Final Report

(March 16, 1994 to August 31, 1997)

for

POLYMERS IN BITUMINOUS MIXTURES
Phase II

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16. Abstract

The effects of polymer modification on the performance of asphalt pavements were studied. Commercially available polymers were selected based on the results of a previous study; these materials are styrene-butadiene-styrene copolymer (SBS), styrene-ethylene-butylene-styrene copolymer (SEBS), styrene-butadiene rubber (SBR), ethylene vinyl acetate copolymer (EVA), epoxy terminated ethylene terpolymer (Elvaloy® AM; EAM), and crumb rubber modifiers (CRM). Four viscosity grade asphalt binders (AC-2.5, AC-5, AC-10, and AC-20) were obtained and used in this study. A comprehensive laboratory investigation was conducted to determine various properties of binders and mixes for both straight asphalt and polymer modified asphalt (PMA). The laboratory investigation included studies of : the fundamental chemical and morphological properties of straight and polymer modifies asphalt binders; the micro-structural characterization of binders and mixes; and the engineering properties of straight and PMA mixes. The main objective of the investigation was the assessment of whether or not PMA binders cause effective improvement in pavement performance. Based on extrapolation of laboratory results and cost considerations, improved pavement performance is expected for roads constructed with polymer modified asphalt binder.

17. Key Words asphalts, mixtures, polymer modifiers, SBS, SEBS, SBR, EAM, CRM, EVA, binders, chemical properties, thermal-mechanical, morphology, microstructure, engineering properties, SHRP specifications, performance grades.

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1. Executive Summary

The effects of polymer modification on the performance of asphalt pavements were studied in two phases. In the Phase I study, completed in 1994, it was determined that certain polymers were promising as additives to asphalt to enhance pavement performance. In the just completed three-year Phase II laboratory study, certain commercially available polymers were selected based on the results of the Phase I study; these materials are styrene-butadiene-styrene copolymer (SBS), styrene-ethylene-butylene-styrene copolymer (SEBS), styrene-butadiene rubber (SBR), ethylene vinyl acetate copolymer (EVA), epoxy terminated ethylene terpolymer (Elvaloy® AM; EAM), and crumb rubber modifiers (CRM). Four viscosity grade asphalt binders (AC-2.5, AC-5, AC-10, and AC-20) were obtained and used in this study. A comprehensive laboratory investigation was conducted to determine various properties of binders and mixes for both straight asphalt and polymer modified asphalt (PMA). The laboratory investigation included studies of:

- The fundamental chemical and morphological properties of straight and polymer modifies asphalt binders.
- The micro-structural characterization of binders and mixes.
- The engineering properties of straight and PMA mixes.

The main objective of the investigation was the assessment of whether or not PMA binders cause effective improvement in pavement performance. During the course of the investigation, several milestone accomplishments were made including:

- Fingerprinting protocols for identification of the type and amount of polymer in PMA's were developed.
- The controlling fundamental benefits of PMA binders were identified.
- Performance-based criteria for PMA binders were developed.
- The expected effective improvement in asphalt pavement performance due to PMA binders was assessed based on extrapolation of laboratory test results and cost considerations.
- A specific pavement testing program was recommended based on the laboratory test results.
- The mixing conditions for straight and PMA binders and the optimum content of each type of polymer were determined based on the rheological properties of the PMA binders.
- The fundamentals of binder-aggregate adhesion and the failure mechanisms of asphalt mixes were determined.
- An extended range of field temperature under which PMA binders show good performance was identified.

Based on extrapolation of laboratory results and cost considerations, improved pavement performance is expected for roads constructed with polymer modified asphalt binder. It is strongly recommended that experimental pavement sections be constructed using polymer modified asphalt. The long-term performance should be monitored to assess whether or not field benefits are similar to those extrapolated from the laboratory data. This effort should be coupled with additional research on the effect of asphalt sources and other issues as identified in this study in order to generalize the effects of polymer modification on asphalt performance and properties.

2. Overview

i. Introduction

Michigan State University, in partnership with the Michigan Department of Transportation has conducted a comprehensive study of the processing, properties and performance of polymer modified asphalts. The study is divided into three sections: the fundamental physical, chemical, and thermodynamic properties of asphalts, modifiers, and blends; the basic morphology and microstructure of modified asphalt-aggregate mixtures; and the engineering and structural properties of modified asphalt-aggregate mixtures.

Polymer modification of the asphalt binder has become a growing area of interest in the asphalt processing industry. Many studies have been done on the effect of polymer modification on the properties of the binders and the pavement performance of the binder-aggregate mixes. Polymer modified asphalts show a significant improvement in the properties of asphalt concrete both at high temperatures.

The most commonly observed types of distress in asphalt concrete (AC) surfaced pavements are rutting (permanent deformation), fatigue cracking, low temperature cracking, raveling, and stripping. At high temperatures, asphalt exhibits viscous flow with little or no elastic behavior. The main distress at high temperatures is rutting which is a result of viscoelastic flow. At low temperatures, asphalt becomes a brittle elastic solid with little or no viscous properties. The thermal cracking is induced due to a lack of viscous flow in asphalt in response to pavement stresses at low temperatures. Unmodified asphalt used in the asphalt concrete mix may perform satisfactorily relative to one distress type and fail prematurely relative to the others.

With polymer modification, the properties of asphalt mixes such as fatigue cracking, permanent deformation resistance, less temperature susceptibility, moisture sensitivity, and thermal cracking resistance can be improved. The goal of polymer modification is to increase the temperature range of both the elastic and viscous properties of the asphalt binders and mixes. Modification of the asphalt binder to enhance its performance at both high and low temperatures and under traffic loading is essential to the success of constructing superior pavements. It has been shown that polymer-modified asphalts improve pavement performance.

ii. Materials studied and research thrusts

Asphalt is a complex mixture of many different hydrocarbons and typically, its constituents are classified into three categories: oils, resins, and asphaltenes. The physical properties of asphalt are directly related to the quantity and quality of asphaltenes and the nature of the dispersion medium, oils and resins. The quality of asphaltenes generally refers to the existence and the amount of various chemical functional groups, such as carboxylic acids, ketones, phenolics, sulfoxides, and acid anhydrides. An average asphalt sample has an asphaltene/resin/oil ratio (w/w) of approximately 20/30/50 and the asphaltene content is higher for harder asphalts.

Polymer modified asphalt binders can be characterized based on Gel Permeation Chromatography (GPC), Fourier Transform Infrared (FTIR) spectroscopy, Thermal Mechanical Analysis (TMA), Differential Scanning Calorimeter (DSC), melt viscosity measurement, Dynamic Shear Rheometer (DSR), and Bending Beam Rheometer (BBR). Melt viscosity, dynamic mechanical analysis, thermal mechanical analysis, and the bending beam rheometer are good methods of characterizing the physical properties of asphalts. It is the industry standard to grade an asphalt by using melt viscosity or penetration. However, this can lead to inconsistencies. Two AC-5 grade asphalts may have the same viscosity but be very different chemically and thus show different performance properties. FTIR and GPC can be used to characterize the chemical structure of binders. GPC allows one to examine the molecular weight distribution of an asphalt binder as well as the determination of the amount of a certain polymer modifier added. FTIR allows one to examine the chemical functional groups present in an asphalt binder as well as the polymer content in the binder with the use of a calibration curve. Rheometers should be used as a good indicator of the blends performance over a wide temperature range. Materials will behave in characteristic ways with respect to rheological testing at different temperatures.

According to the functions and behaviors of various modifiers in the asphalts, modifiers can be categorized into five types: dispersed thermoplastics, network thermoplastics, reacting polymers, fibers, and particles. Dispersed thermoplastics behave like asphaltenes and normally require peptizing agents like resins to stabilize the modified systems. They generally require a considerable amount of material to be added before forming a microstructural network. Network thermoplastics behave like resins and will form a network of themselves inside asphalts. Reacting polymers bond chemically to the asphalt (normally to the asphaltenes) and will form asphalt/polymer networks. Particles behave as aggregates if their sizes are large and behave as dispersed thermoplastics if their sizes are small (below 100mm). Fibers increase the available wetting surface area and behave as binder thickeners which reduce asphalt bleeding. Unfavorable dispersed thermoplastics and fibers were excluded from the investigation for this project based on the discussion with members of the Technical Advisory Committee (TAC). The following is a list of the modifiers which were used in Phase II.

Network Thermoplastics (SBS, SEBS, SBR, and EVA) - The theorized behavior of the network thermoplastic modifiers in asphalt can best be examined by determining the effect of increasing polymer content over a wide range of temperature. It should first be noted that these copolymers are composed of two hard sphere-like ends (e.g. styrene block) joined by an elastic component (e.g. butadiene block).

Reactive Polymers (Elvaloy® AM) - It is theorized that Elvaloy® AM chemically reacts with asphalt cement creating a new material. Elvaloy® AM contains an epoxy functional group that we believe reacts with aromatic carboxylic acid functional groups found in the asphaltene constituent of asphalt binder Because we are using the asphalt itself to create a network-like structure, less Elvaloy® AM would be needed for asphalt modification than network thermoplastics.

Crumb Rubber Particles - Crumb rubber, like asphalt, consists of three constituents: rubber, carbon black, and oils. It is theorized that when CRM is added to asphalt, there is a migration and sharing of oily constituents thus forming an interpenetrating network or an adhesive-like structure. From the literature it appears as if this process is extremely sensitive to both time and temperature.

Asphalt binders mixed with aggregates form asphalt concrete. Therefore, the binder-aggregate mixture is a composite consisting of various phases and interfaces (or interphases). One of the controlling parameters determining the properties of asphalt concrete is the interaction between the binders and aggregates. This was characterized by the systematic study of the interfacial adhesion between the binder and aggregate and the cohesive performance of the binder. Poor adhesive or cohesive performance leads to premature failure, cracking and poor pavement performance. The failure and fracture behavior of asphalt mixtures could be characterized qualitatively by studying the fracture morphology using an Environmental Scanning Electron Microscope (ESEM) and quantitatively by fracture toughness measurement. As a consequence, microstructural and morphological information of mixtures becomes very important in predicting pavement performance of binder-aggregate mixes.

The engineering properties of the binder-aggregate mixes (such as compressive and tensile strengths, creep and plastic characteristics, fatigue life, resilient modulus, viscoelastic properties, and the stability of the AC mixtures) exposed to various combinations of low and high temperatures, moisture conditions, and static and cyclic loads were investigated. Throughout the State of Michigan, several types of distress can be found on asphalt surfaced pavements. These include thermal cracking, block cracking, aging, fatigue cracking, rutting, raveling and stripping, and reflective cracking. The distress mechanism varies from one type of distress to another and it is influenced by the structural properties of the pavement layers and the roadbed soil, construction practices, traffic load and volume, and environmental conditions. Although each of these factors has a specific role on pavement performance, the asphalt courses play a major role and they represent an expensive element of the pavement structure

A major cause of failure of asphalt pavements is aging of the asphalt binder. The aging process can significantly change the properties of the binder. Aging, or age hardening, occurs through two distinct processes. The first is a loss of volatile components in the asphalt during the high-temperature processing. The second is oxidation of the asphalt during road life. Both mechanisms cause an increase in the viscosity of the binder and the stiffness of the pavement. This increased stiffness can lead to a brittle pavement which is highly susceptible to cracking. Many studies have been done on the effect of polymer modification on the physical and mechanical properties of the binder. However, there have been few studies on the effect of polymer modification on aging characteristics. Since aging or thermo-oxidative phenomena affect the physical and chemical properties of the polymer modified binders, efforts must be put on the determination of the aging characteristics of polymer modified asphalt binders and their suitability for paving applications.

One of the most addressed SHRP (Strategic Highway Research Program) binder specifications is the measurement of the rheological properties of the binders at different temperatures. Complex modulus (G*) and phase angle (δ), and creep stiffness (S) are the major properties of the binders which will determine the rutting resistance at high temperatures, the fatigue cracking resistance at service temperatures, and thermal cracking resistance at low temperatures. Table 1 shows the SHRP binder specifications which are divided into three protocols for original binder, TFOT (Thin Film Oven Testing) residue, and PAV (Pressure Aging Vessel) aged residue. The required properties of the binders remain constant for all performance grades but the temperature at which these values are reached varies. Eventually, the temperatures will represent the performance grades of the binders. The SHRP performance grading system was created using unmodified asphalt binders. The binder properties were correlated to pavement performance to determine the specification values. The project addressed the applicability of those specification values to polymer modified asphalts and recommends changes in the SHRP protocol where necessary.

iii. Summary of the results in Phase II that are applicable to current MDOT pavement practice in various areas. Most of the results are related to quality control and SHRP specification of the polymer modified asphalt binders.

This research showed that polymer modified asphalt could be used to extend the temperature range over which asphalt pavements show good performance. This was accomplished by using a soft asphalt to give good low temperature performance and modifying it with polymer to extend the high temperature performance. Some properties of the binders-mixes such as the binder/aggregate adhesion properties improved considerably with adding polymer modifiers at lower temperatures but it should be concluded that the polymer modification improved the performance and properties of asphalt binders-mixes at high temperatures to result in more elastic and ductile behavior as well as intense fibrillation formation. In addition, various test methods and procedures have been newly developed for characterization of asphalt binders and asphalt mixes in terms of basic morphology, microstructure, fracture behavior, aggregate/asphalt binder adhesion, durability, and other engineering properties. The development of this complete test methodology is one of the major achievements made in Phase II.

Table 1. SHRP Binder Specifications

Test Conditions	Specifications
Tests on Original Binder	
* Flash Point Temp. (ASTM D 92)	230°C (min.)
* Brookfield Viscosity at 165°C (ASTM D 4402)	3 Pa·s (max.)
* Dynamic Shear, SHRP B-003: @ max. design temp. and 10 rad/sec (G^*/sin delta)	1.0 kPa (min.)
Tests on RTFO Residue (AASHTO T 240; ASTM D 2872)	
* Dynamic Shear, SHRP B-003: @ max. design temp. and 10 rad/sec (G^*/sin delta)	2.2 kPa (min.)
Tests on PAV (after RTFO) (SHRP B-005) Residue	
* Dynamic Shear, SHRP B-003 @ 10 rad/sec (G^*sin delta)	5000 kPa (max.)
* Bending Beam Creep Stiffness: SHRP B-002:, S, 60s; m at 60 s; at 10°C above min. design temp.	S=300 MPa (max.) m=0.3 (min.)
* Direct Tension (SHRP B-006): Failure Strain, 1.0 mm/min, %, at 10°C above min. design temp.	1.0% (min.)

Each of the modifiers studied to date showed some different characteristics which are related to SHRP specifications and are addressed below.

