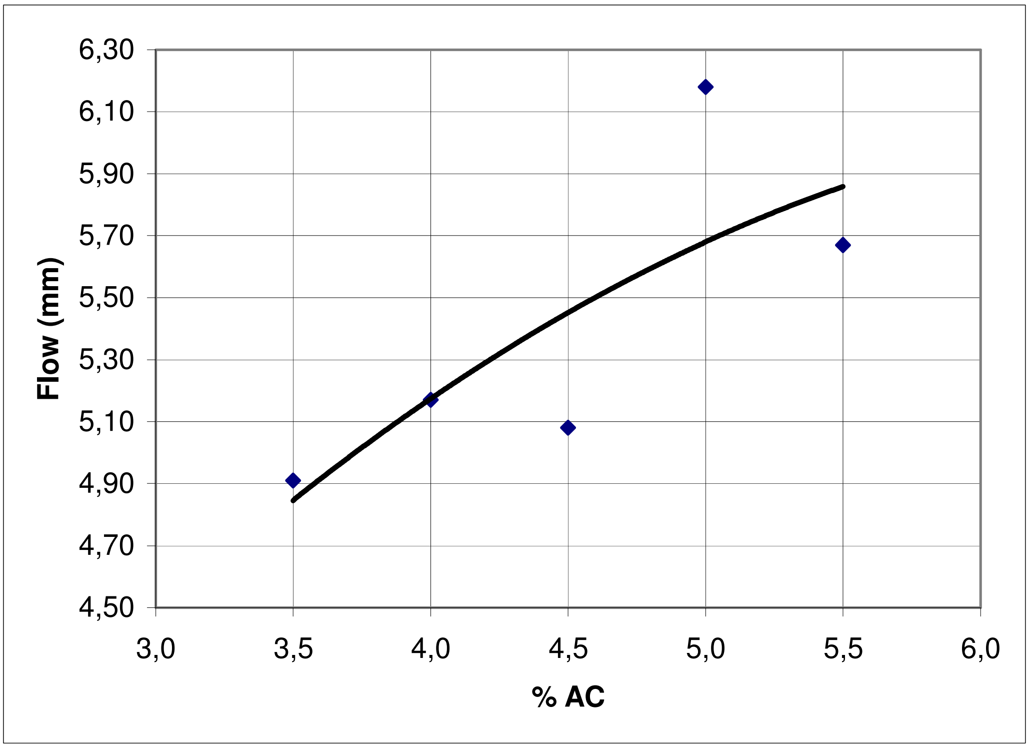

Figure 5.16 Flow vs. % AC Graph of Test 2

According to the test results, the asphalt contents can be found from maximum bulk specific gravity, 4 % air voids and maximum stability which are about 5.35 %, 4.6 % and 4.9 %, respectively. Therefore, the optimum asphalt content was found as 4.95 %. The preliminary mix design results according to the optimum asphalt content are briefly shown in Table 5.13.

Table 5.13 The Mix Design Results of Test 2

Property	**Evaluation of Asphalt Content**
	4.95 % AC
Bulk Specific Gravity (g/cm^3)	2.393
Air Voids (%)	2.30
VMA (%)	14.70
VFA (%)	83
Stability (kg)	1310
Flow (mm)	5.67

5.4.3 Test 3

Table 5.14 Specific Gravity Results of Test 3

Asphalt Content (%)	**Sample No.**	**W_D (g)**	**W_{sub} (g)**	**W_{SSD} (g)**	**G_{mb} (g/cm^3)**	**G_{mb} (g/cm^3) (Avr.)**
3,5	1	1239,9	681,8	1245,4	2,200	2,192
	2	1238,1	671,2	1241,6	2,171	
	3	1240,0	680,6	1242,6	2,206	
4,0	1	1249,4	703,3	1251,8	2,278	2,257
	2	1247,1	694,7	1250,1	2,245	
	3	1245,2	694,5	1248,2	2,249	
4,5	1	1261,9	715,7	1264,6	2,299	2,294
	2	1254,8	711,2	1259,2	2,290	
	3	1256,5	711,0	1258,6	2,295	
5,0	1	1265,4	727,7	1266,9	2,347	2,346
	2	1263,0	726,6	1265,1	2,345	
	3	1262,7	726,2	1264,6	2,345	
5,5	1	1271,1	733,5	1271,9	2,361	2,367
	2	1275,6	738,0	1276,2	2,370	
	3	1270,1	734,6	1270,7	2,369	

Table 5.15 Volumetric Properties of Samples Used in Test 3

Asphalt Content (%)	**G_{mb} (g/cm^3) (Avr.)**	**G_{sb} (g/cm^3)**	**G_{sa} (g/cm^3)**	**G_{se} (g/cm^3)**	**P_b (%)**	**G_b (g/cm^3)**	**G_{mm} (g/cm^3)**	**Va (%)**	**VMA (%)**	**VFA (%)**
3,5	2,192	2,664	2,691	2,678	0,035	0,875	2,497	12,22	20,59	40,65
4,0	2,257	2,664	2,691	2,678	0,040	0,875	2,474	8,74	18,65	53,12
4,5	2,294	2,664	2,691	2,678	0,045	0,875	2,450	6,36	17,75	64,15
5,0	2,346	2,664	2,691	2,678	0,050	0,875	2,427	3,36	16,35	79,43
5,5	2,367	2,664	2,691	2,678	0,055	0,875	2,405	1,59	16,05	90,08

Table 5.16 Stability And Flow Results of Test 3

Asphalt Content (%)	Sample No.	Height of sample(cm)	Correlation Ratios	Stability (kg)	Corrected Stability (kg)	Corrected Stability (kg) (Avr.)	Flow (mm)	Flow (mm) (Avr.)
3,5	1	6,80	0.894	1136	1016	1056	4,57	4,74
	2	6,85	0.885	977	865		4,32	
	3	6,85	0.885	1455	1288		5,33	
4,0	1	6,70	0.918	1751	1607	1384	4,82	5,33
	2	6,75	0.906	1496	1355		5,59	
	3	6,70	0.918	1295	1189		5,59	
4,5	1	6,65	0.930	1329	1236	1308	5,59	5,67
	2	6,65	0.930	1402	1304		5,84	
	3	6,65	0.930	1488	1384		5,59	
5,0	1	6,55	0.951	1477	1405	1393	6,10	5,84
	2	6,55	0.951	1424	1354		6,35	
	3	6,50	0.962	1477	1421		5,08	
5,5	1	6,55	0.951	1364	1297	1223	6,10	6,10
	2	6,55	0.951	1229	1169		6,35	
	3	6,50	0.962	1250	1203		5,84	