Modification of asphalt with SBS resulted in enhanced high temperature properties of the binder. With addition of optimum amount (3-5% (w/w) for SBS), the high temperature Performance Grade of the Strategic Highway Research Program (SHRP) specifications was improved by up to two grades. The measured stiffness at low temperature somewhat decreased with increase of the polymer content in the binders. The SBS modified asphalt binders were found to show less oxidation than the control sample. There was a region between 3-5% (w/w) that exhibited unexpected rheological behavior. Low temperature rheological properties were retained, and in some cases enhanced, upon addition of SBS. No clear trends were seen to relate low temperature properties to polymer content. Overall, SBS modification appears to improve the performance of AC-5 asphalt binders. The improvement is primarily in the high temperature rheological properties, however the low temperature properties are not degraded.

SBR is one of the most common polymers used for modification. An SBR content of 3% (w/w) improves the high temperature performance one grade, while a content of 5% (w/w) improves it by two grades. There is minimal improvement with contents of less than 3% (w/w). At low contents, SBR acts as a dispersed polymer while at higher contents a network forms inside the asphalt. This network lends support to the asphalt at high temperatures improving rutting resistance. In each case, the low temperature grade remained the same as the base asphalt used for modification. The viscosity of SBR modified binders was sufficiently low at contents less than 6% (w/w) to be processed using standard equipment. All in all, SBR appears to be a promising modifier.

Elvaloy® AM is a reacting polymer which bonds to the asphalt. Rather than forming a physical Elvaloy® AM/asphalt network, it is believed that the Elvaloy® AM actually attaches to some of the functional groups in the asphaltenes creating larger asphaltene molecules. The high temperature performance grade was the highest of any modifier used in this study. An improvement of one grade over the control sample was seen with addition of 2% (w/w) Elvaloy® AM. One of the reasons for the large increase in performance grade compared to the virgin asphalt is the high temperature and long time required for blending the asphalt and the modifier. These extreme mixing conditions cause severe oxidation which leads to stiffer binders and better high temperature properties. Because this is a reactive process, the mixing procedure is very sensitive to thermal gradients and environment. Mixing in nitrogen instead of in air helped the retardation of the oxidation of the binders. Elvaloy® AM modified samples had very high viscosity. Samples with 2% (w/w) and greater Elvaloy® AM had viscosity that did not meet the SHRP specification for handling. The low temperature SHRP performance grade was equal to or one grade worse than that of the base asphalt. Elvaloy® AM appeared to show some benefits, however there are some significant drawbacks. Elvaloy® AM also costs almost as twice as the other polymers such as SBS and SBR which might be better candidates for asphalt modification.

There is a great deal of interest in using recycled crumb rubber in asphalt. This is driven by the environmental problem of disposing of used tires. The high temperature properties of CRM modified pavements have been studied. The mixing procedure is a low temperature, low time procedure which should result in minimal oxidation of the asphalt. Dynamic shear rheometry shows that addition of CRM results in an improvement of the high temperature performance grade by one grade for every 5% (w/w) CRM. Viscosity tests show that up to 15% (w/w) CRM can be added to the binders while maintaining a processable viscosity. Studies on the long term (24 hours) high temperature storage of the CRM binders indicate that the presence of CRM either masks or retards the aging process. There are also issues such as how the macroscopic CRM particles affect the binder-aggregate adhesion and the long term aging of the asphalt. There is also the issue of the surface treatment of the CRM particles that would affect the properties of the binders. The effects of surface treatment on crumb rubber particles on performance of CRM modified asphalt binders were investigated by determining stability of binders at the high temperature storage condition. The morphology of a new type of surface treated crumb rubber, CRM XP-81, showed that, after 24 hours of storage at 350°F, there were no signs of aging in the XP-81 samples. It is believed that the surface treatment modifies the oil (low molecular weight fraction of asphalt binder) absorption behavior of the rubber particles. Lap-shear properties using granitic rock substrates at -10°C were significantly improved from those of conventional CRM binders. This must be something to do with differences in aging mechanisms and/or swelling behavior between those CRM binders. CRM modification seemed to prevent or retard the aging process from binder network morphology studies and lap-shear adhesion analyses even though the aging effects dominated the properties of the polymer modified binders-mixes.

EVA appears to be a promising modifier which doesn't suffer from some of the problems of the other modifiers. It dissolves well in asphalt at the same conditions as SBS blending. It improves the high temperature performance one grade with 3% (w/w) polymer and two grades with 5% (w/w). The viscosity remains low enough to process 7% (w/w) EVA modified binders. The low MW polymer can be blended at lower temperatures for shorter times. This can improve the low temperature properties of the modified binder. While these results are still preliminary, it appears that EVA is an excellent choice for asphalt modification.

iv. Deliverables for Phase II

Upon completion of Phase II, this final report addresses the following issues:

1. The physical and engineering properties of asphalt-aggregate mixtures made by using both straight and polymer/fiber modified asphalts. These properties include:
    a) Elastic and resilient properties.

b) Viscoelastic properties.
c) Plastic and creep properties.
d) Fatigue characteristics.
e) Low temperature cracking potential.
f) Stripping potential.

→ The mechanistic response of a material subjected to static or dynamic load can be divided into three components: elastic or resilient, viscoelastic, and plastic deformations. Throughout this study, the three deformations were recorded and analyzed. The results and conclusions or deliverables are summarized below.

a) Elastic or resilient properties – The elastic or resilient deformation or strain is that part of the overall deformation or strain that is recoverable upon the removal of the load. Such a recoverable strain can be divided into two subparts, instantaneous (time independent and recoverable upon the immediate removal of the load) and viscous (time dependent and recoverable after the removal of the load). Hence, two definitions of the resilient modulus can be found, instantaneous and total. In both definitions, the resilient modulus of a material is calculated as the ratio of the applied cyclic stress to the instantaneously recoverable strain or to the total recoverable strain (instantaneous and viscous strains). In this study, both the instantaneous and the total moduli were calculated and analyzed. The test results indicated that the resilient moduli of polymer-modified asphalt mixtures at temperatures of 25 and 60°C (77 and 140°F) were greater than the moduli of the straight mixtures. No significant increases in the resilient modulus were observed at the test temperature of -5°C (23°F). Two significant findings were made from the above observations. First, at relatively high temperatures, the addition of polymer increases the stiffness of the asphalt mixtures, which causes a significant decrease in their rut potential. Second, at low temperatures, the stiffness of the asphalt mixtures is relatively not affected by the addition of polymer which imply that at low temperatures, polymer has no significant impact on the rut potential of asphalt mixtures.

b) Viscoelastic Properties – The viscoelastic deformation or strain is that part of the material response to load that is recoverable with time after the removal of the load. The viscoelastic properties and the stiffness of a material indicate the capability of the material to dissipate the applied load. In the phase II study, the viscoelastic deformation or strain was studied as a part of the elastic or resilient strain as specified by the AASHTO and ASTM standards (i.e., instantaneous and total moduli) relative to cyclic load tests. In general, the trend in the total modulus of the polymer-modified asphalt mixtures relative to the straight ones was similar as that of the resilient modulus. Thus, the percent improvement in the viscoelastic properties was almost the same as that of the elastic properties. The implication of this is that, polymer-modified asphalt mixtures have better capability of spreading the applied traffic load to wider areas. Hence, lower stresses and less damage are delivered to the lower pavement layers. The reason for this is that, the AASHTO and ASTM procedures call for the calculation of the total resilient modulus which is the ratio of the cyclic stress to the sum of the resilient and viscoelastic strains.

c) Plastic and Creep Properties - The plastic properties of a given material indicate the capability of the material to resist fatigue cracking and permanent deformation or rut. During the phase II study, the vertical and horizontal plastic strain of the test samples were recorded. Two approaches were used to compare the resistance to plastic deformation of straight and PMA mixtures. These are the number of cycles to attain a particular magnitude of plastic deformation and the plastic deformation rate (the amount of plastic deformation per load cycle. It was found that polymer modified AC mixtures have considerably higher number of load cycles to attain certain levels of plastic deformation at 77 and 140°F than the straight mixtures. Moreover EAM modified mixture did not even fail after 3,000,000 load cycles at 77°F. The deformation rates for PMS mixtures tested at 23, 77 and 140°F were also significantly lower than those of straight mixtures. The significance of these findings is that PMA mixtures have significantly higher fatigue life and lower rut potential than the straight mixtures.

d) Fatigue Characteristics - Fatigue cracking is one of the major structural distress that can be found in asphalt pavements. The major causes of fatigue cracking is relatively weak pavement structure, low tensile strength in the asphalt layer, inadequate drainage, and repeated traffic load. With an increasing number of load repetitions, the horizontal plastic (permanent) strain accumulates in the asphalt layer until micro-cracks are developed. With time, the micro-cracks develop to cracks and propagate from the bottom of the asphalt layer toward the pavement surface. Hence, fatigue cracks may exist in asphalt pavements for long time before they can be detected by visual inspection of the pavement surface. The fatigue characteristics of polymer-modified and straight asphalt mixtures were studied. Based on the test results, a consistent fatigue life criterion based on the rate of accumulation of plastic deformation was developed and presented in section III.8.1 of this report. The test results indicate that the fatigue lives of PMA mixtures are significantly higher than the fatigue lives of the straight asphalt mixtures. The EAM polymer system showed the highest increase in the fatigue life than all other polymers, followed by SEBS system. The increase in the fatigue life is mainly due to increase in the resistance of PMA mixtures to horizontal plastic deformation. The test data showed that the fatigue life of asphalt pavements can be increased by several fold with the addition of the polymer systems used in this study.

e) Low Temperature Cracking – The main causes of low temperature cracking in asphalt pavements are low tensile strength, stiffness and brittleness and/or hardening of the asphalt layer. When the pavement temperature drops, the pavement contracts causing the build up of tensile stress in the asphalt layer. When the tensile stresses exceeds the tensile strength of the asphalt concrete, the pavement develops cracks. Low temperature cracking may be caused by multiple temperature cycles or by a single cycle which is mainly related to the stiffness and brittleness of the asphalt concrete. In this study, date relative to the tensile strength, stiffness (resilient modulus) and plastic deformation rates of the asphalt mixtures were collected at 23°F and analyzed. On the average, the tensile strengths and the resilient modulus of PMA mixtures at 23°F were not significantly different than the straight mixtures. However, the horizontal plastic deformation rates were significantly lower at both high and low temperatures. That is, the addition of polymer to asphalt mixtures, improve their plastic characteristics and it does not affect their elastic properties. Since low temperature cracking is affected by the plastic properties, PMA mixtures have significantly lower low temperature cracking potential than straight asphalt mixtures.

(f) Stripping – The stripping potential of polymer modified asphalt concrete mixtures is dependent on the aggregate, the chemistry and physical properties of the asphalt cement and the adhesion between the aggregate and polymer modified asphalt cement. While the stripping potential as defined by standard tests was not determined, for the choices of asphalt, polymer modifier and aggregate used in this research program, the following conclusions can be made:

- Overall, from the analyses of five modifiers (SBS, SEBS, SBR, Elvaloy® AM, and CRM) polymer modification improved (1) the binder/aggregate adhesion strength and toughness, especially at lower temperatures where the failure mode transition occurred, (2) polymer modified asphalt binder concrete showed more ductile deformation and fracture processes by more intense fibrillation formation, and (3) polymer modification seemed to prevent or retard the aging process from binder network morphology studies and lap-shear adhesion analyses.
- Effects of thermal-salt water exposure cycles on adhesion properties and behavior of polymer modified asphalt binders have been determined by the lap-shear performance [ref II.13].
- Both fresh mixed and aged AC-5 and AC-10 binders modified with SEBS and CRM were studied at two different temperatures, 0°C and -10°C. Surprisingly enough, there was no dramatic property degradation or catastrophic failure due to the cycle for both fresh and aged binders regardless of polymer modification.
- The fracture morphology of unmodified asphalt concrete samples undergoing thermal-cycling durability tests showed a slight coarsening of the binder.
- The polymer modified asphalt concrete samples did not show any change in the morphology from that of fresh samples. This indicates that the polymer modified asphalt can enhance the durability of asphalt concrete to some extent [ref II.13].

- Various test methods and procedures have been newly developed for characterization of asphalt binders and asphalt concretes in terms of basic morphology, microstructure, fracture behavior, aggregate/asphalt binder adhesion, and durability. It has been proved from the phase II results that these methods and procedures are reliable and meaningful in evaluating polymer modification of asphalt systems as well as in determining material parameters that can be used in predicting performance in actual applications.
- The study of binder microstructure has led to a fundamental understanding of the nature of asphalt binders. The proprieties and nature of the network structure is found to control the properties of the asphalt binder and asphalt concrete.
- The ESEM technique developed during this study provides a good qualitative tool for characterizing asphalt binders, aging and asphaltene content.
- The study of polymer phase morphology also leads to an understanding of the different mechanisms with which polymers enhance the asphalt binder properties and fracture morphology of asphalt concrete.
- Polymer modification of binders was seen to conclusively retard the aging process in asphalt concrete.

2. Comparative analyses between the properties, and benefits of bituminous mixes made by using straight and polymer/fiber/rubber modified asphalts.

→ Detailed analyses for the benefits of each modifiers and the properties of the modified binder-mixes are addressed and compared in the report. It could be concluded that the polymer modification improved the performance and properties of asphalt binders and mixes from the analyses of five modifiers (SBS, SEBS, SBR, Elvaloy® AM, and CRM). Especially, modification of asphalt with polymers resulted in enhanced high temperature properties of the binder. With addition of optimum amount of modifiers, the high temperature Performance Grade of the Strategic Highway Research Program (SHRP) specifications was improved by up to two grades and the increase in the softening points for PMA's indicated an improvement in the stiffness and rutting resistance of the binders. The additional fibril network structure formed within polymer modified asphalt played an important role in the high temperature property improvement. At low contents, SBS, SBR, EVA act as dispersed polymers while at higher contents a network forms inside the asphalt. This network lends support to the asphalt at high temperatures improving rutting resistance. Elvaloy® AM is a reacting polymer which bonds to the asphalt. Rather than forming a physical Elvaloy® AM/asphalt network, it is believed that the Elvaloy® AM actually attaches to some of the functional groups in the asphaltenes creating larger asphaltene molecules. The high temperature performance grade was the highest of any modifier used in this study. However, one of the reasons for the large increase in performance grade compared to the virgin asphalt is the high temperature and long time required for blending the asphalt and the modifier. Mixing in nitrogen instead of in air helped the retardation of the oxidation of the binders.

The binder/aggregate adhesion strength and toughness increased considerably with adding polymer modifiers, especially at lower temperatures where the failure mode transition occurred. Polymer modified asphalt binder mixes showed more ductile deformation and fracture process due to more intense fibrillation formation and it seemed to prevent or retard aging process based on binder network morphology studies and lap-shear adhesion analyses. The measured stiffness at low temperature somewhat decreased with increase of the polymer content in the binders. There is a great deal of interest in using recycled crumb rubber in asphalt since it would improve the low temperature ductility as long as. the binder is processable, which can be managed when up to 15% (w/w) CRM are added.

3. Recommendations relative to the critical polymer/fiber/rubber contents in the asphalt mixes.

→ The optimum and critical modifier contents for the asphalt/polymer blends were determined. The optimum contents were determined by several ways such as by examining rheological properties as a function of polymer content or the SHRP specification requirements.

In the SBS or SEBS modified asphalt binder system, there was a rapid improvement of the rheological properties with increasing polymer content up to 3% (w/w). However, it is also important to note that there is a reduction and then an increase in the modulus properties for polymer contents between 3-5% (w/w). When the economics concerning the costs and benefits of increasing the polymer content were concerned, the recommended optimum contents in the selective blends are as follows: 3 or 5% (w/w) for AC-5 and 2 or 5% (w/w) for AC-10.

The optimum SBR contents in the blends were determined for four different grades of asphalt binders. The desirable contents for SBR modification were 3 or 4% (w/w). The softest AC-2.5 grade asphalt was found to need 4% (w/w) and the other higher grade asphalt need 3% (w/w) to show the best rheological properties.

For the Elvaloy® AM modified binders., the optimum contents were determined based on the rheological properties and economical concerns. The softer the asphalt is, the more amount of Elvaloy®AM was needed. The softest AC-2.5 grade asphalt was found to need 3% (w/w) and higher grade asphalts need 1.5 and 1% (w/w) for AC-5 and 10, respectively, to show the best rheological properties.

The rheological properties showed a continual improvement with increasing CRM content. The optimum content will be based on the amount of material required to reach the desired SHRP performance grade. However, more than 15% (w/w) CRM in the blend caused high melt viscosity resulting in processing problems.

The optimum Polybilt EVA contents in the blends were determined for AC-5 and AC-10 grades of asphalt binders. In case of AC-5, adding more than 5% (w/w) EVA did not significantly enhance the rheological properties. In case of AC-10, adding more than 3% (w/w) EVA in the binder did not significantly enhance the rheological properties.

4. The suitability and applicability of the SHRP, MDOT, and other specifications to the polymer/fiber/rubber modified asphalt cements.

→ The SHRP performance grading system was created using unmodified asphalt binders. The binder properties were correlated to pavement performance to determine the specification values. This section addresses the applicability of those specification values to polymer modified asphalts and recommends changes in the SHRP protocol where necessary.

For the flash point and the viscosity test specifications, there is no reason that it should not apply to modified binders.

Rutting resistance and fatigue cracking resistance are measured by dynamic shear rheometry on the unaged and aged asphalt binder. While aggregate properties and aggregate-binder interfacial properties are important in preventing rutting and fatigue behavior, the binder itself plays a role. Modification of binders should increase the rutting resistance and/or fatigue resistance of most asphalts. However, the specification should not be altered because the same specification limits are applicable to both unmodified an modified binders.

The mass loss test is used to provide field personnel's safety standard. The specification calls for a maximum mass loss of one percent. Mass is lost through volatilization and is gained through oxidation. If the ability to measure these two processes independently is developed, excessive aging can be measured by determining the mass loss of asphalt binder.

Potential for low temperature cracking is measured using a bending beam rheometer. The specification calls for a minimum m-value of 0.300 and a maximum stiffness of 300 MPa. When the temperature drops, the asphalt concrete shrinks. Tensile stresses accumulate in the pavement because friction against the lower pavement layers inhibits movement. When these stresses exceed the tensile strength of the material, low temperature cracks form. The two properties chosen by SHRP to characterize low temperature performance are m-value and stiffness. To prevent cracking, the accumulation of stresses needs to be prevented. The ideal binder will have a low stiffness to minimize stress and a high m-value to dissipate the stress quickly. There are some fundamental assumptions that are made when using these two values (stiffness and m-value) to predict thermal cracking. The first is that the cracks are caused by tensile stress exceeding tensile strength. The SHRP specification assumes that tensile strength of all asphalts will be approximately equal. This makes m-value and stiffness the only two parameters that need to be characterized. These assumptions do not hold for polymer modified binders since polymer modification may alter the tensile strength of the binders. An increase in tensile strength will allow for greater stress accumulation before cracking. This means that modified pavements with a larger tensile strength and a stiffness or m-value slightly off specification will likely perform better than a normal asphalt that barely meets the specifications. The specification should be changed to incorporate tensile strength measurements. A separate study should be done to determine the effect of tensile strength on low temperature pavement performance in order to determine the cut-off values.

5. Asphalt mix design procedures that are based on the engineering properties and performance of the bituminous mixes. These procedures include:
    a) Aggregate gradation.
    b) Percent sand and fines in the aggregate mixes.
    c) The percent air voids in mineral aggregates (VMA).
    d) The percent air voids in the bituminous mixes.
    e) The type, shape, and angularity of the aggregates in the bituminous mixes.
    f) Mixing and compaction temperatures.
    g) A preliminary quality control plan.
    h) A preliminary finger printing procedure to identify polymer/fiber/rubber types and content.
    i) A recommended set of specifications.
    j) Preliminary recommendations relative to PMA recyclability.

→ The original objectives of this part of the study include the development of asphalt mix design procedures based on the engineering properties and performance of the bituminous mixes. During the course of the study, the Technical Advisory Committee (TAC) recommended the use of one common aggregate. The aggregate was obtained from Spartan Asphalt. Seven aggregate gradations were established. Unfortunately, only one gradation met the MDOT specifications relative to air voids and VMA. Hence, the TAC approved the use of one aggregate and one gradation and the existing MDOT asphalt mix procedure.

a) Aggregate Gradation - The asphalt mix design procedure, the aggregate gradation, the aggregate mixing condition, void analysis, and morphology analysis for polymer modified asphalt aggregate mixtures are presented in Chapters 5-II. The aggregate gradation used throughout this study was selected based on a trial and error procedure. As stated above, seven aggregate gradations (G1 through G7) were made. The asphalt mixtures were made and compacted using the Marshall mix design procedure. The G7 gradation satisfied the MDOT specifications of voids in mineral aggregate (VMA) and the MDOT criteria for asphalt mix design. The G7 gradation was accepted by the Technical Advisory Committee (TAC) and hence it was used throughout the study. Since only one aggregate gradation was used, no recommendation can be made relative to changes to the MDOT aggregate gradation specifications or the optimum aggregate gradation to be used for PMA.

b) Percent Sand and Fines in the Aggregate Mixes - The percent sand and fines in the aggregate mixes satisfied the applicable MDOT specification (see sections III.3.1, 3.2 and 3.3). Since one aggregate gradation was used, no variations in the fine and sand contents were studied and hence, no recommendation can be made relative to the optimum percent sand and fine contents.

c) The Percent Voids in Mineral Aggregates (VMA) – For the same reasons stated above, only one VMA values was used throughout the study. Consequently, no optimum VMA value can be recommended.

d) The Percent Air Voids in Bituminous Mixes - For the same reasons stated above, a target air voids in the asphalt-aggregate mixtures of 3.0 % was used throughout the study. Once again, no conclusion can be reached relative to the optimum percent air voids.

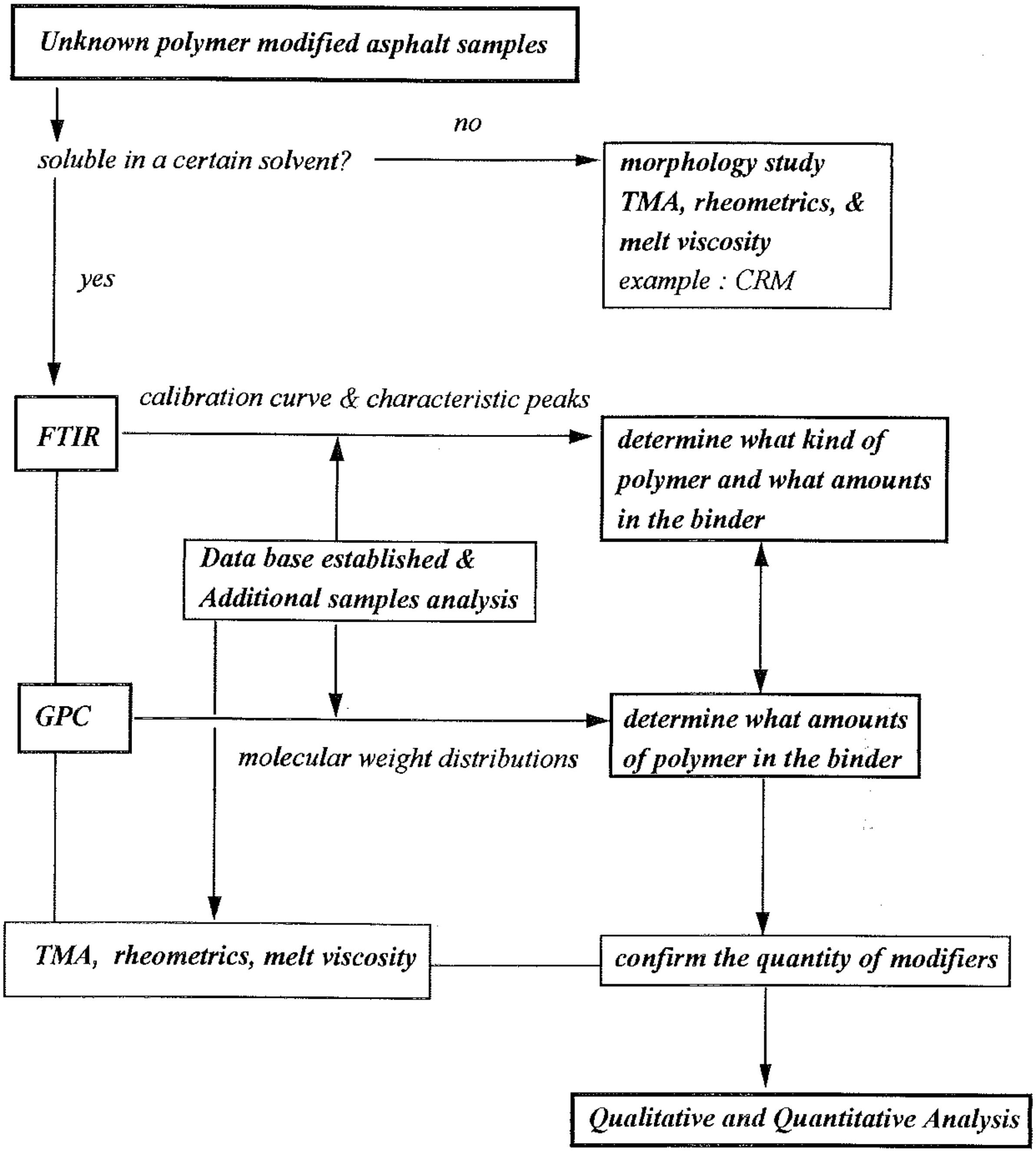
e) The Type, Shape, and Angularity of the Aggregates in the Bituminous Mixes - The type and shape, and the angularity of the aggregates satisfied the applicable MDOT specifications. Since one aggregate source and one gradation were used, no variations in the aggregate type, shape, and angularity were analyzed in this study and therefore no recommendations can be made relative to the optimum values of these variables.

f) Mixing and Compaction Temperatures – For straight asphalt mixtures, the mixing and compaction temperatures were set as 290°F based on MDOT procedures. For polymer modified asphalt mixtures, new mixing and compaction procedures were developed. The mixing and compaction temperatures were selected based on providing viscosity value within the range used for straight asphalts and based on the range of temperatures recommended by industry.

g) A Preliminary Quality Control Plan – The MDOT quality control procedures were written relative to straight asphalt-aggregate mixtures. During this study, finger printing procedures were developed whereby the type and content of polymer can be identified. It is recommended that these procedures for PMA mixtures be included in the existing MDOT quality control methods. To characterize an unknown binder, core information such as chemical and physical properties, compositions, and sources of straight asphalt binders, polymer modifiers, and modified asphalt binders will be needed for the establishment of the preliminary quality control plan.

h) Finger Printing Procedure : A finger printing protocol was developed as shown in the flow chart (Figure 1) in order to identify unknown polymer and to determine the amount of polymer in modified asphalt binders. The protocol can be used to determine what polymers were actually added to asphalt binders and in what amounts. Samples of the core of asphalt aggregate and/or binder can be analyzed with this finger printing protocol. Additional materials such as samples of neat polymer, unmodified asphalt, and polymer modified binder are required if the polymer and asphalt properties are not available in the data base for comparison purposes. A data base of materials including several polymers and an asphalt binder from one source was established during this project. The protocol involves using FTIR, GPC and other physical properties tests such as TMA, rheometrics and melt viscosity measurements and comparing results for the unknown with data in the data base if available or comparing with data developed for the specific polymer and asphalt in question. FTIR is used to examine the chemical functional groups present in an asphalt binder as well as the modifier content in the binder with the use of a calibration curve. The binders need to have characteristic functional groups to be specified with FTIR. GPC results combined with FTIR results can give information on the amount of the modifier in the binder. GPC is used to examine the molecular weight distribution of an asphalt binder as well as the determination of the amount of a certain polymer modifier added. The binders need to be dissolved in a certain solvent for running in GPC. The finger printing protocol for binders with insoluble modifiers such as CRM does not include GPC and FTIR but includes a morphology study to identify the nature of particles and other physical properties tests. In this case, it is necessary to have a sample of the particles added. The relatively high molecular weight portion on GPC curve can indicate the polymer modifier in the binder or simply oxidation products due to the extreme mixing/curing conditions. In some cases, it is difficult to determine if property enhancement is due to addition of polymer (for example, Elvaloy® AM) or oxidation of the asphalt. This is due to the fact that, in FTIR, EAM has a characteristic peak which is the same as that for oxidized asphalt. So in these cases, it would be necessary to have a sample of the new polymer and unmodified asphalt for comparison purposes. The protocol for the oxidation or aging effects is based on both GPC tests and FTIR measurements, specially in case of Elvaloy® AM modified binders and oxidized asphalt which have similar C=O characteristic peaks. GPC and FTIR are used for both qualitative and quantitative analysis. To further verify effects of polymer modification, other properties are to be measured as part of the protocol. These include TMA, rheometrics, and melt viscosity measurements. Thermal mechanical analysis is used to look at the melt temperatures and softening points of the binders modified with the modifiers. A Dynamic Shear Rheometer is used to measure the storage modulus (G'), loss modulus (G") and

Figure 1 Flow Chart for Finger Printing Protocol



Tanδ of all binders at service temperatures. These values are converted to the dynamic shear moduli (G*/Sinδ) and to determine the SHRP specification performance grade. The BBR instrument is used to measure the stiffness and m-values of the modified binders that had been aged at normal conditions to be sure this specification is met even though the m-value did not appear to be a function of polymer content for materials in this study. Melt viscosity should be used to evaluate melt viscosity of the binders to match the industry processing standard. These tests reflect the changes due to the addition of modifiers and can confirm the quantity of modifiers added in some cases.

i) A Recommended Set of Specifications - Most of the SHRP binder specifications for unmodified binders are recommended for use for polymer modified binders but the low temperature specification may need to be modified for PMA binders. A new low temperature specification has not been recommended yet but more work needs to be done to establish this. Moreover optimum polymer content is also specified based on the type of the polymer used. In general, it is some percent of the asphalt content and based on the rheological properties of the binder. The results of this study indicate that the existing MDOT specifications need to be enhanced to address polymer-asphalt mixtures. It is recommended that the following specifications be added to the existing straight asphalt mixture specifications.