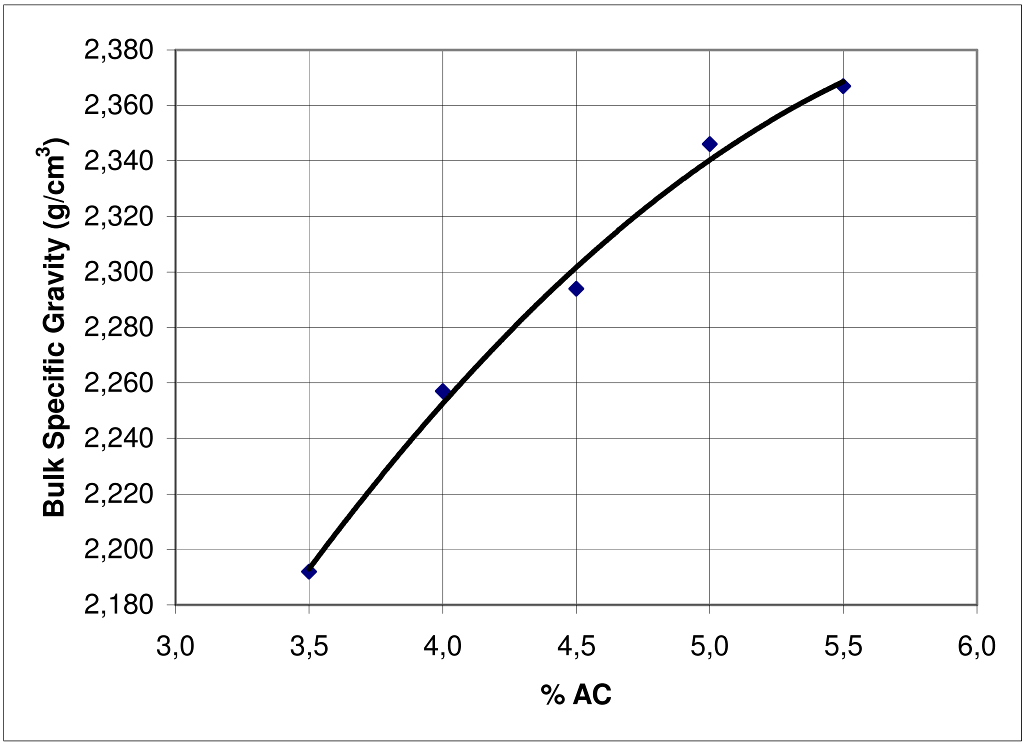

Figure 5.17 Bulk Specific Gravity vs. % AC Graph of Test 3

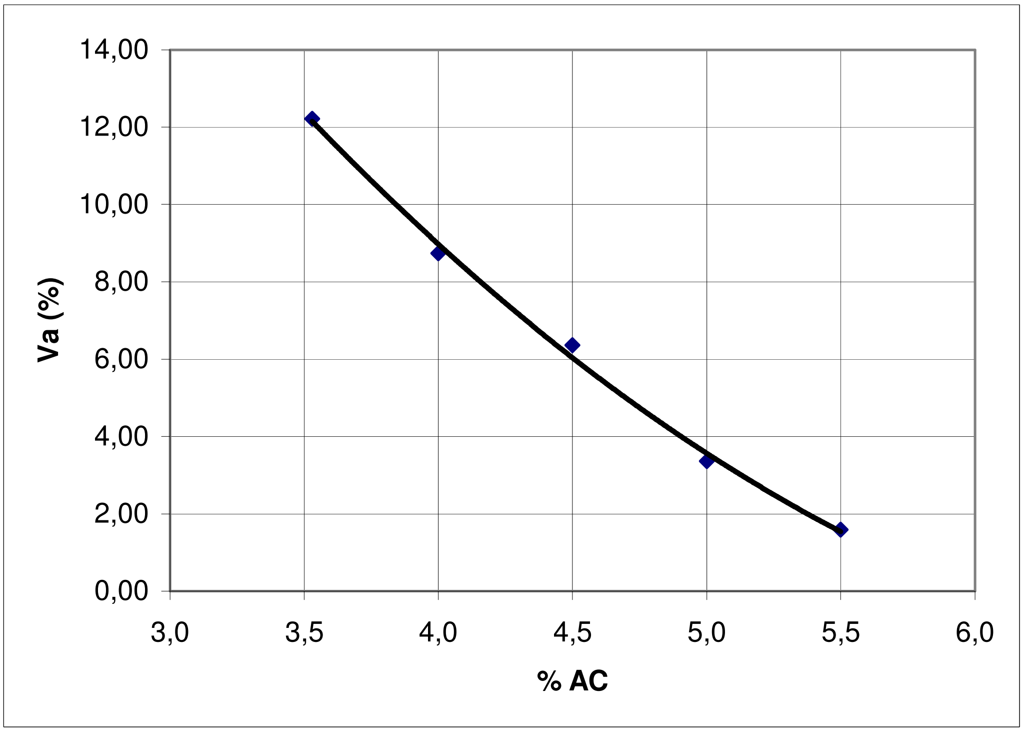

Figure 5.18 Air Voids vs. % AC Graph of Test 3

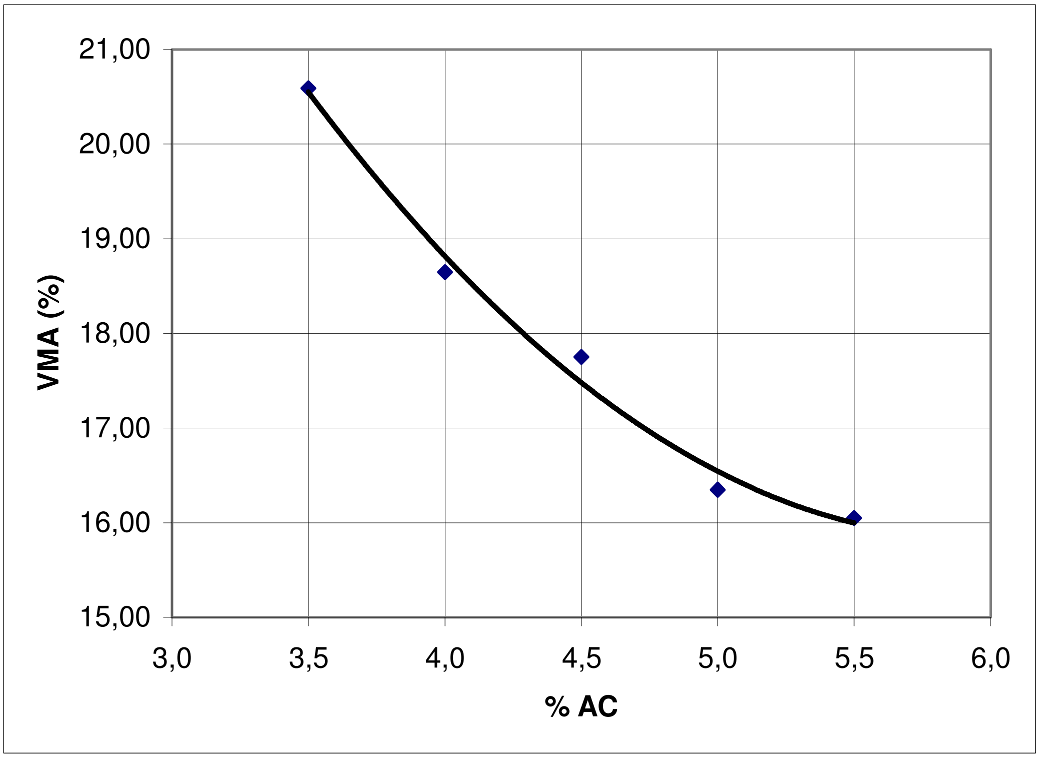

Figure 5.19 Voids in Mineral Aggregate (VMA) vs. % AC Graph of Test 3

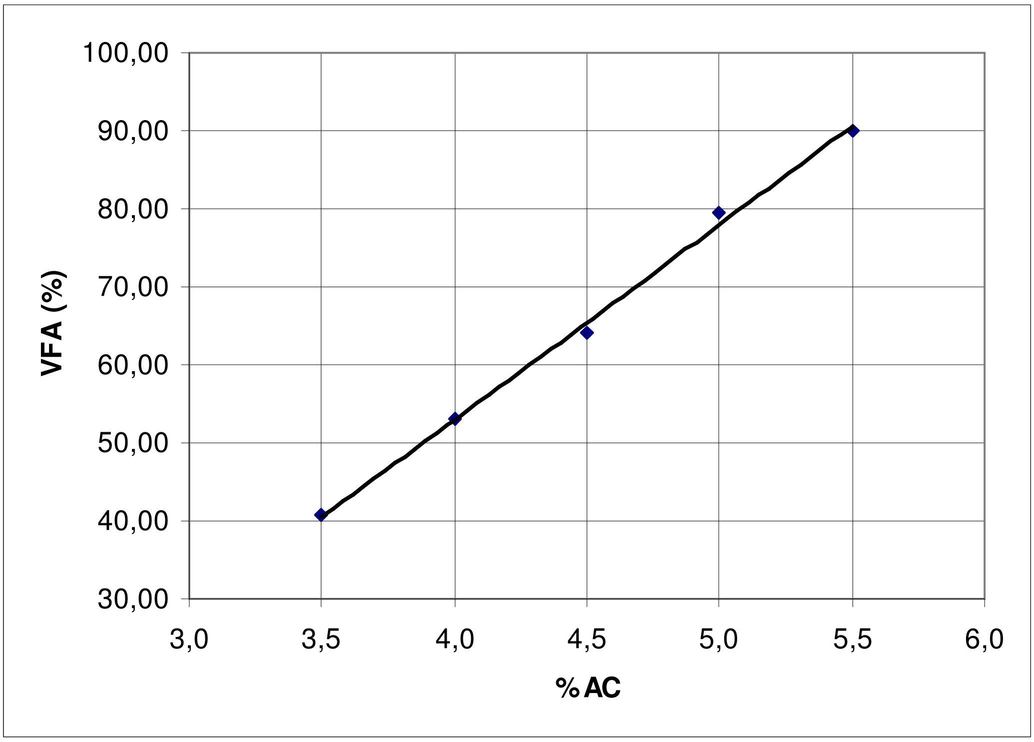

Figure 5.20 Voids Filled with Asphalt (VFA) vs. % AC Graph of Test 3

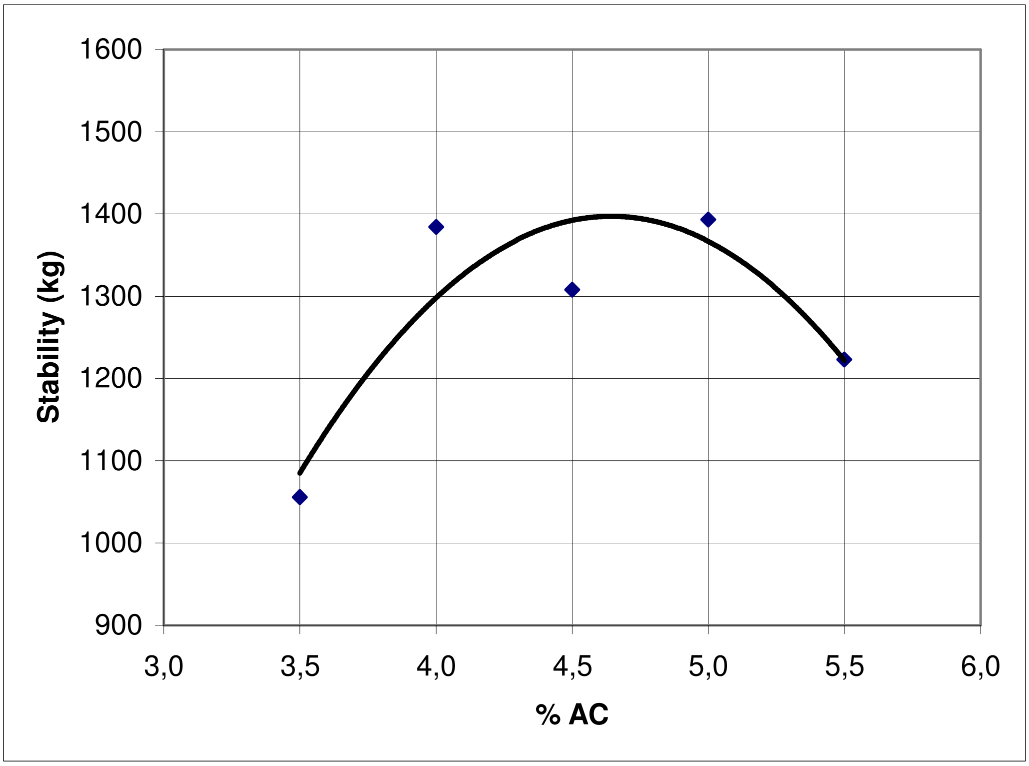

Figure 5.21 Stability vs. % AC Graph of Test 3

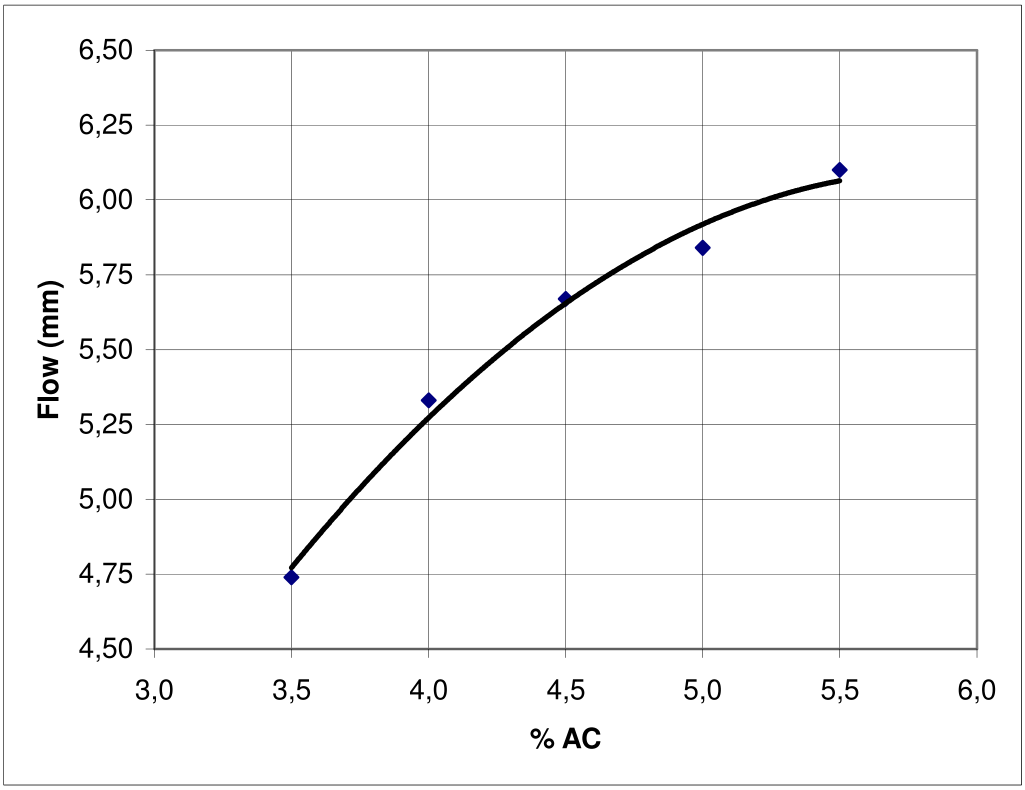

Figure 5.22 Flow vs. % AC Graph of Test 3

According to the test results, the asphalt contents can be found from maximum bulk specific gravity, 4 % air voids and maximum stability which are about 5.5 %, 4.9 % and 4.7 %, respectively. Therefore, the optimum asphalt content was found as about 5.05 %. The preliminary mix design results according to the optimum asphalt content are briefly shown in Table 5.17.

Table 5.17 The Mix Design Results of Test 3

Property	**Evaluation of Asphalt Content**
	5.05 % AC
Bulk Specific Gravity (g/cm^3)	2.342
Air Voids (%)	3.0
VMA (%)	16.45
VFA (%)	79
Stability (kg)	1360
Flow (mm)	5.90

5.4.4 Test 4

Table 5.18 Specific Gravity Results of Test 4

Asphalt Content (%)	**Sample No.**	**W$_D$ (g)**	**W$_{sub}$ (g)**	**W$_{SSD}$ (g)**	**G$_{mb}$ (g/cm^3)**	**G$_{mb}$ (g/cm^3) (Avr.)**
5,0	1	1268,9	690,0	1277,2	2,161	2,187
	2	1266,2	695,8	1274,8	2,187	
	3	1269,5	700,1	1274,0	2,212	
5,5	1	1272,5	707,1	1278,4	2,227	2,227
	2	1276,2	712,8	1281,3	2,245	
	3	1273,9	704,2	1280,6	2,210	
6,0	1	1281,2	728,5	1282,9	2,311	2,305
	2	1276,3	722,8	1278,0	2,299	
	3	1279,5	725,6	1280,9	2,304	
6,5	1	1284,4	731,1	1285,1	2,318	2,308
	2	1286,1	728,7	1287,0	2,304	
	3	1284,5	729,0	1286,9	2,302	
7,0	1	1295,8	738,6	1296,4	2,323	2,310
	2	1286,4	727,5	1287,9	2,296	
	3	1287,1	730,9	1288,0	2,310	

Table 5.19 Volumetric Properties of Samples Used in Test 4

Asphalt Content (%)	**G_{mb} (g/cm^3) (Avr.)**	**G_{sb} (g/cm^3)**	**G_{sa} (g/cm^3)**	**G_{se} (g/cm^3)**	**P_b (%)**	**G_b (g/cm^3)**	**G_{mm} (g/cm^3)**	**Va (%)**	**VMA (%)**	**VFA (%)**
5,0	2,187	2,664	2,691	2,678	0,050	0,828	2,409	9,21	22,02	58,17
5,5	2,227	2,664	2,691	2,678	0,055	0,828	2,385	6,59	20,99	68,60
6,0	2,305	2,664	2,691	2,678	0,060	0,828	2,361	2,39	18,68	87,21
6,5	2,308	2,664	2,691	2,678	0,065	0,828	2,338	1,15	18,88	93,92
7,0	2,310	2,664	2,691	2,678	0,070	0,828	2,315	0,25	19,37	98,70

Table 5.20 Stability And Flow Results of Test 4

Asphalt Content (%)	Sample No.	Height of sample(cm)	Correlation Ratios	Stability (kg)	Corrected Stability (kg)	Corrected Stability (kg) (Avr.)	Flow (mm)	Flow (mm) (Avr.)
5,0	1	7,10	0.836	1118	935	922	7,87	7,87
	2	7,00	0.856	1023	876		7,87	
	3	6,90	0.875	1091	955		7,87	
5,5	1	6,90	0.875	1136	994	974	8,13	8,04
	2	6,95	0.866	1091	945		7,87	
	3	6,95	0.866	1136	984		8,13	
6,0	1	6,70	0.918	1341	1231	1178	7,87	8,07
	2	6,70	0.918	1251	1148		7,87	
	3	6,70	0.918	1258	1155		8,46	
6,5	1	6,70	0.918	1500	1377	1342	10,16	10,07
	2	6,75	0.906	1429	1295		10,41	
	3	6,70	0.918	1476	1355		9,65	
7,0	1	6,75	0.906	1224	1109	1117	11,43	10,58
	2	6,80	0.894	1227	1097		10,16	
	3	6,70	0.918	1247	1145		10,16	