- Prior to mixing, preheat the asphalt and the polymer to the specified temperatures of 350°F for SBS, SEBS and SBR polymers and of 380°F for Elvaloy® AM polymers .
- Mix the asphalt-polymer for a period of 2 hours using a high shear mixer with 1,600 rpm.
- During mixing, maintain the temperature of the asphalt-polymer mix at 350°F for SBS, SEBS and SBR polymers and at 380°F for Elvaloy® AM polymers .
- Preheat all aggregate asphalt-polymer and compaction equipment (molds and hammer) to the proper temperature specified in item 3 above.
- Mix and compact the asphalt-polymer and aggregate using the existing MDOT asphalt mix and compaction specifications. Care should be taken to maintain the polymer-asphalt-aggregate mixture temperatures close to those specified in item 3 above.

During the polymer-asphalt aggregate mixing, it was noticed that the PMA mixtures were easy to handle at these levels of temperatures. The MDOT procedure (the Marshall procedure) regarding the mixing and compaction of the asphalt-aggregate mixtures was used throughout this study. One other point should be noted that recently, MDOT has added superpave mixes to its asphalt mix list. The new MDOT specifications relative to superpave mix and compaction procedures were not analyzed in this study.

j) Preliminary Recommendations Relative to PMA Recyclability – Polymer modified asphalt should be recyclable but the mixing conditions may need to reflect the conditions for the specific polymer. The recyclability of PMA mixtures may be determined by using the fingerprinting analyses and other properties measurements as was discussed in this report along with measurements to determine the SHRP specifications. Especially, the recycle of rubber waste from scrap tires has been steadily considered as an environmental solution in rubber industry. Since environmental issues are raised, addition of crumb rubber to asphalt pavement represents a potential application for scrap tires. The addition of crumb rubber into the binder was shown to improve the low temperature ductility.

6. The effects of storage temperature and time on the engineering properties and performance of the asphalt mixes.

→ Environmental effects as well as the effects of storage conditions for the asphalt binder aggregate mixes were studied during Phase II.

Based on the adhesion properties, the effect of storage time at the processing temperature on the lap-shear test results showed that the high temperature (375°F) storage for 24 hours deteriorated asphalt binder properties regardless of polymer modification except the Elvaloy® AM system. In the case of the EAM binders, the lap-shear properties are improved after 24 hours curing under N_2 environment. It can be concluded that the EAM modified binders need to be cured for longer time and under air-sealed or N_2 purged environment, which may cause some conflict in real pavement process. From the optical microscopic examination, the low adhesive strength was simply due to poor wetting of binders onto the rock substrate which was mostly caused by thermal degradation and/or loss of low molecular weight oil phase.

When the PMA mixtures stored for 7 days at 140°F, the resilient modulus showed no significant difference from that of unaged asphalt mixtures at room temperature (77°F). After the oven aging, a considerable increase in resilient modulus at 140°F was found in the PMA mixtures with respect to unaged samples. The aged mixtures showed slightly lower resilient modulus than the unaged mixtures at a low temperature of 23°F.

7. A draft implementation plan for Phase III of this study that will include a field experiment design matrix, long term pavement performance monitoring, and a pavement instrumentation plan.

→ Based on the results of Phase II as well as literature reviews and discussions with other research teams, there is a need for additional studies.

Phases I and II provided a portion of the foundation for utilizing polymer modified asphalt for improving roads. In order to take full advantage of this advancing technology, a Phase III study is necessary with the objective of assessing and improving long term asphalt pavement performance. The goals of this Phase III study are

1) conduct long term road tests on several test sections of polymer modified asphalt pavement to determine performance,

2) obtain and evaluate test data on road performance and develop a predictive method for long term pavement performance and

3) conduct important research to investigate additional issues as recommended in the Phase II study: namely, EVA, various asphalt sources, specifications, quality assessment and control, cost and benefits, mix protocol, multiple modifiers and additional polymers.

Results of these field tests and research will be used to relate actual pavement performance to laboratory results of the Phases II and III studies and to determine the actual costs and benefits for polymer modified asphalts.

The main focus of this program will be the relation of the laboratory results from Phases I, II and III to long term pavement performance (LTPP). From Phases I and II of this project, it was concluded that modified asphalts did indeed perform better than neat asphalts. The actual road test results and results from additional research will be used as input to define new road tests if needed. It is anticipated that the overall project will be carried out over about 12 years (approximately 2 years for detailed planning and construction plus 10 years to obtain and analyze data and to conduct research). The pavement performance is related to the processing of a binder in which the binder properties are controlled by the chemical, physical, and thermodynamic properties of asphalt, modifiers, and processing conditions; the production of a binder/aggregate mix in which the mix properties depend upon the properties of binders and aggregates as well as the mixing plan; and the pavement construction in which the performance is a function of mix properties, construction practice, pavement design, and environmental considerations.

v. The effectiveness of the additives in terms of costs and benefits

The benefits of adding polymers to asphalt were determined strictly in terms of improved laboratory performance. Data regarding field performance will be obtained during the third phase of this project and a transfer function will be developed that relates the laboratory performance of compacted AC mixtures to pavement performance.

SBS polymers cost \$2.55 per kilogram (SBS Kraton® D1101, 1997 dollars). With addition of amount of 3% (w/w) for SBS, the SBS modified asphalt binder would cost \$197 per ton of the binder. The SBS modified asphalt binder was prepared at 350°F for 2 hours in the laboratory. In industry, the SBS modifier is first blended with asphalt at high concentrations such as 12-15%(w/w) using a mixing condition like our laboratory mixing condition. Then, the polymer modified binder is mixed with aggregate and additional asphalt binder in a conventional mix plant to achieve a desirable polymer content in the mix. Without considering the processing cost which was not available, the SBS modified binder mixture costs $34.38 per ton of the mixture compared to the cost per ton of unmodified AC mixture of $29.64. The cost of SBS PMA mixtures was calculated to be 16 percent more than the straight mixtures. Modification of asphalt with SBS resulted in enhanced high temperature properties of the binder. With addition of optimum amount (3-5% (w/w) for SBS), the high temperature Performance Grade of the Strategic Highway Research Program (SHRP) specifications was improved by up to two grades. The SBS modified asphalt mixtures considerably increased the indirect tensile strength, toughness, and resilient modulus at room temperature (77°F) and high temperature of 140°F.

SEBS costs $5.02 per kilogram (SEBS Kraton® G1650, 1997 dollars). The SEBS modified asphalt binder was mixed at 350°F for 2 hours in the laboratory. The mixing procedure of the SBS modifier in the field is similar with that of SBS system which is first blended with asphalt at high concentrations such as 12-15%(w/w) and then, the binder is mixed with aggregate and additional asphalt in a conventional mix plant to achieve a desirable polymer content in the mix. The benefits and the effects of SEBS modification on the asphalt binder mix pavement are very similar to SBS but the cost of SEBS is almost as twice as that of SBS.

SBR is one of the most common polymers used for modification. SBR costs $5.02 per kilogram (Ultrapave® UP 70, 1996 dollars). The cost of the SBR modified binder mixtures is about 32.60 dollars per ton of the mixture. SBR is vigorously mixed in a conventional mix plant for relatively short time. According to the supplier, no additional facility is required and the existing mix equipment can be used. The laboratory mixing condition was determined to be 30 minutes at 350°F. An SBR content of 3% (w/w) improves the high temperature performance one grade, while a content of 5% (w/w) improves it by two grades. SBR acts as a dispersed polymer while at higher contents a network forms inside the asphalt. This network lends support to the asphalt at high temperatures improving rutting resistance. The mixtures modified with SBR increased the indirect tensile strength at high temperature of 140°F and toughness at low temperature of 23°F. This shows improvement in resistance to the rutting and temperature cracking, respectively.

Elvaloy® AM is a reacting polymer which bonds to the asphalt rather than forming a physical Elvaloy® AM/asphalt network. The high temperature performance grade was the highest of any modifier used in this study. One of the reasons for the large increase in performance grade compared to the virgin asphalt is the high mixing temperature (380°F) and long mixing time (up to 24 hours) condition which causes severe oxidation which leads to stiff binders. Because of this reactive process, the mixing procedure is very sensitive to thermal gradients and environment. Mixing in nitrogen instead of in air helped the retardation of the oxidation of the binders. The premixing condition results in additional processing costs. Reactive EAM modifier requires a special mixing procedure which needs separate binder and polymer mixing under nitrogen (if necessary) before adding aggregate as shown in the schematic diagram in Figure 2 unlike the other modifiers. Elvaloy® AM also costs $4.85 per kilogram (1996 dollars) which is twice as expensive on a per kilogram as the other polymers such as SBS and SBR but only one half as much as is required to achieve improved binder properties. The cost of the mixture with 1.5% EAM binder is about $33.49 per ton. Based on the laboratory engineering properties, the EAM polymer shows very high benefits in improved fatigue life by as much as 15 times that as the straight binder mixture. However, it should be noted here that EAM modified AC mixtures showed aging behavior during the severe processing conditions, which caused the mixes to be stiffer. Mixing in nitrogen instead of in air helped the retardation of the oxidation of the binders. The low temperature SHRP performance grade was equal to or one grade worse than that of the base asphalt.

Recycled crumb rubber in asphalt for modification is of high interest. This is driven by the environmental problem of disposing of used tires. Even though the CRM itself does not cost a lot ($0.77 per kilogram; Ultrafine GF-80, 1996 dollars), the binder requires as much as 15% (w/w) of CRM in the binder to show the improvement of the high temperature performance grade as the other modifiers. The cost of CRM modified asphalt binder (15% (w/w)) mixture is about $35 per ton. There are two mixing methods used in the asphalt industry to combine CRM powders with asphalt : the 'wet' and the 'dry' methods. The dry method involves adding CRM particles to the asphalt and aggregate in the mix plant and it is simple but is limited to producing asphalt mix. The wet method can have many applications but require additional equipment for premixing at 380°F for 1-2 hours due to the viscosity of the CRM binders. Dynamic shear rheometry shows that addition of CRM results in an improvement of the high temperature performance grade by one grade for every 5% (w/w) CRM. Viscosity tests show that up to 15% (w/w) CRM can be added to the binders while maintaining a processable viscosity. The CRM modified asphalt mixes increased the indirect tensile strength at high temperature of 140°F and toughness at low temperature of 23°F. Studies indicated that it may need a long term (24 hours) high temperature mixing or storage of the CRM binders to acquire full swelling reaction with the binder and that the presence of CRM either masks or retards the aging process.

EVA ($2.11 per kilogram; Polybilt 152) appears to be a promising modifier which does not suffer from some of the problems of the other modifiers. It dissolves well in asphalt at the same conditions as SBS blending. Polybilt modified asphalt is usually handled as standard asphalt (350°F for 1-2 hours). Due to the viscosity of the EVA modified binders, increasing mixing temperature up to 25°F from conventional mixing condition may be required. It improves the high temperature performance one grade with 3% (w/w) polymer and the viscosity remains low enough to process 7% (w/w) EVA modified binders. The low molecular weight polymer can be blended at lower temperatures for shorter times. This can improve the low temperature properties of the modified binder. While these results are still preliminary, it appears that EVA may a good choice for asphalt modification.

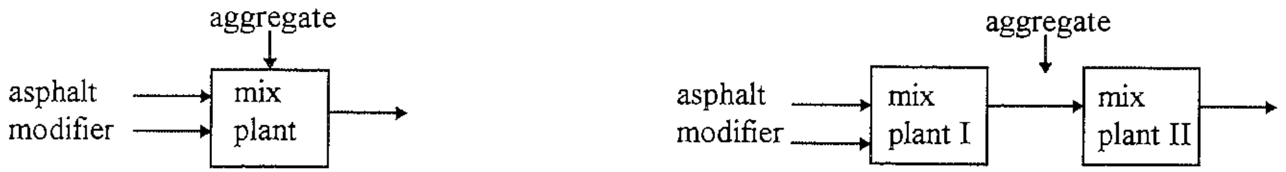
These estimated benefits are based on laboratory test data for the PMA mixtures. Verification of benefits and cost is possible after the field data are obtained and processing costs are determined. In the laboratory, the binder mixing conditions for each modifier were somewhat different as shown in Table 2 and the processing costs are expected to be related to the laboratory conditions.

vi. Recommendation of future work

The details related to the recommended future work are discussed in Chapter 7. Future work is recommended as follows:

1. The use of multiple asphalt sources and various aggregates to allow generalization of the results.
2. Determination of the relationship between a binder's chemical properties and its physical properties.
3. Detailed investigation of failure behavior in the interface (interphase) of asphalt binders and aggregate.
4. A road test section with various polymer contents to enable better interpretations of laboratory data and how that data can be better applied to real world paving applications.
5. An investigation into the applicability of the current SHRP low temperature tests for polymer modified binders.
6. Investigate mixtures of polymers

Figure 2. Mix Plant



Type I : SBS, SEBS, SBR, EVA and CRM

Type II : reactive EAM

Table 2. Laboratory Mixing Conditions

	Neat AC-5	3% SBS @ $1.16/kg	3%SEBS @ $2.28/kg	3% SBR @ $2.42/kg	1.5% EAM @ $4.85/kg	3% EVA @ $2.11/kg	12% GF-80A @ $0.77/kg
asphalt	$125	$121	$121	$121	$123	$121	$110
modifier	$ 0	$ 35	$68	$73	$ 73	$63	$ 93
binder cost (ton)	$125	$156	$189	$194	$196	$184	$203
binder mixing	n/a	350°F/ 2 h	350°F/ 2 h	350°F/ 0.5 h	380°F/ 2 h	350°F/ 2h	350°F/ 2h
aggregate mixing	290°F	350°F	350°F	350°F	380°F	n/a	350°F

3. Research Objectives

The effects and benefits of adding polymer and crumb rubber to asphalt pavements were systematically and extensively investigated during Phase I. Findings in Phase I showed that polymer modification can improve the performance of asphalt mixes based on laboratory tests. The objectives of Phase II are discussed below. To predict performance of modified asphalt surfaced pavement, the chemical and thermo-mechanical properties of the modified asphalt binders need to be obtained. The microstructures, failure mechanisms, and engineering properties of both binder and binder/aggregate mixtures need to be understood in order to relate PMA composition to PMA pavement performance. Adhesion between binder and other mixture constituents such as aggregates and particle additives is also important in understanding pavement performance. Although laboratory tests will indicate the improved performance of the binders and mixes, field data need to be available to quantitatively predict pavement performance and thereby predict the economic benefits of adding modifiers to asphalts. The detailed results for each objective are discussed in Chapter 4, 'Strategic Research Milestones'.

The objectives of Phase II

1. *Establish performance based criteria for selecting asphalt binder modifiers for a given asphalt binder grade.*
   To predict performance based criteria for modified asphalt surfaced pavement, the thermo-mechanical and rheological properties of the modified asphalt as well as binder morphology and engineering properties were obtained. These properties could establish their own criteria in selecting modifiers but overall performance based criteria could not be easily established because of the road tests were not performed during Phase II.

2. *Research on relationships between the 'chemical and physical properties' of the modified asphalt binders and the 'thermo-mechanical and rheological properties' of the asphalt binders.*
   The asphalt binder properties, polymer modifier properties, and their interaction fundamentally affect the binder blend properties. The fundamental information on the binders' chemical and physical properties such as the molecular weights of polymers and the asphalts was studied to gain a better understanding of the binders' rheological and thermo-mechanical properties. Important factors such as asphaltene content and polarity were investigated in order to develop predictive performance models. These fundamental information were critical to investigate the performance of pavement. Recyclability of recovered asphalt binders-mixes

was also determined based on the information, which is getting more important in Michigan as in the other states. The thermo-mechanical and rheological properties of the asphalt binders were studied to choose the proper binder types and modifications under severe Michigan weather. This goes hand in hand with the use of many different asphalt sources.

3. *Study the effects of static and cyclic loads, low and high temperatures, and various environments on the morphology and microstructure characteristics of the asphalt binders and asphalt-aggregate mixtures.*

   Microstructural and morphological information of mixtures is important in predicting pavement performance based on the physical and chemical data of binders and aggregates. This goal could be fulfilled by conducting four tests: morphology analysis, fracture tests, void analysis, and binder/aggregate bonding analysis. The determination of failure mechanisms in the interface is important to the understanding of asphalt mixture properties. The mechanisms are functions of binder properties, aggregate properties, binder-aggregate adhesion and void concentration and distribution. To characterize the failure mechanism and the locus of failure of modified asphalt concrete, it was necessary to use the microscopic observation methods available in the Environmental Scanning Electron Microscope (ESEM). This allowed direct viewing of the surfaces at high magnifications. This test provided information on void formation, surface crack initiation, crack propagation and crack bridging mechanisms of both modified and unmodified asphalt concrete sections. The failure mechanisms and morphological properties of both binder and binder/aggregate mixtures were affected by combinations of static and cyclic exposures of moisture, temperature, and load.

4. *Determine the engineering properties of the modified asphalt binders and the binder-aggregate mixtures over the range of environmental and load conditions.*

   Throughout the State of Michigan, several types of distress can be found on asphalt surfaced pavements. These include thermal cracking, aging, fatigue cracking, rutting, raveling and stripping. The distress mechanism varies from one type of distress to another and it is influenced by the structural properties of the pavement layers and the roadbed soil, construction practices, traffic load and volume, and environmental conditions. The various engineering properties (such as indirect tensile strengths, fatigue life, resilient modulus) of asphalt mixtures were determined. The binder mixtures were exposed to various combinations of low and high temperatures and static and cyclic loads. Mostly, the engineering properties of the mixes depended on the modifiers and the amounts in the binder mixtures. The detailed properties are discussed in Chapter 4. III.

5. *Identify test types, SHRP specifications, and critical values for the acceptance and rejection of modified asphalt based upon established performance criteria.*
Polymer modified asphalt binders could be characterized based on Gel Permeation Chromatography (GPC), Fourier Transform Infrared (FTIR) spectroscopy, Thermal Mechanical Analysis (TMA), Differential Scanning Calorimeter (DSC), melt viscosity measurement, Dynamic Shear Rheometer (DSR), and Bending Beam Rheometer (BBR). Mainly, the rheological properties ($G^*/\sin\delta$) of the binders were used to determine the high temperature SHRP specification. Aged binders were analyzed using the Bending Beam Rheometer to determine the low temperature SHRP performance grade. Although the SHRP PG also depends on the other properties, it has been shown that the m-value is the major factor that has control over the low PG in every case. Homogeneous mixing behavior is one of the most important factors in determining the suitability of the polymer modified binders. The mixing behavior was studied by using several test such as FTIR, GPC, TMA and it determined whether the modified asphalt binders could be accepted or rejected. The acceptance and rejection of the modified asphalt binders would also depend on the selection of proper modifier and its amount required to reach the desired SHRP performance grade or criteria.

4. Strategic Research Milestones

Research results of Phase II are summarized according to the proposed milestones for each research area. A comparative study between unmodified and modified asphalts was carried out in each part. Research tasks in Phase II include:

1. Selecting modifiers for comparative analysis based on the findings in Phase I. The selection should be based on the availability of materials to MDOT, costs, and performance requirements in Michigan.

   → A few modifiers (SBS, SEBS, SBR, Elvaloy® AM, CRM, and EVA) were selected for Phase II study. Optimum asphalt binders/modifiers mixing conditions and binders/aggregates compacting conditions were also determined.
2. Measuring critical properties using methods applicable to both modified and unmodified binders and binder/aggregate mixes.

   → The fundamental chemical and physical properties were determined. Thermo-mechanical and rheological properties were critical to determine the binder's pavement performance. The basic microstructure and morphology study for the binder and aggregate mixture were parallel conducted with the engineering properties evaluations.
3. Relating asphalt and modifier properties as well as processing conditions to binder properties; relating binder and aggregate properties as well as mixing plans to mix properties; and relating mix properties and simulated service conditions to pavement performance.

   → The viscosity grade of asphalt binders played an important role to determine the mixing conditions of the binders with polymer modifiers. The binders should be processed homogenous enough to show consistent properties in pavement and binder itself. The polymer modified binder's properties at high and low temperatures are very related to the original unmodified binders.
4. Identifying the fundamental properties in each relationship in task 3 and verifying the predictive models for each step for both modified and unmodified asphalts.

   → The rheological properties of the polymer modified binders were main factors for the determination of suitability of the binders. Aggregate-asphalt binder adhesion behavior was investigated. Fracture toughness and crack propagation of asphalt concrete with the modifiers were studied during the project. The load deformation behavior of unmodified and modified asphalt mixtures were also studied by using the indirect tensile cyclic test. The study of fatigue behavior and the tensile properties of the asphalt mixtures at various levels modification was also conducted. Environmental durability of asphalt binder and asphalt concrete with modifiers studied was also determined during the project.

5. Determining the suitability of SHRP and MDOT specifications and recommending test methods and specifications for modified and unmodified binders and binder/aggregate mixes for use on Michigan roads.

   → In order to determine the suitability of the use of the binders and mixes for specific paving applications, the development of performance based binder specifications is needed. Several specifications are currently being used and specially, the Strategic Highway Research Program (SHRP) performance based asphalt binder specifications have been widely adopted to evaluate both unmodified and polymer modified binders. The SHRP tests simulate the three critical stages of the binder's service life: neat binders, processing aging, and long term aging. Aging during processing and/or compaction is simulated in the laboratory by using Thin Film Oven Test (AASHTO T 240; ASTM D 2872) and long term aging during service life is simulated by using Pressure Aging Vessel Test (SHRP B-005).

6. Preparing final reports based on the findings in Phase II and recommending research plans for Phase III.

The detailed proposed research tasks and results will be shown in I-III below.

Budget for Phase II

Proposed:	$ 998,000
Approximate Spent:	$ 1,002,000

I. Fundamental Chemical, Physical, and Thermodynamic Properties of Modifiers, Asphalts, and Binders

Proposed:	Collection of materials to be used in phase II including: asphalt binders and modifiers.
Results:	Met. Four viscosity grade asphalt binders (AC-2.5, 5, 10, and 20) were collected from Amoco. The modifiers used for the project and their suppliers are as follows : SBS and SEBS (Shell), SBR latex (Textile Rubber and Chemical), Elvaloy® AM(Dupont), CRM(Rouse Rubber), and EVA (Exxon).

Proposed: Review of the basic characteristics of the selected modifiers.

Results: Met. All relevant information has been gathered from suppliers and other sources. The information of the modifiers was reviewed in Chapter I.

Proposed: Determination of optimum mixing condition of SBS and SEBS with various asphalt binders used during Year 1.

Results: Met. The optimum mixing conditions based on rheological data have been determined to be '350°F for 2 hours' for AC-5/SBS, AC-5/SEBS, AC-10/SBS and AC-10/SEBS blends series.

Proposed: Determination of optimum mixing condition of SBR with various asphalt binders used during Year 2.

Results: Met. The optimum mixing conditions based on rheological data have been determined to be '350°F for 30 minutes' for AC-2.5, 5, 10 and 20 binders with SBR.

Proposed: Determination of optimum mixing (curing) conditions of Elvaloy® AM modifiers with various asphalt binders used during Year 2.

Results: Met. The optimum curing times based on rheological data have been determined to be '380°F for 2 hours' for AC-2.5/EAM, AC-5/EAM and AC-10/EAM blends series. However, the mixing condition developed for AC/EAM blending system in air could be modified by mixing in nitrogen. The mixing in the nitrogen atmosphere minimized the chance for the binders to be oxidized during mixing. Without severe oxidization, the binders could be further mixed at 380°F for obtaining fully cured asphalt/ EAM binders.

Proposed: Determination of optimum mixing conditions of CRM modifiers with various asphalt binders used during Year 3.

Results: Met. The optimum CRM mixing conditions (350°F for 30 minutes) for AC-10 and AC-20 binders based on rheological data have been determined for the blends.

Proposed: Determination of optimum mixing conditions of EVA modifiers with various asphalt binders used during Year 3.

Results: Met. The optimum EVA mixing conditions (350°F for 2 hours) based on rheological data and visual observation on the homogeneity of the blends.

Proposed:	Determination of optimum amounts of modifiers for asphalt binders.
Results:	Met. The optimum amounts determined based on rheological properties and economical concerns for all of the modified asphalt binders. The results are summarized in Chapter 5.
Proposed:	Determination of softening points and melting points of the binders used.
Results:	Met. The glass transition temperatures (T_g) of AC-5 and AC-10 were measured by using differential scanning calorimetry (DSC). DSC was also used to characterize the change of physical and steric structures of asphalts upon quenching. The softening points and melting points of SBS (AC-5 and 10), SBR (AC-2.5, 5, 10, and 20), Elvaloy® AM (AC-2.5, 5, and 10), CRM (AC-5, 10, and 20), and EVA (AC-5 and 10) modified asphalt blends were determined using thermal mechanical analysis (TMA). The results of the softening and melting points of the binders are summarized in Chapter 5.
Proposed:	Determination of molecular weight distribution of the binders used.
Results:	Met. Gel permeation chromatography (GPC) was used to examine the molecular weight information of SBS, SEBS, EAM modified asphalt binders as well as modifiers and asphalt binders. Gel Permeation Chromatography (GPC) was also used to examine the molecular weight information of aged asphalt binders. However, SBR, CRM, and EVA modified binders could not be tested because of their insolubility in the solvent (THF) used for a current GPC system.
Proposed:	Determination of useful chemical functional groups of the binders used.
Results:	Met. Fourier-Transform Infrared Spectroscopy (FTIR) has been used to analyze polymers as well as aged and unaged polymer modified asphalt binders. FTIR has been used to analyze polymers (SBS, SEBS, SBR, Elvaloy® AM, and EVA) as well as the modified AC-2.5, AC-5, AC-10, and AC-20 binders.
Proposed:	Laboratory aging of selective binders using SHRP equipment.
Results:	Met. Selective binders were aged using the Thin Film Oven (TFO) and Pressure Aging Vessel (PAV) tests at normal conditions. The SHRP tests simulate the three critical stages of the binder's service life: neat binders, processing aging, and long term aging. Aging during processing and/or

compaction is simulated in the laboratory by using TFO test (AASHTO T 240; ASTM D 2872) and long term aging during service life is simulated by using PAV test (SHRP B-005). One of the most addressed SHRP binder specifications is the measurement of the rheological properties of the binders at different temperatures before and after aging.

Proposed: Dynamic mechanical analysis of the binders used.

Results: Met. The optimum mixing conditions as well as the optimum modifier contents for asphalt binders were determined based on rheological properties the blends. Rheological properties of both unaged and aged asphalts were measured. Rheological properties of both unaged and aged asphalt binders were measured between -5 and 30°C (aged) or between 30 and 70°C (unaged) by using a dynamic shear rheometer (RMS).

Proposed: Bending beam analysis of the aged binders.

Results: Met. The SHRP Bending Beam Rheometer was used to measure the stiffness and m-value of the aged binders (AC-5/SBS, AC-10/SBS, AC-2.5/SBR, AC-5/SBR, AC-5/EAM , AC-5/CRM, AC-10/CRM, and AC-5/EVA) at various temperatures.

Proposed: Viscosity measurements of the binders used during the project.

Results: Met. The viscosity of all the binders mixed with modifiers (AC-5/SBS, AC-5/SEBS, AC-10/SBS, AC-10/SEBS, AC-2.5/SBR, AC-5/SBR, AC-2.5/EAM, AC-5/EAM AC-5/CRM, AC-10/CRM, AC-20/CRM, AC-5/EVA and AC-10/EVA blends) were measured at various polymer contents and temperatures using a Brookfield viscometer.

Proposed: Determinations of performance based binder specifications.

Results: Met. Both the SHRP and MDOT specifications were reviewed and commented. The rheological properties (G*/sinδ) of unaged binders were used to determine the high temperature SHRP specification. Aged binders were analyzed using the Bending Beam Rheometer to determine the low temperature SHRP performance grade. Although the SHRP PG also depends on the other properties, it has been shown that the m-value is the major factor that has controlled the low PG in every case The PG of the representative binders were summarized in the table below.

Test Temperatures Passed SHRP Specification for the Representative Binders

AC-5 Binders	High Temperature °C, (G*/sin δ)	Low Temperature °C, (S and m-value)	Final PG
0% SBR	58	-12	58-22
5% SBR	70	-18	70-28
0% EAM[1]	76	-6	76-16
1.5% EAM[1]	76	-6	76-16
0% EVA	58	-18	58-28
3% EVA	64	-18	64-28
0% CRM[2]	64	-12	64-22
10% CRM[2]	76	-12	76-22

1. mixed in air 2. with AC-10

Proposed:	Suggestion of a criterion for quality control with respect to the binder properties studied.
Results:	Met. The proposed fingerprinting protocol which was developed for straight and modified asphalt binders based on the characterization methods was suggested as a criterion in quality control of the binders.

II. Basic Morphology and Microstructure of Polymer/Fiber-Asphalt-Aggregate Mixtures

Proposed:	Collection of materials to be used including: asphalt binders, modifiers, and aggregate.
Results:	Met. All materials were collected.
Proposed:	Determination of void morphology and it's statistical quantification in terms of polymer modification using materials used during the project.
Results:	Met. Three types of voids found in asphalt concrete have been characterized. The void distribution achieved with polymer modified mixes is dependent on the viscosity of the binder at processing temperatures. It may thus be advisable to process polymer modified mixes at higher temperatures than unmodified mixes. The optimum processing conditions and aggregate gradation to optimize air-void content is an area that bears further study.
Proposed:	Identification of morphology and deformation behavior of asphalt binders with the modifiers studied during the project.