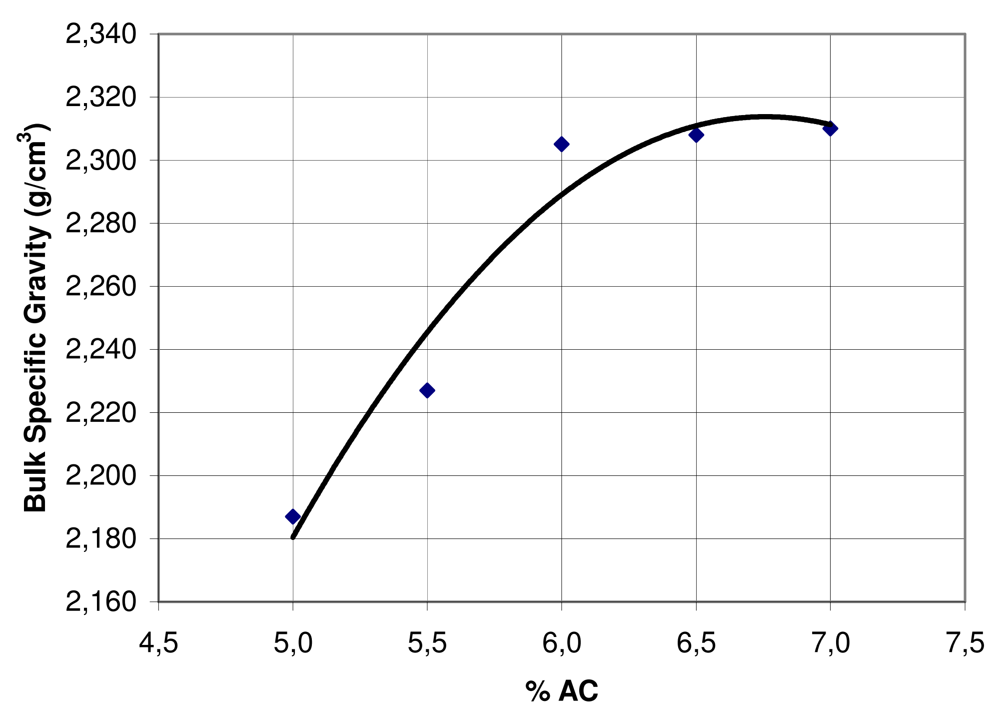

Figure 5.23 Bulk Specific Gravity vs. % AC Graph of Test 4

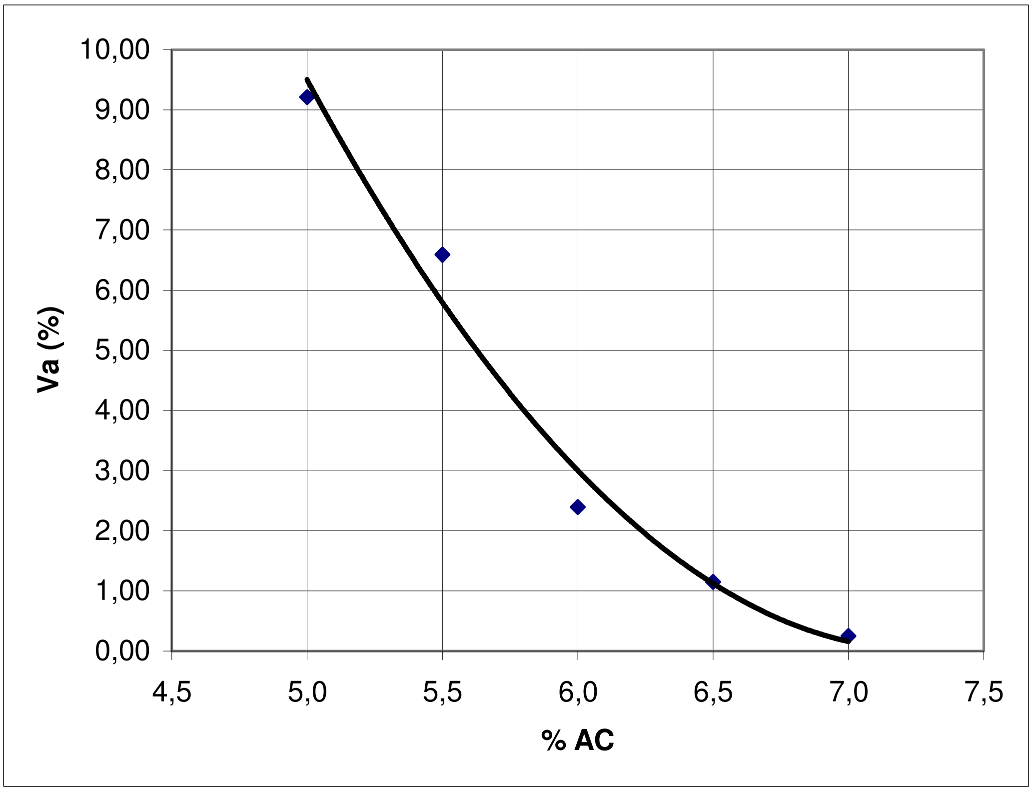

Figure 5.24 Air Voids vs. % AC Graph of Test 4

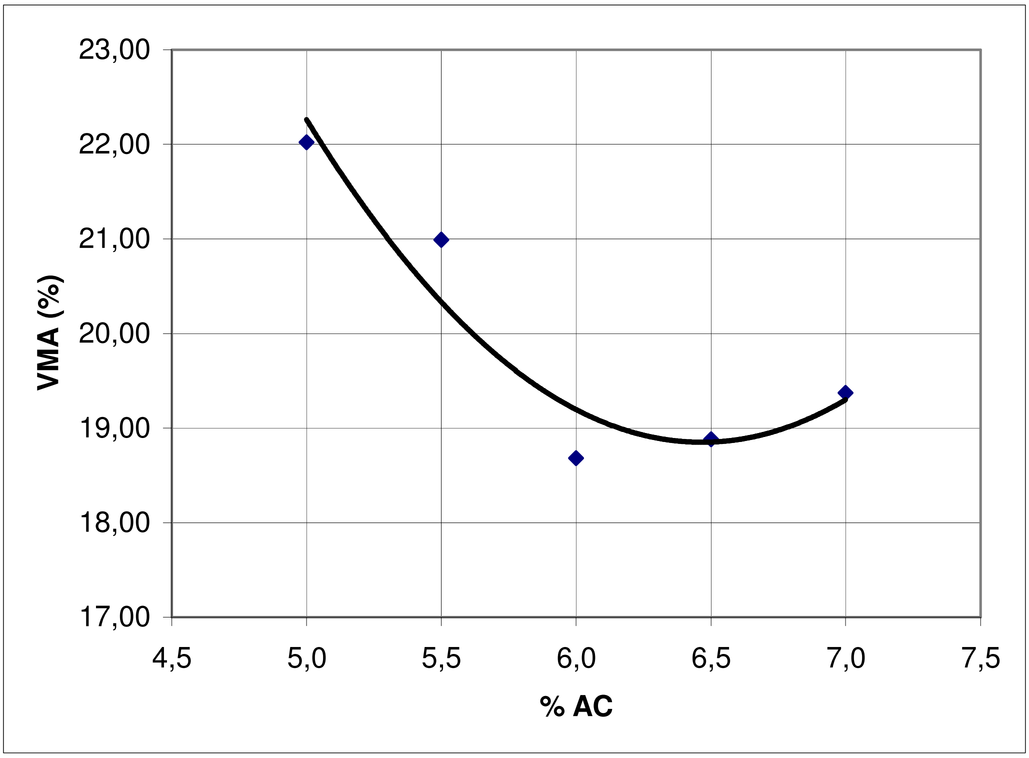

Figure 5.25 Voids in Mineral Aggregate (VMA) vs. % AC Graph of Test 4

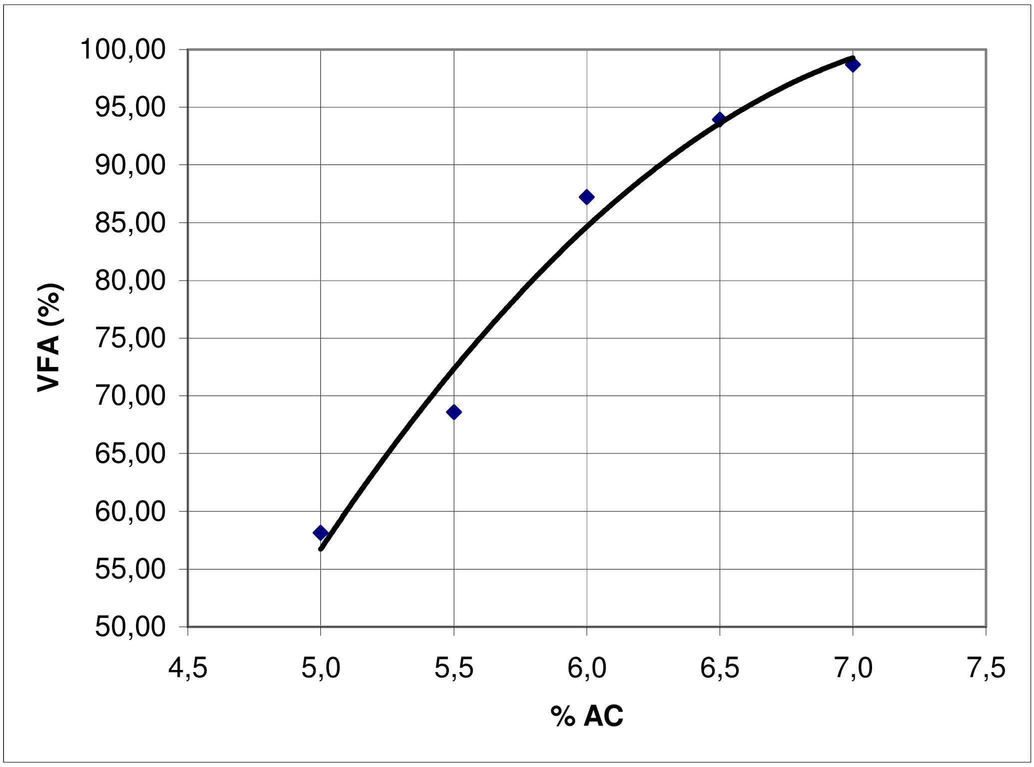

Figure 5.26 Voids Filled with Asphalt (VFA) vs. % AC Graph of Test 4

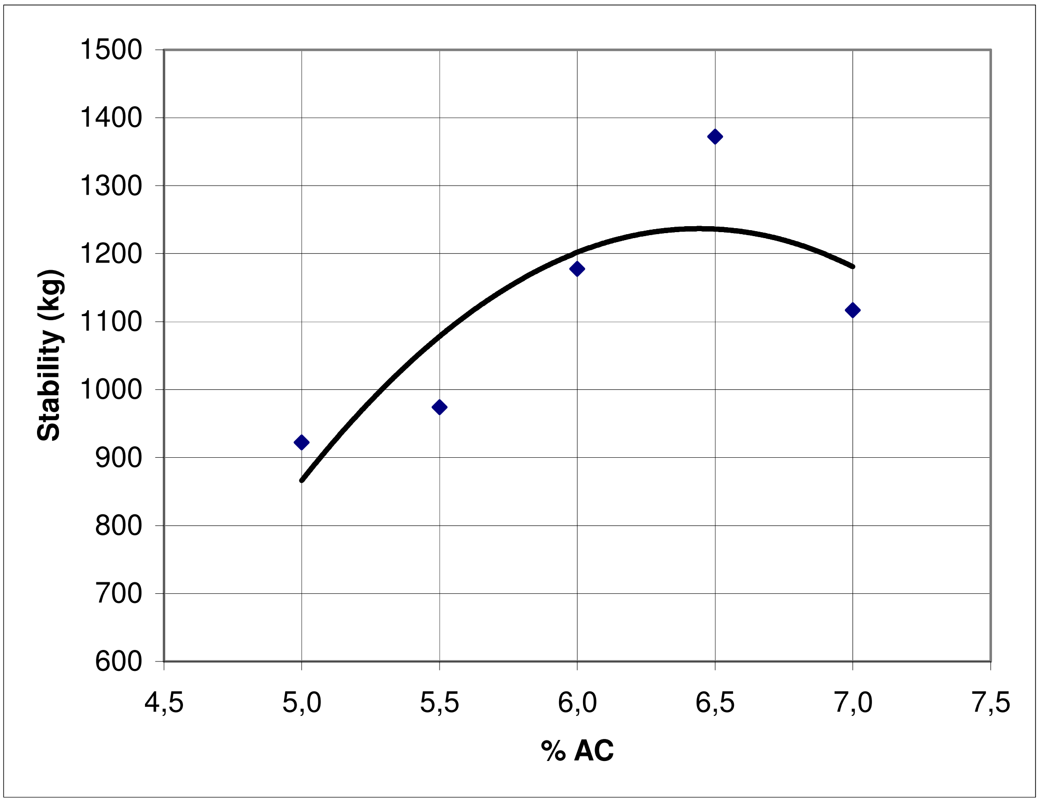

Figure 5.27 Stability vs. % AC Graph of Test 4

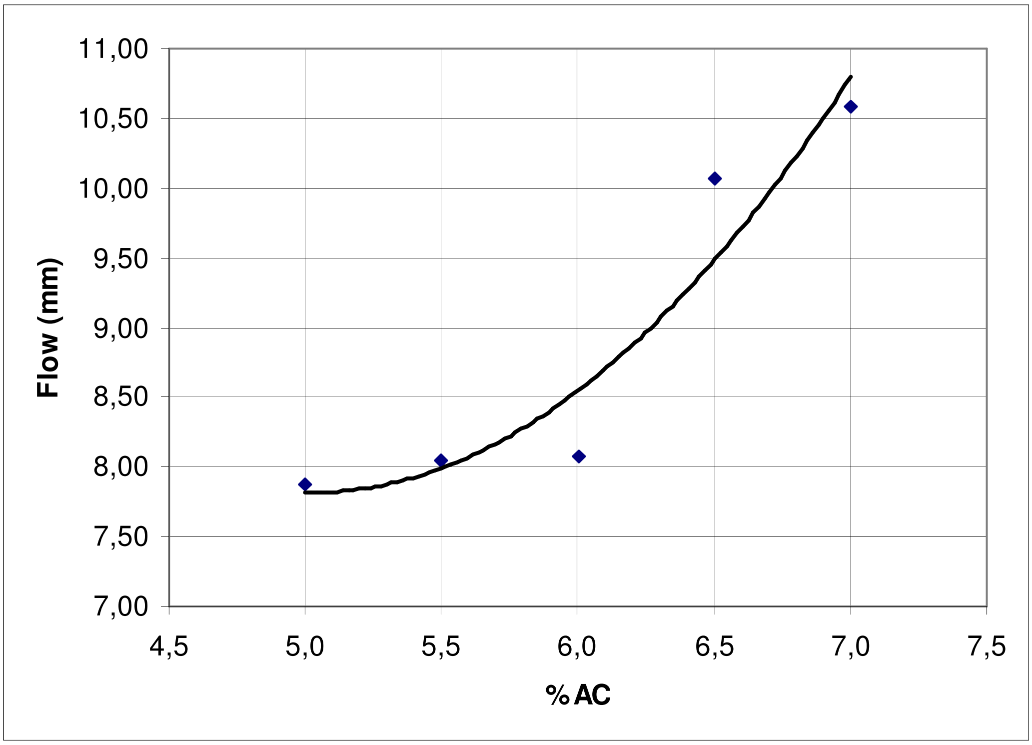

Figure 5.28 Flow vs. % AC Graph of Test 4

According to the test results, the asphalt contents can be found from maximum bulk specific gravity, 4 % air voids and maximum stability which are about 6.8 %, 5.8 % and 6.5 %, respectively. Therefore, the optimum asphalt content was found as about 6.4 %. The preliminary mix design results according to the optimum asphalt content are briefly shown in Table 5.21.

Table 5.21 The Mix Design Results of Test 4

Property	**Evaluation of Asphalt Content**
	6.4 % AC
Bulk Specific Gravity (g/cm^3)	2.310
Air Voids (%)	1.35
VMA (%)	18.85
VFA (%)	92
Stability (kg)	1240
Flow (mm)	9.30

According to the preliminary mix design results the optimum asphalt contents were found as 4.55 %, 4.95 %, 5.05 % and 6.4 % for Test 1, Test 2, Test 3 and Test 4, respectively. According to these optimum asphalt contents, final tests were done and resulted.

5.4.5 Final Tests

Table 5.22 Specific Gravity Results of Final Tests

Test No.	**Asphalt Content (%)**	**Sample No.**	**W_D (g)**	**W_{sub} (g)**	**W_{SSD} (g)**	**G_{mb} (g/cm^3)**	**G_{mb} (g/cm^3) (Avr.)**
Test 1	4,55	1	1249,6	736,5	1252,0	2,424	2,427
		2	1251,1	739,1	1252,5	2,437	