Results: Met. Systematic ESEM studies have been conducted to identify the nature of the binder network structure and to characterize (i) the combined effects of asphalt binder type and polymer modification, (ii) effects of aging of binders, (iii) effects of exposure temperature, and (iv) effects of mixing between the aged and fresh binders with respect to recycling or rejuvenation of the old asphalt pavement. Systematic ESEM and Laser Scanning Microscopy (LSM) studies coupled with the image analysis have been also carried out to identify the size, distribution, morphology of the polymer phase, and its interaction with the binder network structure in various polymer modified asphalt binders. In-situ ESEM deformation tests were utilized to investigate the network deformation behavior.

The network structure became coarse when the asphalt is aged. This had proven to be a very reliable qualitative test to identify aged binders.

Addition of SBS, SEBS, SBR and CRM to the asphalt binder did not cause a visible or remarkable change in the network structure itself even though all polymers were generally seen to slow the aging process. 0%(w/w) Elvaloy® AM modified binders which were processed at higher temperatures (380°F) appeared similar to the aged binders.

The phase morphology of SBS, SEBS and SBR latex was determined using Confocal Laser Scanning Microscopy. SBS modifier was seen to form discrete, well-dispersed spherical phases while SEBS was seen to form well-dispersed spherical phases as well as block-like particles about 5μm width and 20μm length. SBR was seen to form fine spherical 3-5μm particles at low concentration while at higher concentrations (3-5wt.%) it disperses in the asphalt binder in the form of thin linearly aligned. The phase morphology of crumb rubber (GF-80) could not be determined using the LSM technique since there is no significant fluorescence from the rubber particles. The phase morphology of Elvaloy AM which reacted with binders could not be determined by using the LSM or the ESEM, either.

Proposed: Evaluation of crack propagation and fracture toughness of asphalt concrete with the modifiers studied during the project.

Results: Met. Effects of polymer type, polymer concentration, service temperature on micro-deformation mechanisms and crack propagation modes were investigated using ESEM and in-situ deformation stage. For unmodified asphalt mixtures, it has a tendency for the fracture to proceed along the aggregate boundaries. The failure was observed to be both adhesive and cohesive. Only a few fibrils were observed across the fracture surface in unmodified concrete samples.

The fracture morphology was strongly affected by the addition of polymer modifiers. The most noticeable feature was an increase in the number of fibrils formed and their deformation behavior. The morphology seen in SEBS modified AC-5 samples was similar to that of SBS modified AC-5. But the fibril formation was not as dense as that seen in SBS. With the addition of SBR latex, the micrographs showed a high density of tough fibrils and large crack widths. The fibril density obtained with SBR was the highest amongst all the polymer modified binders studied. Fibrils were also seen to be clearly attached to the aggregates at their ends. This type of morphology is likely to prove beneficial in terms of crack inhibition and crack healing in asphalt concrete. Elvaloy AM modified AC-5 binders appeared to have a much higher stiffness compared to the other previously studied polymer modified systems. The modified binder formed coarse bridges across the crack face, but very low fibril densities were observed. With the addition crumb rubber modifiers, the asphalt binder fibrils were observed to have much higher elongation at break (~600 microns) and the fibril density showed a slight increase as compared to unmodified AC-5.

Efforts had been made to develop a most proper fracture toughness test method for the asphalt concrete materials during Year 1. The J-integral fracture toughness test method was chosen and then it's reliability and reproducibility have been examined for the asphalt concrete beam samples at various temperatures. During Years 2 and 3, efforts have been focused on two tasks, namely (i) in-situ tensile fracture behavior and (ii) fracture toughness evaluation of polymer modified asphalt concretes. The J_{IC} fracture toughness was evaluated for all polymers and can be seen in Table II.6.

Proposed: Investigation of mechanical performance of the AC concrete by characterizing aggregate-asphalt binder adhesion behavior.

Results: Met. In phase II of the program, two types of asphalt binders (viscosity graded AC-5 and AC-10) and five different polymer modifiers, namely, SBS, SEBS, SBR, EAM, and CRM in either fresh or aged (TFO/PVA processed) state were investigated in terms of polymer concentration and service temperatures.

Newly developed adhesion test methods for aggregate/asphalt binder systems, namely modified Lap-shear and Cross-lap Tension were successfully used to investigate both adhesive and cohesive failure modes. In order to evaluate the lap-shear asphalt binder-aggregate adhesion behavior, new defined energy values. i.e., elastic strain energy, tenacity and toughness were determined from all previous lap-shear test results. In general, from both Mode I cross-lap tension and Mode II lap-shear analyses, the effects of polymer modification on the adhesion behavior of asphalt binders in either fresh or aged state were strongly temperature dependent, i.e., a negative effect at higher temperatures and a positive effect at lower temperatures, normally 0°C or below. However, the degree of improvement was varied depending upon modifier types and concentration.

Both polymer concentration and test temperature dependency of the EAM modified binders were similar to those of the other polymer modified asphalt binders including SBS, SEBS, and SBR. However, even though the strength of Elvaloy AM modified binders is equivalent to or slightly higher than those of others at the higher temperature, the value drops down to the lowest at -20°C partly due to the high T_g and associated brittleness of the thermoset on the adhesion strength, or due to the high temperature processing resulting in aging or oxidation. The effect of CRM modification on lap-shear properties and behavior was not much different to any of other polymer modifiers even though the CRM concentration scale is much higher than that of the other modifiers.

It is of interest to note that the optimum polymer content in AC-10 was always higher than that of AC-5 for all polymer modifier types. This indicates that the asphalt composition also controls the binder/aggregate adhesion mechanisms. In other word, it is important to study the effects of asphalt binder sources on polymer modification. More improvement was observed from AC-5 binders than from AC-10 binders.

Proposed: Determination of environmental durability of asphalt binder and asphalt concrete with modifiers studied during the project.

Results: Met. A durability evaluation methodology was developed. Investigation of aging effects on asphalt binder/aggregate adhesion was done as a function of modifier concentration and temperature. A core durability experimental program was conducted. This core program was designed to simulate real service environmental condition involving freeze-thaw thermal cycles of asphalt binders and concretes saturated with salt-water. Effects of thermal-salt water exposure cycles on adhesion properties and behavior of polymer modified asphalt binders have been determined by the lap-shear performance. Both fresh mixed and aged AC-5 and AC-10 binders modified with SEBS and CRM were studied at two different temperatures, 0°C and -10°C. Surprisingly enough, there was no dramatic property degradation or catastrophic failure due to the cycle for both fresh and aged binders regardless of polymer modification. The fracture morphology of unmodified asphalt concrete samples undergoing thermal-cycling durability tests showed a slight coarsening of the binder. The polymer modified asphalt concrete samples did not show any change in the morphology from that of fresh samples.

III. Basic Structural and Engineering Properties of Polymer/Fiber-Asphalt-Aggregate Mixtures

Proposed:	Collection of materials to be used during the project.
Results:	Met. Materials including asphalt binders, modifiers and aggregates are collected.

Proposed:	Experimental outline and set up as well as aggregate preparation.
Results:	Met. The coarse and fine aggregates used in the asphalt mixtures were obtained from Spartan Asphalt and were stored at the storage facility of MSU in four different piles according to the aggregates sizes. A mix design of the straight and the modified asphalt mixtures was conducted using the standard Marshall Mix design procedure and the gyratory compactor. The temperature-controlled chamber for the MTS system was used to conduct two types of tests to evaluate the structural properties of straight and polymer modified asphalt mixtures. These includes; Indirect Tensile Cyclic Load Test (ITCT) and Indirect Tensile Strength Test (ITST). For all tests, Marshall size samples (4-inch diameter & about 2.5-inch thick) were used. To accomplish the objectives of this study, several materials and test methods were used. Prior to commencement of the tests, experiment design matrices for ITT and ITCT were established.

Proposed:	The physical properties of asphalt-aggregate mixtures.
Results:	Met. The physical properties of the aggregates such as specific gravity, absorption capacity and durability were evaluated. Marshall mix design

procedure was used to determine the suitable aggregate gradation and the physical properties of the mixes which satisfy MDOT specifications.

Proposed: Study of indirect tensile strength test of the asphalt aggregates mixtures.

Results: Met. The modified asphalt mixtures with SBS, SEBS, SBR, EAM, and CRM as well as the unmodified asphalt mixture were used to study the load deformation behavior using the indirect tensile test. AC-5 mixtures modified with 5%SBS or 5%SEBS considerably increased the indirect tensile strength and toughness at 77 and 140°F. This implies an increased resistance to rutting and fatigue cracking.

AC-10 mixtures modified with 3%SBR considerably increased the indirect tensile strength at high temperature of 140°F and toughness at low temperature of 23°F than other AC-10 PMA mixtures. This shows improvement in resistance to the rutting and temperature cracking, respectively.

AC-20 mixtures modified with 3%SBR or 2%EAM considerably increased the indirect tensile strength & toughness at 140°F, and, the toughness at 23°F. This indicates higher resistance to rutting at high temperature and temperature cracking at low temperatures. However, no significant difference in indirect tensile strength and toughness was found at 77°F.

AC-10 mixtures modified with 10%CRM showed higher indirect tensile strength and toughness at 77°F and significant increase in the toughness at low temperature of 23°F as compared to other AC-10 PMA mixtures. This indicates more resistance to temperature cracking.

Proposed: Study of indirect tensile cyclic load test of the asphalt aggregates mixtures.

Results: Met. The modified asphalt mixtures with SBS, SEBS, SBR, EAM, and CRM were used for the indirect tensile cyclic load test. Fatigue life of PMA mixtures was considerably higher than the straight AC mixtures. EAM system showed the higher fatigue life than all other polymers, followed by SEBS system. The increase in fatigue life is due to the increase in the resistance to horizontal plastic deformation with polymer modification.

AC-5 mixtures modified with 5%SEBS showed higher percent increase in the average values of resilient modulus as compared to all other polymers at 77°F. This implies more resistance to rut potential for SEBS polymer system than other polymers.

AC-10 PMA mixtures showed considerable increase in resilient modulus at high temperature of 140°F. However, SBR polymer system showed no significant difference. This indicates that other than SBR all other systems improve the resilient properties of AC-10 mixtures at high temperature. There was no significant difference between the average resilient modulus values of AC-20 straight and AC-20 PMA mixtures at the test temperature of 77°F.

No significant increase in the fatigue life and resilient modulus was found for AC-10/10%CRM mixtures.

Polymer modification improved the resistance to both vertical and horizontal plastic deformation at 77 and 140°F, which indicates more resistance to rutting and fatigue cracking. SBR and EAM modified AC-5 and AC-10 mixtures showed higher resistance to vertical plastic deformation at 77°F than other PMA mixtures. SEBS and EAM showed higher resistance to horizontal plastic deformation than other mixtures at test temperatures of 77 and 140°F.

Deformation rate showed that the PMA mixtures improved the resistance to fatigue cracking at 77°F and rutting at 140°F. EAM and SEBS polymer systems had lower deformation rate as compared to other polymer systems.

Proposed:	Study of the effect of aging on the asphalt properties.
Results:	Met. No significant difference was found in the average values of the indirect tensile strength and toughness between oven aged and unaged AC-10 PMA mixtures at test temperatures of 77 and 23°F. AC-10 and AC-20 straight mixtures showed considerable increases in the indirect tensile strength and toughness after oven aging. However, PMA AC-10 and AC-20 mixtures did not show any significant difference after oven aging at test temperature of 77°F. This indicates that the AC-10 and AC-20 PMA mixtures reduce the effect of oven aging.

5. Technical Summary

The research progress is divided into three areas of study: fundamental chemical, physical, and thermodynamic properties of modifiers, asphalts, and binders; basic morphology and microstructure of polymer/fiber-asphalt-aggregate mixtures; and basic structural and engineering properties of polymer/fiber-asphalt-aggregate mixtures. Each study includes material selection, experimentation, determination of the suitability of SHRP and MDOT specifications to polymer modified asphalt binders and mixes, identification of the fundamental binder properties and mixture morphology that control the pavement performance, and preliminary cost comparison and recyclability study.

I. Fundamental Chemical, Physical, and Thermodynamic Properties of Modifiers, Asphalts, and Binders

The overall goal of this study is to obtain fundamental information about modifiers, asphalts, and binders. This information is essential to understand why the binders behave in a certain way. By relating these fundamental properties to the engineering properties of binder and mixture, morphology properties, and pavement performance, the controlling fundamental properties can be identified. It is the intent of this task to provide enough fundamental data of modifiers and asphalts to predict the engineering properties of binders. The experimental tests in this task focus on the asphalt and modifier characterization and relationships of properties to performance.

1.1. Determination of Optimum Mixing Conditions

The final performance properties of an asphalt/polymer blend are directly related to the mixing procedure used. The mixing procedure is dependent on four main variables: materials, temperature, time, and shear. Increased time, temperature, and shear will enhance mixing, but will also increase aging and degradation of both the asphalt and polymer. Optimum mixing conditions for asphalt modification were defined based on rheological properties of asphalt/polymer blends. The optimum s defined as the point at which there is no longer a significant increase in the rheological properties with increasing polymer modifier content.

An industry standard to confirm the homogenous mixing of asphalt and polymer is visual observation. However, this could to be a poor practice for laboratory procedures. The laboratory developed procedure calls for heating of the asphalt to 270°F for one hour (to obtain a good melt) followed by mixing of polymer and asphalt with a certain mixing temperature and time depending on the polymer modifier. It is suggested that MDOT asks the suppliers for their mixing procedures to catch any obvious flaws in the procedure.

Mixing procedures of SBS and SEBS polymers with asphalt binders were developed based on the supplier's information. It is suggested that the mixing temperature does not exceed 350°F to avoid the degradation of the polymers. The optimum mixing time was confirmed based on the rheological properties to insure optimum binder performance. AC-5 and 10 grade asphalt binders were prepared by mixing at 350°F for 2 hours with a high stirring speed of 1600 rpm.

For the mixing of SBR latex with asphalt binder, four different AC (2.5, 5, 10 and 20) grades binders were prepared. In Figure I.1, the mixing time of 30 minutes at 350°F was enough to show desirable rheological properties to but the binders looked inhomogeneous and seemed to have unstable phase behavior. This is often characteristic of SBR modified binders. The current industry practice is to flash evaporate the latex into the hot mix, which may provide sufficient mixing due to the violent nature of the evaporation.

Mixing procedures were also developed for the Elvaloy® AM/asphalt blends. The supplier recommended higher mixing temperature (380°F) and longer mixing time (up to 24 hours) in nitrogen. However, mixing in nitrogen is not practical in real world. As references, Elvaloy® AM modified asphalt binders were mixed at 380°F for 2 hours in nitrogen atmosphere and the container of the binder was nitrogen purged, sealed and stored in a hot oven (380°F) for more curing (up to 24 hours). The several fundamental properties of the binder were tested. When the binders were mixed for two hours at 380°F in air, the binders seemed to show desired rheological properties because the aging of the binders dominated the properties. In the laboratory, the binders were prepared by mixing for 2 hours at 380°F in air and most of the results in this report are for the binders mixed in air.