		3	1245,3	732,7	1247,2	2,420	
Test 2	4,95	1	1260,4	738,6	1261,2	2,412	2,405
		2	1257,1	731,7	1258,0	2,389	
		3	1256,6	736,8	1257,2	2,415	
Test 3	5,05	1	1260,3	722,8	1262,1	2,337	2,342
		2	1265,3	726,3	1267,7	2,337	
		3	1259,3	725,4	1260,5	2,353	
Test 4	6,40	1	1284,3	728,8	1287,8	2,297	2,296
		2	1283,1	726,3	1286,2	2,292	
		3	1285,6	729,0	1288,1	2,299	

Table 5.23 Volumetric Properties of Samples Used in Final Tests

Test No	**Asphalt Content (%)**	**G_{mb} (g/cm^3) (Avr.)**	**G_{sb} (g/cm^3)**	**G_{sa} (g/cm^3)**	**G_{se} (g/cm^3)**	**P_b (%)**	**G_b (g/cm^3)**	**G_{mm} (g/cm^3)**	**Va (%)**	**VMA (%)**	**VFA (%)**
Test 1	4,55	2,427	2,664	2,691	2,678	0,0455	1,034	2,497	2,80	13,04	78,56
Test 2	4,95	2,405	2,664	2,691	2,678	0,0495	0,940	2,453	1,96	14,09	86,20
Test 3	5,05	2,342	2,664	2,691	2,678	0,0505	0,875	2,425	3,41	16,51	79,34
Test 4	6,40	2,296	2,664	2,691	2,678	0,0640	0,828	2,343	1,98	19,32	89,75

Table 5.24 Stability And Flow Results of Final Tests

Test No	Asphalt Content (%)	Sample No.	Height of sample(cm)	Correlation Ratios	Stability (kg)	Corrected Stability (kg)	Corrected Stability (kg) (Avr.)	Flow (mm)	Flow (mm) (Avr.)
Test 1	4,55	1	6,40	0.988	1199	1185	1220	3,56	3,81
		2	6,40	0.988	1298	1282		4,06	
		3	6,35	1.000	1192	1192		3,81	
Test 2	4,95	1	6,45	0.975	1250	1219	1272	4,57	4,83
		2	6,45	0.975	1283	1251		4,83	
		3	6,40	0.988	1361	1345		5,08	
Test 3	5,05	1	6,55	0.951	1455	1384	1343	5,59	5,17
		2	6,55	0.951	1417	1348		5,08	
		3	6,55	0.951	1364	1297		4,83	
Test 4	6,40	1	6,65	0.930	1480	1376	1348	9,65	9,30
		2	6,70	0.918	1414	1298		8,78	
		3	6,70	0.918	1492	1370		9,46	

5.5. Discussion of Test Results

According to the final tests results, some specific changes with respect to the modifier ratios were observed.

The optimum asphalt content of the compacted specimens were found as 4.55 % for conventional mixture (containing 0 % PPF-Test1), 4.95 % for asphalt mixture containing 0.3 % PPF (Test 2), 5.05 % for asphalt mixture containing 0.6 % PPF (Test 3) and 6.4 % for asphalt mixture containing 1 % PPF (Test 4). It can be seen from the test results that the optimum asphalt content increases when the addition of PPF in asphalt mixture increases. Also, according to the studies performed by Fortier and Vinson [13], and by White, Huang and Montgomery [33], the optimum asphalt content was increased because the fibers contribute to the total surface area of the mix. The changes of the optimum asphalt content in accordance with the tests are shown in Figure 5.29.

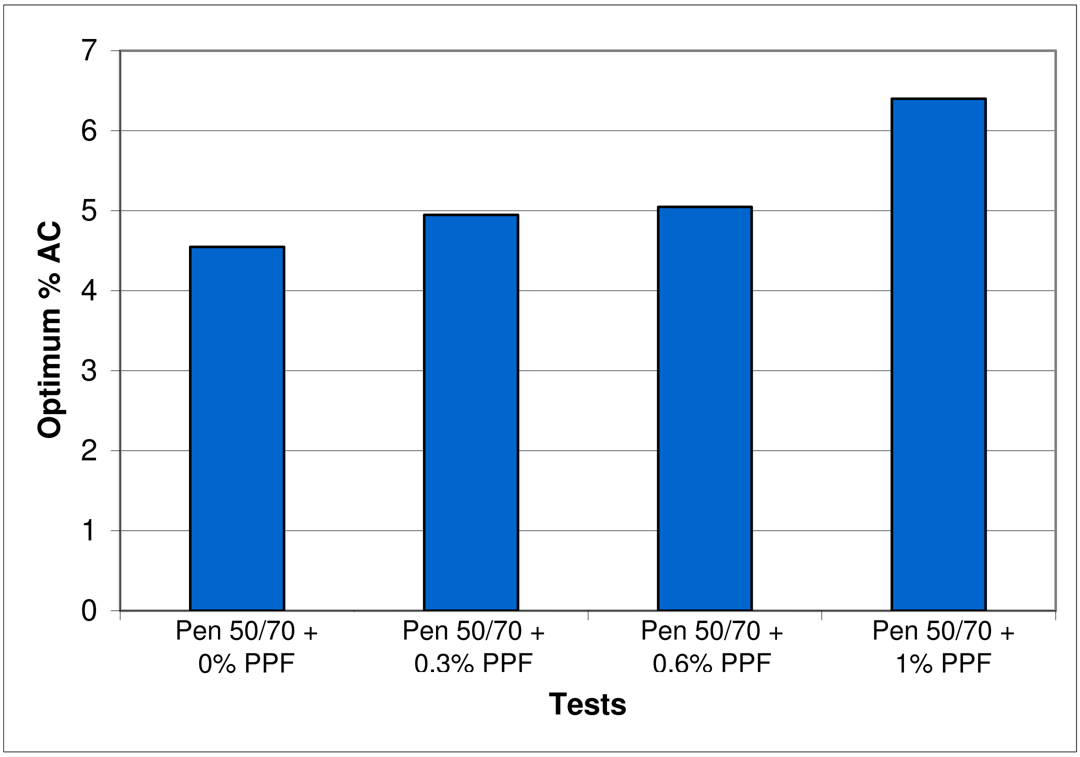

Figure 5.29 The changes of the optimum asphalt content in accordance with the tests

The bulk specific gravities of the compacted specimens were found as 2.427 g/cm^3 for conventional mixture (containing 0 % PPF-Test 1), 2.405 g/cm^3 for asphalt mixture containing 0.3 % PPF (Test 2), 2.342 g/cm^3 for asphalt mixture containing 0.6 % PPF (Test 3) and 2.296 g/cm^3 for asphalt mixture containing 1 % PPF (Test 4). It can be seen from the test results that the bulk specific gravity decreases when the addition of PPF in asphalt mixture increases. The reasons for the decrease of bulk specific gravity are lightness of PPF and the increase in volume of specimens depending on the increase of PPF. The changes of the bulk specific gravity in accordance with the tests are shown in Figure 5.30.

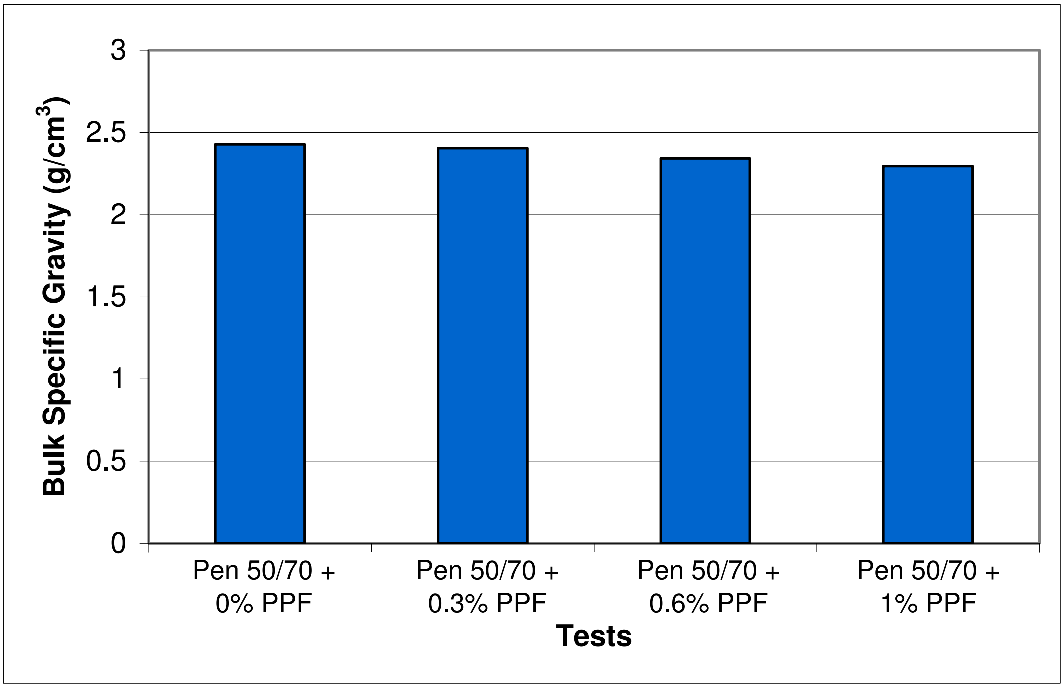

Figure 5.30 The changes of the bulk specific gravity in accordance with the tests

The stability values of the compacted specimens were measured as 1220 kg for conventional mixture (containing 0 % PPF-Test 1), 1272 kg for asphalt mixture containing 0.3 % PPF (Test 2), 1343 kg for asphalt mixture containing 0.6 % PPF (Test 3) and 1348 kg for asphalt mixture containing 1 % PPF (Test 4) by the stability tests. The changes of the stability values in accordance with the tests are shown in Figure 5.31.

The increase of stability values means the increase of load quantity that asphalt mixture can carry, so it shows that under a heavier vehicle load, asphalt mixture will expose to deformation lately.

These tests results show that the stability values slightly increase when the PPF ratio in asphalt mixture increases. The stability values increase about 4.3 %, 10.1 % and 10.5 % at asphalt mixture including 0.3 % PPF, 0.6 % PPF and 1 % PPF, respectively. According to these results, almost no changes were seen between the asphalt mixtures including 0.6 % PPF and 1 % PPF in terms of the stability values.