The best mixing condition for crumb rubber modifiers with asphalt binders was determined to be '30 minutes and 350°F' based on the rheological properties and economic concerns as well as literature results. Even though the crumb rubber particles dispersed well enough during the mixing time (30 minutes) with a low shear (1200 rpm), the crumb rubber modifiers might need more mixing to obtain full absorption of oil phase into the CRM to be essential for showing better binder performance.

Degree of blending of the EVA modifiers with asphalt was best checked by turning off the mixer and observing for incorporated polymer floating to surface. A mixing condition of '350°F and 2 hours' based on the investigation of rheological properties as well as homogeneity of binders was selected. The mixing condition is identical to that used for SBS and SEBS. Low viscosity grade AC-5 asphalt binder with low molecular weight EVA Polybilt 104 required milder mixing condition than that for high viscosity grade AC-10 binder with high molecular weight EVA Polybilt 152.

Optimum Mixing Condition for the Binders Used during Phase II

Binders	**Mixing Conditions**
SBS	2 hours /350°F, high shear
SBR	30 minutes /350°F, high shear
EAM	2 hours /380°F in air, high shear
CRM	30 minutes /350°F, low shear
EVA	2 hours /350°F, high shear

I.2. Determination of Optimum Amounts of Modifiers

The optimum and critical polymer contents were determined for the asphalt/polymer blends being studied during this project. The optimum contents were determined by several ways such as by examining the flattening of the tanδ (G"/G") curve with respect to temperature for increasing polymer contents or by determining the storage modulus as a function of polymer content.

In the SBS modified AC-5 binder system, there was a rapid improvement of the rheological properties with increasing polymer content up to 3% (w/w). However, it is also important to note that there is a reduction and then an increase in the modulus properties for polymer contents between 3-5% (w/w) as shown in Figure I.2. The unique result of the rheological properties of the SBS modified binders at the polymer content between 3-5% (w/w) is a real phenomenon that has been seen in multiple tests of our material system at least. A possible explanation of the observed behavior is that as some content of polymer is added to the asphalt, the colloidal stability of the asphalt system itself may be broken down due to the solubility of the oils in the polymer, or some other structural phenomenon. This phenomenon deteriorates the thermo-physical properties of materials. At the same time, the addition of polymer is enhancing the overall rheological properties of the entire blend and furthermore, a formation of pseudo network structure or entanglements improves the rheological properties of the blend system dramatically at a certain polymer content. The decrease in properties at a certain weight percent modification can be an important factor when selecting the desirable SBS polymer content for the ideal binder system. Therefore, more experiments examining the chemical structure of the binders, morphology, and other engineering properties should be conducted. When the economics concerning the costs and benefits of increasing SBS polymer content were concerned, the optimum contents of SBS in the selective blends are as follows.

	Optimum Content, %(w/w)
AC-5/SBS	3 or 5
AC-5/SEBS	2 or 5
AC-10/SBS	2
AC-10/SEBS	2 or 4

The optimum SBR contents in the blends were determined for four different grades of asphalt binders. The desirable contents for SBR modification were 3 or 4% (w/w). The softest AC-2.5 grade asphalt was found to need 4% (w/w) and the other higher grade asphalt need 3% (w/w) to show the best rheological properties.

For the following asphalt/polymer blending systems, the optimum Elvaloy® AM contents were determined based on the rheological properties and economical concerns. The softer the asphalt is, the more amount of Elvaloy®AM was needed.

	Optimum Content, %(w/w)
AC-2.5/EAM	2.5 or 3
AC-5/EAM	1.5
AC-10/EAM	1

The rheological properties showed a continual improvement with increasing CRM content. The optimum content will be based on the amount of material required to reach the desired SHRP performance grade. There was no content at which increases in modifier did not result in increases in properties. However, more than 15% (w/w) CRM in the blend caused high melt viscosity relating to processing problems.

The optimum Polybilt EVA contents in the blends were determined for AC-5 and AC-10 grades of asphalt binders. In case of AC-5, adding more than 5% (w/w) EVA did not significantly enhance the rheological properties regardless of EVA molecular weight in the range of service temperatures. In case of AC-10, adding more than 3% (w/w) EVA in the binder did not significantly enhance the rheological properties.

1.3. Determination of Useful Chemical Functional Groups

Fourier-Transform Infrared Spectroscopy (FTIR) has been used to analyze polymers as well as aged and unaged asphalt binders. IR characteristic absorption peaks for CH_3, CH_2, aromatic carbon, and carboxyl groups in the asphalt binders are at wavelengths of 1375, 1450, 1600, and 1700 cm^{-1}, respectively.

The IR characteristic absorption peaks for polymer modifiers are very useful to determine the quality and quantity of the modifiers in the binders. SBS has a characteristic peak at a wavelength of 965 cm^{-1} which is due to contribution of the trans-1, 4 butadiene. The absolute ratio of the 965 cm^{-1} adsorption band to the 1375 cm^{-1} band of an SBS modified asphalt could be calibrated and used to determine the SBS polymer content in the binder. On the other hand, SEBS polymers which have '1, 2 butadiene (butylene)' instead of the 'trans-1, 4 butadiene' did not show the characteristic peak at 965 cm^{-1}. This could distinguish SEBS modified asphalt binders from SBS modified binders. The equation of the calibration curve which is valid only for the given SBS/AC-5 blend is as follow.

Polymer content (% (w/w)) = (Ratio - 0.037) / 0.064 for SBS/AC-5.

The IR characteristic absorption peak for SBR is also located at wavelengths of 965 cm^{-1}, which is due to the trans-1,4 contribution of butadiene (C-C=C-C). The absolute ratio of the 965 cm^{-1} adsorption band to the 1375 cm^{-1} band of a SBR modified asphalt can be used to determine the polymer content in the binder. The calibration curve is valid only for the given asphalt/polymer blend. The calibration curves are :

Polymer content (% (w/w)) = (Ratio - 0.2189) / 0.0626 for SBR/AC-2.5 ;
Polymer content (% (w/w)) = (Ratio - 0.0628) / 0.0539 for SBR/AC-5 ;
Polymer content (% (w/w)) = (Ratio - 0.0858) / 0.0438 for SBR/AC-10 ;
Polymer content (% (w/w)) = (Ratio - 0.3007) / 0.0463 for SBR/AC-20.

Elvaloy® AM modified asphalt binders have also a unique characteristic peak for C=O bonds from EAM at 1740 cm^{-1}. The calibration curve are achieved based on the absolute ratio of the 965 cm^{-1} adsorption band to the 1740 cm^{-1} band for the given EAM/asphalt blends. The calibration curves are :

Polymer content (% (w/w)) = (Ratio - 0.3041) / 0.1680 for EAM/AC-2.5 ;
Polymer content (% (w/w)) = (Ratio - 0.3551) / 0.1427 for EAM/AC-5 ;
Polymer content (% (w/w)) = (Ratio - 0.2743) / 0.1657 for EAM/AC-10.

When Elvaloy® AM was mixed with asphalt binders in nitrogen purge, the peak at 1700 cm^{-1}, which is believed to be for C=O bonds produced from oxidation of asphalt binders, was not distinctive compared to that of the binders mixed in air. Normalized FTIR curves for AC-2.5/EAM binder are shown in Figure I.3. The absolute ratio of the 1740 cm^{-1} to the 1600 cm^{-1}

band of an EAM modified asphalt can still be used to determine the polymer content in the binder. The FTIR was used to investigate the difference between the binders mixed in air and nitrogen.

The IR characteristic absorption peaks for Ethylene-vinyl acetate (EVA) are at wavelengths of 1740 and 1240 cm^{-1}, which are due to the C=O and C-O bond, respectively. The absolute ratio of the 1740 or 1240 cm^{-1} adsorption band to the 1600 cm^{-1} band of an EVA modified asphalt can be used to determine the polymer content in the binder. The calibration curve is valid only for the given asphalt/polymer blend. For example, the calibration curves based on 1740/1600 cm^{-1} peak ratio for EVA modified blend series are :

Polymer content (% (w/w)) = (Ratio - 0.224) / 0.281 for AC-5/EVA PB104
Polymer content (% (w/w)) = (Ratio - 0.286) / 0.175 for AC-10/EVA PB152.

CRM modified binders were not tested in FTIR because of its insolubility and lack of characteristic peaks of CRM.

I.4. Molecular Weight Distribution

Gel permeation chromatography (GPC) was used to examine SBS, SEBS, and EAM modified asphalt binders as an effective tool for determining the polymer content of asphalt/polymer blends. The SBS polymer being studied had a weight average molecular weight of approximately 62,000 g/mole and a polydispersity of two. The SEBS polymer being studied had a weight average molecular weight of about 45,000 g/mole and a polydispersity of 1.35. The other modifiers such as SBR, CRM, and EVA could not be tested because of their insolubility in the current GPC solvent, THF. SBR itself was not characterized because the polymer could not be dissolved in THF due to its latex form. Elvaloy® AM itself did not dissolve in THF but the EAM modifier binders could be characterized with GPC. The GPC results of Elvaloy® AM modified asphalt binders showed relatively high molecular weight asphalt ingredients possibly formed by chemical reactions between the asphalt and Elvaloy® AM (Figure I.4). Further characterization needs to be done to determine whether this high MW material is reacted polymer/asphalt or simply oxidation products due to the extreme mixing/curing conditions. It is important to notice that even the unmodified binders treated at 380°C for 2 hours show relatively high portion of high molecular weight material due to the thermal oxidation. Whether the high molecular weight material was due to oxidation, reaction, or both could not be determined directly from the GPC results.

1.5. Softening and Melting Points

The T_gs of SBS and SEBS polymers ranged from -60 to -90°C and the T_gs of AC-5 and AC-10 ranged from -10 to -15°C from the measurement using differential scanning calorimetry (DSC) tests. Upon addition of polymer to asphalt, the glass transition of the blend becomes a broad range between those of the individual components. Thermal mechanical analyzer (TMA) were used to look at final melt temperatures and softening points of the binders. The softening point was taken as the intersection of the extrapolation of the two straight portions of the TMA curve and the final melt temperature, corresponding to a 1 mm depression of the sample, was also measured. At the respective optimum SBS polymer contents (3-5% (w/w)), there is an increase of approximately 25°C in the final melt temperature with respect to the unmodified binders.

SBR modified AC-2.5, 5, 10, and 20 grade asphalt binders were also tested using TMA. With addition of more than 4 %(w/w), there is an increase of approximately 4°C in the final softening point for the AC-5/SBR blends with respect to the straight binders (treated at the same mixing condition of the SBR blends). AC-2.5 and AC-10 binders showed a slight increase in softening point (3-4°C) over the control binder. The softening point showed the same trend although not as significant. The melt temperatures measured also showed similar trend and are tabulated in the table below.

AC-2.5/SBR Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	22	31
0	24	33
1	26	34
3	27	39
4	25	38

AC-5/SBR Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	26	33
0	28	38
1	27	36
2	30	42
3	27	39
4	27	42
5	31	46
6	30	46

AC-10/SBR Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	31	40
0	32	41
1	35	48
2	36	49
3	35	49
4	36	46
5	37	49

AC-20/SBR Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	35	47
0	40	48
1	40	48
3	38	50

There is an increase of approximately 5°C in the final softening point for the AC-5/2% (w/w) EAM blends with respect to the unmodified binders (treated at the same curing condition for EAM blends which was mixed at 380°F for 2 hours in air). AC-2.5 binders showed that Elvaloy® AM modification caused a significant increase in softening point and melting point (10-15°C) over the control binder which were mixed at 380°C for 2 hours. Also, the addition of more than 2% (w/w) in AC-10 binder showed an increase in softening point of 15°C with respect to the unmodified but processed AC-10 asphalt binder.

TMA indicated that the AC-5/EAM binder mixed under nitrogen did not show any increase in the softening point and melting point compared to AC-5 virgin binder. The table below compare the softening and melting points of the selected binders. Even the storage of the mixed binder at 380°F for additional 24 hour did not increase its softening point, which indicating there was no severe oxidation reaction in the binder.

Softening Points of AC-2.5/EAM Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	22	31
0	38	46
1	38	48
2	42	54
3	49	60

Softening Points of AC-5/EAM Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	30	38
0	43	52
1	42	48
1.5	45	44
2	48	57
3	45	56
4	56	72

Softening Points of AC-10/EAM Blends

Polymer Content (%)	Softening Point (°C)	Melt Temperature (°C)
	(by intercept)	(by 1 mm depression)
virgin	35	47
0	41	52
1	55	58
2	56	69

Comparison of TMA Data for EAM Modified Binders (N_2 vs. air)

Binders	Softening Points (°C)	Melting Points (°C)
AC-5 (virgin)	29	38
AC-5 (processed in air)	43	52
AC-5/2% EAM (mixed in air)	48	57
AC-5/2% EAM (mixed in N_2)	28	40
AC-5/2% EAM (cured in N_2)	29	40

TMA for CRM binders indicated a relatively linear increase with increasing CRM amounts in both softening points and melting points for all three binders tested. For example, with more than 15% (w/w) CRM in AC-5, the binders showed more than 10°C increase in the softening point.

TMA Data for AC-5/GF80A CRM Asphalt Binders

	Softening Point (°C)	Melting Point (°C)
0% GF80A	23	34
5% GF80A	25	36
10% GF80A	28	39
15% GF80A	33	44
20% GF80A	37	51

TMA Data for AC-10/GF80A CRM Asphalt Binders

	Softening Point (°C)	Melting Point (°C)
0% GF80A	29	38
5% GF80A	28	39
10% GF80A	36	46
15% GF80A	37	50
20% GF80A	41	55

TMA Data for AC-20/GF80A CRM Asphalt Binders

	Softening Point (°C)	Melting Point (°C)
0% GF80A	34	42
5% GF80A	36	47
10% GF80A	41	51
15% GF80A	45	55
20% GF80A	49	61

The softening points of unmodified and EVA (Polybilt 104 and 152) modified asphalt binders were also measured using TMA tests. With addition of EVA polymers, there is a linear increase in the softening point and melting point for the asphalt/polymer blends. The increase of the softening points is the highest (more than 25°C) among the modifiers which were used in this projects. For EVA (Polybilt 152) modified AC-10 binders, the increase of the softening points is more than 20°C for 5% (w/w) EVA/AC-10 binder (Figure I.5).