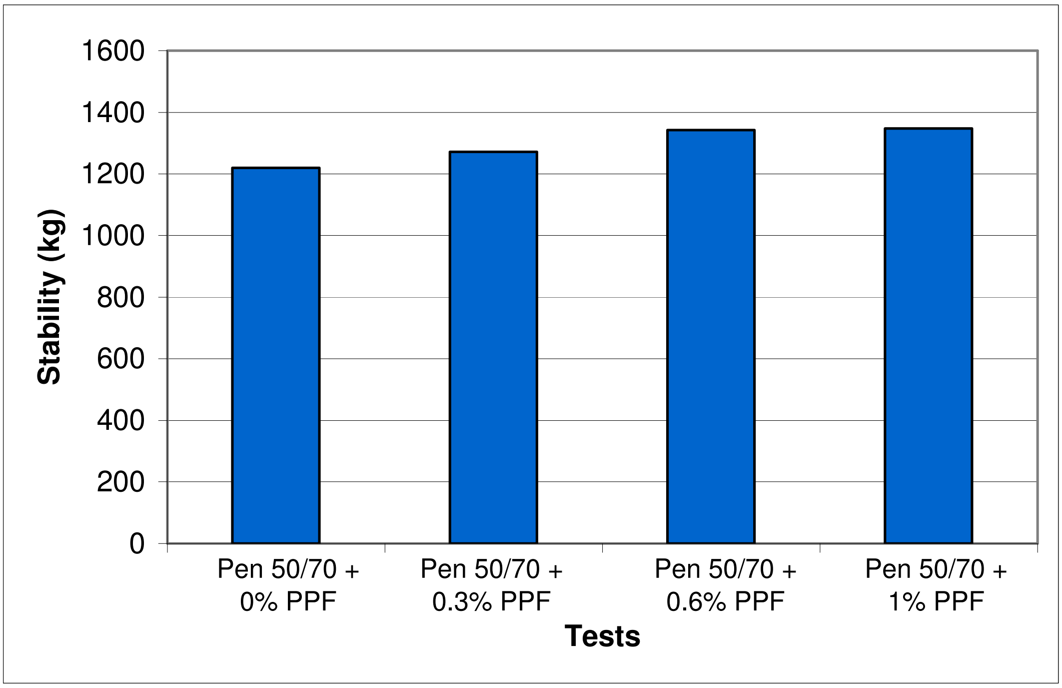

Figure 5.31 The changes of the stability values in accordance with the tests

The flow values of the compacted specimens were measured as 3.81 mm for conventional mixture (containing 0 % PPF-Test1), 4.83 mm for asphalt mixture containing 0.3 % PPF (Test 2), 5.17 mm for asphalt mixture containing 0.6 % PPF (Test 3) and 9.30 mm for asphalt mixture containing 1 % PPF (Test 4) by the flow tests. The changes of the flow values in accordance with the tests are shown in Figure 5.32.

These tests results show that the flow values highly increase according to the addition of PPF. The flow values increase about 26.8 %, 35.7 % and 144.1 % at asphalt mixture containing 0.3 % PPF, 0.6 % PPF and 1 % PPF, respectively. The increase of flow values may stem from the increase in volume of specimens depending on the addition of PPF. Flow can be explained as the deformation of asphalt concrete and it can be understood from the tests results that the polypropylene fibers increase the deformation capability of asphalt concretes.

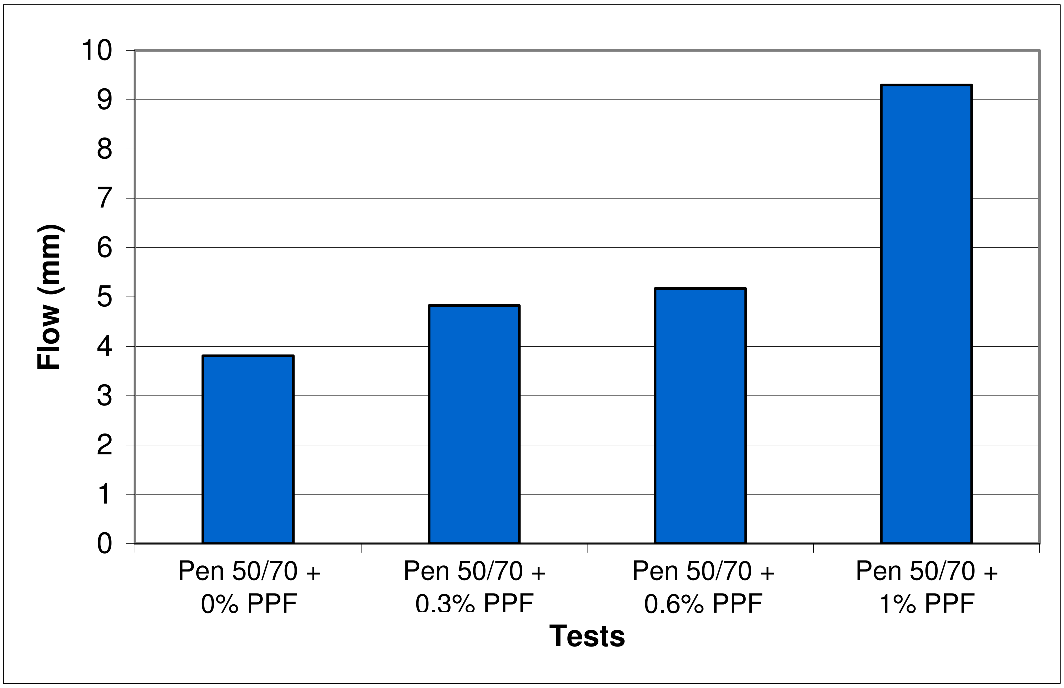

Figure 5.32 The changes of the flow values in accordance with the tests

When all of the test results are analyzed carefully, it can be observed that the asphalt mixture with 0.6 % PPF is more applicable and preferable than the other asphalt mixtures.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this thesis, the effect of the use of polyfibers on asphalt mixture properties was researched. Polyfiber (polypropylene fiber-PPF) with the length of 19 mm was applied in the experimental studies with the ranging of PPF in asphalt mixtures specified as 0.3 %, 0.6 % and 1 % by the total weight of the mixture. Marshall Mix Design Method was used to determine the optimum asphalt contents. Marshall specimens were prepared with a similar aggregate gradation of binder layer Type 1 as given in the manual of the General Directorate of Highways of Turkey. 50/70 penetration bitumen was used in all the experiments at 143 ˚C mixing temperature. Stability and flow tests were conducted on these specimens.

According to the test results obtained from the laboratory studies, the following conclusions can be drawn:

- The optimum asphalt content of asphalt mixtures increases when the percentage of PPF in asphalt mixture increases.

- The bulk specific gravity of asphalt mixtures decreases when the percentage of PPF in asphalt mixture increases. This seems to be due to the increase in volume of the modified mixtures.

- Addition of PPF into asphalt mixtures increase the stability values approximately 4.3 %, 10.1 % and 10.5 % for asphalt mixtures containing 0.3 % PPF, 0.6 % PPF and 1 % PPF, respectively. There was not much difference for the stability values of asphalt mixtures containing 0.6 % PPF and 1 % PPF by weight of the mixtures.

- Addition of PPF also increases the flow values of mixtures. Results indicated that the flow increases approximately 26.8 %, 35.7 % and 144.1 % for asphalt mixtures containing 0.3 % PPF, 0.6 % PPF and 1 % PPF, respectively. This could be explained such that the PPF increases the deformation capability of asphalt mixtures.

- It can be observed that the asphalt mixture with 0.6 % PPF is more applicable and preferable than the other asphalt mixtures according to the basic tests results. However, this needs to be verified by using different aggregates and asphalt cement.

6.2 Recommendations

It can be recommended that several tests have to be done before making specific decision. Moreover, the different length of PPF (such as 9 mm or 12 mm) can be used for asphalt mixtures and the tests results can be discussed. In addition, the asphalt mixtures can be prepared with various types and gradations of aggregates and different asphalt cements. The mixing and compacting temperature of asphalt mixture can be changed and low temperature performance of asphalt mixture can be analyzed. And finally, a detailed cost-benefit analysis should be applied in order to optimize its use.

REFERENCES

[1] Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D., and Kennedy, T. W. (1996). *Hot Mix Asphalt Materials, Mixture Design, And Construction.* (2nd ed.). Lanham, Maryland: NAPA Education Foundation.

[2] Terrel, R. L., and Walter, J. L. (1986). Modified asphalt pavement materials, The European experience. *Association of Asphalt Paving Technologists*, Vol.55.

[3] Wu, S., Mo, L., Shui, Z., and Chen, Z.(2005). Investigation of the conductivity of asphalt concrete containing conductive fillers. *Carbon*, **43**, 1358-1363.

[4] Asi, I. and Assa'ad A. (2005). Effect of Jordanian oil shale fly ash on asphalt mixes. *Journal of Materials In Civil Engineering*, **17**, 1-7.

[5] Terrel, R. L., and Rimsritong, S. (1979). Wood lignins used as extenders for asphalt in bituminous pavements. *Association of Asphalt Paving Technologists*, Vol.48.

[6] Wen G., Zhang Y., Zhang Y., Sun K., and Fan Y. (2002). Rheological characterization of storage-stable SBS-modified asphalts. *Polymer Testing*, **21**, 295-302.

[7] Al-Dubabe, I. A., Al-Abdul Wahhab, H. I., Asi, M. I., and Ali M. F. (1998). Polymer modification of Arab asphalt. *Journal of Materials In Civil Engineering*, **10**, 161-167.

[8] Khattak, M. J. and Baladi, G. Y. (1998). Engineering properties of polymer modified asphalt mixtures. *77th Transportation Research Board, TRB*, No.1518.

[9] Raad, L., Saboundjian, S., and Minassian, G. (2001). Field aging effects on the fatigue of asphalt concrete and asphalt-rubber concrete. *80th Transportation Research Board, TRB*, No.3097.

[10] Khattak, M. J. and Baladi, G. Y. (2001). Fatigue and permanent deformation models for polymer-modified asphalt mixtures. *80th Transportation Research Board, TRB*, No.2813.

[11] Kim, S., Loh, S., Zhai, H., and Bahia, H. U. (2001). Advanced characterization of crumb rubber modified asphalts using protocols developed for complex binders. *80th Transportation Research Board, TRB*, No.2986.

[12] Chipps, J. F., Davison, R. R., Estakhri, C. K., and Glover, C. J. (2001). Field tests and economic analysis of high-cure crumb rubber modified asphalt binders in dense-graded mixes. *80th Transportation Research Board, TRB*, No.399.

[13] Fortier, R. and Vinson, T. S. (1998). Low-temperature cracking and aging performance of modified asphalt concrete specimens. *77th Transportation Research Board, TRB*, No.528.

[14] Raad, L., and Saboundjian, S., (1998). Fatıgue behavior of rubber modified pavements. . *77th Transportation Research Board, TRB*, No1325.

[15] Raad, L., Saboundjian, S., Sebaaly, S., and Epps, J. (1998). Thermal cracking models for AC and modified AC mixes in Alaska. *77th Transportation Research Board, TRB*, No1429.

[16] Anderson, D. A., Christensen, D. W., Marasteanu, M. O., and Mehta, Y. (1999). Field performance of modified asphalt binders evaluated with superpave test methods: I-80 test project. . *78th Transportation Research Board, TRB*, No452.

[17] Johnson, D. R. and Freeman, R. B. (1999). Field performance of polymer-modified asphalt concrete designed for medium traffic. . *78th Transportation Research Board, TRB*, No716.

[18] Stastna, J., Liu, C., and Zanzotto, L. (1999). Rheological characteristics of selected polymer modified asphalts through their dynamic compliances. . *78th Transportation Research Board, TRB*, No1376.

[19] Bahia, H. U., Rangel, A., and Yang, Y. J. (1999). Evaluation of separation and thermal degradation of modified binders in the PAV procedure. *78th Transportation Research Board, TRB*, No312.

[20] Bahia, H. U. and Zhai, H. (1999). Storage stability of modified binders using the newly developed LAST procedure. *78th Transportation Research Board, TRB*, No889.

[21] Bahia, H. U., Zhai, H., and Turner, P. (1999). Critical properties of modified binders: summary of results from NCHRP 9-10 project. . *78th Transportation Research Board, TRB*, No173.

[22] Wong, C. C. and Wong, W. (2007). Effect of crumb rubber modifiers on high temperature susceptibility of wearing course mixtures. *Construction and Building Materials*, **21**, 1741-1745.

[23] Ruan, Y., Davison, R. R., and Glover C. J. (2003). The effect of long-term oxidation on the rheological properties of polymer modified asphalts. *Fuel*, **82**, 1763-1773.

[24] Stastna, J., Zanzotto, L., and Vacin, O. J. (2003). Viscosity function in polymer-modified asphalts. *Journal of Colloid and Interface Science*, **259**, 200–207.

[25] Cortizo, M.S., Larsen, D.O., Bianchetto, H., and Alessandrini, J.L. (2004). Effect of the thermal degradation of SBS copolymers during the ageing of modified asphalts. *Polymer Degradation and Stability*, **86**, 275-282.

[26] Kim, K. W., Doh, Y. S., and Lim, S. (1999). Mode I reflection cracking resistance of strengthened asphalt concretes. *Construction and Building Materials*, **13**, 243-251.

[27] Ouyang, C., Wang, S., Zhang, Y., and Zhang Y. (2005). Preparation and properties of styrene-butadiene-styrene copolymer/kaolinite clay compound and asphalt modified with the compound. *Polymer Degradation and Stability*, **87**, 309-317.

[28] Hınıslıoğlu, S. and Ağar, E. (2004). Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. *Materials Letters*, **58**, 267– 271.

[29] Tayfur, S., Özen, H., and Aksoy, A. (2007). Investigation of rutting performance of asphalt mixtures containing polymer modifiers. *Construction and Building Materials*, **21**, 328-337.

[30] Al-Abdul Wahhab, H. I., Asi, I. M., Abaker, I., and Baig, M. G. (2002). Performance modification of Saudi-asphalt binders using SABIC polymers. *The 6th Saudi Engineering Conference, KFUPM*, **2**, 379-393.

[31] Messersmith, P., Jones, C., and Wells, C. (1999). A contractor's experience with polymer modified asphalt in Alabama. . *78th Transportation Research Board, TRB*, No158.

[32] Huang, H. and White, T. D. (1998). Concrete pavement crack and seat performance and fiber modified overlay. *77th Transportation Research Board, TRB*, No157.

[33] Huang, H., White, T. D., and Montgomery, J. (1999). Effect of fibers on HMA performance. *78th Transportation Research Board, TRB*, No290.

[34] Komatsu, T., Kikuta, H., Tuji, Y., and Muramatsu, E. (1998). Durability assessment of geogrid-reinforced asphalt concrete. *Geotextiles And Geomembranes*, **16**, 257-271.

[35] Ouyang, C., Wang, S., Zhang, Y., and Zhang Y. (2006). Improving the aging resistance of styrene-butadiene-styrene tri-block copolymer modified asphalt by addition of antioxidants. *Polymer Degradation and Stability*, **91**, 795-804.

[36] Ahmedzade, P., Tigdemir, M., and Kalyoncuoğlu, S.F. (2007). Laboratory investigation of the properties of asphalt concrete mixtures modified with TOP–SBS. *Construction and Building Materials*, **21**, 626-633.

[37] Bishara, S. W., King, G. N., Mahoney, D. and McReynolds, R. L. (2001). Modification of binder with acid; advantages and disadvantages. *80th Transportation Research Board, TRB*, No.641.

[38] Kandhal, P. S. (1993). *Waste Materials in Hot Mix Asphalt.* New York: ASTM Special Technical Publication.

[39] Solaimanian, M., Kennedy, T. W., and Tripathi, R. (1998). Performance characteristics of asphalt binders and mixtures modified by waste toner. *77th Transportation Research Board, TRB*, No680.

[40] Choubane, B., Sholar, G. A., Musselman, J. A., and Page, G. C. (1999). A ten-year performance evaluation of asphalt-rubber surface mixes. *78th Transportation Research Board, TRB*, No926.

[41] Navarro, F.J., Partal, P., Martinez-Boza, F., and Gallegos, C. (2004). Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens. *Fuel*, **83**, 2041-2049.

[42] Yildirim, Y., Hazlet, D., and Davio, R. (2004). Toner-modified asphalt demonstration projects. *Resources, Conservation and Recycling*, **42**, 295–308.

[43] Chiu, C. and Lu, L. (2007). A laboratory study on stone matrix asphalt using ground tire rubber. *Construction and Building Materials*, **21**, 1027–1033.

[44] Putman, P. J. and Amirkhanian, S. N. (2004). Utilization of waste fibers in stone matrix asphalt mixtures. *Resources, Conservation and Recycling*, **42**, 265–274.

[45] Karian, H. G. (2003). *Handbook of Polypropylene And Polypropylene Composites.* (2nd ed.). New York, USA: Marcel Dekker, Inc.

[46] Galanti, A. V. and Mantell, C. L. (1965). *Polypropylene Fibers And Films.* New York, USA: Plenum Press.

[47] Larson, T. D. (1963). *Portland Cement And Asphalt Concretes.* USA: McGraw – Hill Book Company.

[48] Wallace, H. A. and Martin, J. R. (1967). *Asphalt Pavement Engineering.* USA: McGraw – Hill Book Company.

[49] Lexington, K. (1997). *Mix Design Methods.* (6th ed.). USA: Asphalt Institute.

[50] KGM. (2000). *Yollar Fenni Şartnamesi.* Ankara: Teknik Araştırma Dairesi Başkanlığı, Yayın No:170/2.

[51] ASTM C 127, *Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate*. USA: American Society for Testing and Materials.

[52] ASTM C 128, *Standard Test Method for Specific Gravity and Absorption of Fine Aggregate*. USA: American Society for Testing and Materials.

[53] ASTM D 70, *Standard Test Method for Specific Gravity and Density of Semi-Solid Bituminous Materials*. USA: American Society for Testing and Materials.

[54] ASTM D 5, *Standard Test Method for Penetration of Bituminous Materials*. USA: American Society for Testing and Materials.

[55] ASTM D 36, *Standard Test Method for Softening Point of Bitumen*. USA: American Society for Testing and Materials.

[56] ASTM D 113, *Standard Test Method for Ductility of Bituminous Materials*. USA: American Society for Testing and Materials.

[57] ASTM D 1559, *Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus*. USA: American Society for Testing and Materials.