TMA Data for AC-5/EVA PB104 Modified Asphalt Binders

	Softening Point (°C)	Melting Point (°C)
0% EVA 104	28	36
1.5% EVA 104	27	37
3% EVA 104	32	44
5% EVA 104	45	56
7% EVA 104	52	63

TMA Data for AC-5/EVA PB152 Modified Asphalt Binders

	Softening Point (°C)	Melting Point (°C)
0% EVA 152	28	36
1.5% EVA 152	30	38
3% EVA 152	34	46
5% EVA 152	44	57
7% EVA 152	56	68

TMA Data for AC-10/EVA PB152 Modified Asphalt Binders

	Softening Point (°C)	Melting Point (°C)
0% EVA 152	27	39
1% EVA 152	30	41
3% EVA 152	35	47
5% EVA 152	47	62
7% EVA 152	62	71

I.6. Viscosity Measurement

The melt viscosity of AC-5/SBS, AC-5/SEBS, AC-10/SBS, and AC-10/SEBS blends were measured at various polymer contents and temperatures using a Brookfield viscometer. All samples tested met the SHRP binder specification (maximum 3 Pa·s) at 135°C for melt viscosity. All SBR modified AC-5 samples and Elvaloy® AM samples containing less than 2% (w/w) met the SHRP binder specification. All SBR modified AC-2.5 samples met the SHRP specification and exhibited a good linear fit on a semi-log plot. For crumb rubber modified AC-5, AC-10 and AC-20 binders, the viscosity of AC-5 and AC-10/CRM binders met the SHRP specification (maximum 3Pas at 135°C) for all contents less than 20% (w/w). AC-20/CRM blends also passed the SHRP specification except 15 and 20% (w/w) CRM. Selective CRM modified binders were stored in a hot oven (350°F) for additional time to examine storage effects on the binder. The additional storage in the oven would be expected to bring about more interactions (swelling) between CRM and asphalt binders without severe aging in the binders. The additional swelling of CRM particles of oils from asphalt phase resulted in an increase of melt viscosity of the binders. In order to investigate viscosity changes of the CRM binders with storage, the melt viscosity at 280°F (137°C) was obtained for the binders with different crumb rubber contents. The rate of the increase of the viscosity was higher for the higher amount of CRM as shown in Figure I.6. It might indicate that, for the higher concentration CRM, more reaction time in the binders was needed. The viscosity of AC-5/EVA PB152 and AC-5/EVA PB104 blends measured at various EVA polymer contents and temperatures met the SHRP specification (maximum 3 Pa·s) at 135°C and exhibited a linear fit on a semi-log plot. AC-10 binders also met the SHRP specification.

I.7. Dynamic Mechanical Analysis

Rheometrics has been used to measure the storage modulus (G'), loss modulus (G") and tan δ at service temperatures. These values were converted to the dynamic shear moduli (G*/sin δ) to investigate the SHRP specification Performance Grade (PG). As shown in Table I.1, the limiting dynamic shear modulus (G*/sin δ) criterion is 1 kPa, indicating that stiffer (higher G*) and more elastic (lower δ) binders are desirable. The addition of the SBS to AC-5 grade asphalt increases the high temperature PG of the SHRP specification by up to 4 or 5 grade compared to the virgin asphalt binder. That is, the performance grade (PG) of the original binder was PG-52 and the PG grade of the original binder after two hours mixing was increased to PG-70 due to the oxidation. The SBS modified binders showed an additional increase to PG of 76 or 82.

The high temperature SHRP PG were determined by obtaining the dynamic shear modulus (G*/sin δ) for SBR and all four asphalt systems. The addition of optimum SBR amount to the original binders increases the SHRP specification PG by up to 2 or 3 grades. Figure I.7 shows the dynamic shear modulus data of SBR modified AC-5 binders and the resulting PGs are summarized in the table in the next page.

The addition of the optimum EAM amount to the original binders increases the SHRP specification PG by up to 1 or 2 grades. The addition of more amount EAM can result in a higher PG. The Elvaloy® AM modified asphalt binders reached higher PG with less amount of polymer than the other polymers modified binders but the unmodified (0% (w/w)) but processed binder also showed high PG of 70 because of possible hardening of the binder from oxidation during the mixing. On the other hand, there was a distinguishable difference in the tan δ and G*/sin δ values of the binders mixed between in nitrogen and in air. The binders mixed in nitrogen showed less stiff behavior in the high temperature range (30-80°C).

SHRP Specification PG Based on G*/sin δ for SBR Modified Binders

	AC-2.5	AC-5	AC-10	AC-20
0% SBR	52	58	64	70
1% SBR	58	58	70	70
2% SBR	58	64	70	70
3% SBR	58	64	76	70
4% SBR	58	64	76	76
5% SBR	64	70	76	82
6% SBR	70	70	76	82
7% SBR	70	70	76	82

SHRP Specification PG Based on G*/sin δ for EAM Modified Binders

Binders	AC-2.5 2 hr (air)	AC-5 2 hrs (air)	AC-10 2 hrs (air)
0% EAM	70	76	76
1% EAM	70	76	82
2% EAM	70	82	82
3% EAM	82	82	82
4% EAM	N/A	82	N/A

Binders	high temperature PG
AC-5 (virgin)	58
AC-5 (processed in air)	76
AC-5/2% EAM (mixed in air)	82
AC-5/2% EAM (mixed in N_2)	76
AC-5/2% EAM (cured in N_2)	76

The addition of CRM (GF80A) to the original AC-10 binder increased the high temperature SHRP specification PG. There is an increase of one grade from PG 64 for each 5% (w/w) CRM added. The addition of the crumb rubber to the unmodified AC-5 and 20 binder also increased the SHRP specification PG from 58 to 82 and from 70 to more than 88, respectively.

SHRP Specification PG Based on G*/sin δ for CRM Modified Binders

CRM amount	AC-5/GF80-A	AC-10/GF80A	AC-20/GF80A
0 %	58	64	70
5 %	64	70	70(76)
10 %	70	76	76(82)
15 %	82(76)	82	88
20 %	82	88	>88

The addition of optimum EVA amount (about 5% (w/w)) to the original AC-5 binders increased the SHRP specification PG by up to 2 grades regardless of the EVA molecular weight. On the other hand, the addition of optimum EVA amount (about 3% (w/w)) to AC-10 binders increased the high temperature SHRP PG by only one grade.

SHRP Specification PG Based on G*/sin δ for EVA Modified Asphalt Binders

EVA amount	AC-5/EVA 104	AC-5/EVA 152	AC-10/EVA 152
0 %	58	58	64
1.5 %	64(58)	64(58)	64 (1 %)
3 %	64	64	70
5 %	70	70(76)	76
7 %	76	76	82(76)

1.8. Preparation of Aged Asphalt Binders

Aging, or age hardening, occurs through two distinct processes. The first is a loss of volatile components in the asphalt during the high-temperature processing. The second is oxidation of the asphalt during road life. Both mechanisms cause an increase in the viscosity of the binder and the stiffness of the pavement. Aging during processing and/or compaction is simulated in the laboratory by using Thin Film Oven Test (TFOT) and long term aging during service life is simulated by using Pressure Aging Vessel (PAV) test. Some representative polymer modified blends were aged using the Thin film Oven at a temperature of 163°C for a time period of five hours including 15 minutes of equilibrium time. Weight loss due to aging was measured to ensure that it was less than 1 % (w/w). The TFOT aged samples were subjected to further aging in the Pressure Aging Vessel Test. The vessel was exposed to high pressure (about 300 psi or 1774 kPa) and temperature (100°C) for 20 hours to simulate the effects of long term aging. The sample pans were then placed in an oven at 163°C for 30 minutes to remove entrapped air from the samples. The samples were then transferred to a storage container for further testing such as Bending Beam Rheometer (BBR) testing.

All samples aged under normal conditions met the SHRP binder specification for average percent mass loss. A decrease in the average percent mass loss was observed with respect to increasing polymer content in some binders but there was no specific trend regarding to the modifiers or asphalt binder grades. GPC and FTIR results might show to support the finding that polymer modification retards the aging of the base asphalt. Rheometrics has been also used to measure the dynamic shear modulus (G*sin δ) of the aged binders to investigate the effect of modification on the SHRP specification performance grade, which is discussed in Chapter 1.10 .

1.9. Bending Beam Analysis

The SHRP Bending Beam Rheometer was used to measure the stiffness and m-value of the aged binders at various temperatures. Only the AC-5 asphalt binders modified with more than 4% (w/w) of SBS polymer met the SHRP binder specification (maximum 300 MPa) for measured Stiffness (S) at 60 seconds at a test temperature of -24°C but no samples met the SHRP binder specification for the 'm-value' (the slope of the stress vs. strain curve during the creep stiffness test ; minimum 0.3) at -24°C. No AC-10 samples with SBS met the SHRP binder specification for measured stiffness at -24°C. As the polymer content increased, the creep stiffness of the aged binders was found to decrease. This indicates enhancement of the low temperature properties of the binders. In general, it was found that low temperature physical properties of the binder were controlled more by a change in asphalt grade than by the addition of SBS.

The stiffness at 60 seconds of aged SBR modified AC-5 was investigated as a function of polymer content at a temperature of -12, -18, and -24°C. At -24°C, as SBR content is increased, the stiffness of the binder decreases thus enhancing the low temperature properties. However, at -12 and -18°C, the effect of polymer content is minimal. All the AC-5/SBR binders satisfied the SHRP specification for stiffness (S) value at 60 sec at the test temperatures of -12 and -18°C. However, at -24°C, only 4-7 % (w/w) SBR modified binders could pass the SHRP specification. The AC-5/SBR blends showed acceptable m-value at the temperatures of -12 and -18°C but none of the binders passed the specification at -24°C. SHRP assumed that the m-value would increase with the increase of polymer content. It appears from this data that the m-value is not a function of polymer content. This further reinforces the earlier suggestion of controlling the low temperature properties of a binder by using softer asphalt, and not by increasing the polymer content. In case of AC-2.5 binders, all the AC-2.5/SBR binders satisfied the SHRP specification for Stiffness (S) at the test temperatures of -18°C and -24°C. The AC-2.5/SBR blends showed acceptable m-value at the temperatures of -18°C but none of the binders passed the specification at -24°C (they showed the very close values to the specification minimum). The table below shows the low temperature SHRP PG for the SBR modified binders.

Low Temperature SHRP PG for SBR Modified Binders

	AC-5	AC-2.5
0% SBR	-12	-18
1% SBR	-18	-18
3% SBR	-18	-18
5% SBR	-18	-18

A similar trend of enhanced low temperature properties has not been seen for the Elvaloy® AM polymer modified blend. At -6, and -12°C, the stiffness values are almost same for different EAM contents and the stiffness values are much lower than 300 MPa, the maximum criterion for the SHRP specification. However, it is important to note that the m-values for AC-5/EAM binders, which need a minimum value of 0.300 to satisfy the SHRP specification, do not meet the specification at -12°C. These low temperature properties are much worse than for the AC-5/SBR blends. These results suggest again that the low temperature properties of a blend should be controlled by lowering the asphalt grade, and not by increasing polymer content. The EAM modified asphalt binders had very excellent high temperature properties but did not have good low temperature properties. When the EAM modified binders system are compared with AC-5/SBR blends system, it is observed that only '2 hours mixing at 380°F in air' for AC-5/EAM blends improved the high temperature PG significantly but caused the low temperature properties to deteriorate. This indicates that the increased high temperature properties of the binder are due mainly to oxidation.

The aged AC-5/CRM (0% and 15% (w/w)) binders met the SHRP binder specification for the measured creep stiffness and the m-value at -12 and -18°C. For AC-10 binders with 0 or 10% (w/w) EAM met the SHRP binder specification for the measured creep stiffness and the m-value at -12°C. However, these samples showed the measured m-values which are too close to the limiting values to meet the specification at -18°C. The aged AC-5/EVA (0 and 3% (w/w)) passed the specification at -12 and -18°C. In general, it was found that low temperature physical properties of the binders were not deteriorated with an addition of EVA or CRM into the asphalt binders.

1.10. SHRP Specifications

One of the most addressed SHRP binder specifications is the measurement of the rheological properties of the binders at different temperatures. Complex modulus (G*) and phase angle (δ), and creep stiffness (S) are the major properties of the binders which will determine the rutting resistance at high temperatures, the fatigue cracking resistance at service temperatures, and thermal cracking resistance at low temperatures. The SHRP binder specifications are divided into three protocols for original binder, TFOT residue, and PAV aged residue. The required properties of the binders remain constant for all performance grades but the temperatures at which these values are reached varies. Eventually, the temperatures will represent the performance grades of the binders.

To get more exact PG values for the polymer modified asphalt binders, other experimental results like 'G″=G*sin δ' values are usually considered. Fatigue cracking is more a serious problem for more brittle pavements formed due to aging or oxidation and can be governed by lowering the loss modulus parameter. For example, Figure I.8 shows that G*sin δ showed decreases as the SBR contents in the binder increases, indicating the improved fatigue resistance. However, there is likely to be little change in the reported values because dynamic shear and m-value are generally the limiting specifications.

Tables below summarize the SHRP specification PG grades based on the rheological properties in three different temperature ranges for AC-5/SBR and AC-5/EAM binders. The desired value of creep stiffness is when the binders have been loaded for two hours. However, the concept of time-temperature superposition, SHRP confirmed that by raising the test temperature 10°C, an equal creep stiffness can be obtained only after a 60 second loading. The final PGs were made based on the low temperature SHRP specification as well as high temperature SHRP specification PG.

Test Temperatures Passed SHRP Specification for the Binders

	High Temperature °C, (G*/sin δ)	Room Temperature °C, (G*sin δ)	Low Temperature °C, (S and m-value)	Final PG
0% SBR	58	22	-12	58-22
1% SBR	58	19	-18	58-28
3% SBR	64	16	-18	64-28
5% SBR	70	16	-18	70-28
7% SBR	76	4	-18	76-28
0% EAM*	76	25	-6	76-16
1.5% EAM*	76	19	-6	76-16
3% EAM*	82	19	-6	82-16

* mixed in air

In addition, it was found that low temperature physical properties of the binders were not deteriorated with an addition of EVA or CRM into the asphalt binders as seen in the table below.

Test Temperatures Passed SHRP Specification for the Binders

	High Temperature °C, (G*/sin δ)	Low Temperature °C, (S and m-value)	Final PG
AC-5/0% EVA	58	-18	58-28
AC-5/3% EVA	64	-18	64-28
AC-10/0% CRM	64	-12	64-22
AC-10/10% CRM	76	-12	76-22

The bending beam rheometer may be insufficient to fully characterize low temperature performance of polymer modified binders. It is desirable to have a low stiffness and high m-value to prevent stresses from building. However, the tensile properties of the asphalt can be improved using polymer modifiers. This means that they could possibly withstand a greater stress buildup than other asphalt without cracking. Also, polymer modification can change the fracture mechanism which could affect low temperature performance. The temperature at which the fracture mechanism changes from adhesive to cohesive is affected by polymer modification. This has been reported in the Microstructure and Morphology section. This leads to the hypothesis that the specification, as written, will likely be over conservative. That is, material which meets the specification should definitely perform as well as specified, and will probably perform better than its SHRP low temperature PG. Further testing needs to be done to determine the effect of polymer modification on tensile properties, as well as the effect of those properties on the low temperature performance of the binder.

Summary of the Results

- The optimum mixing conditions based on rheological data have been determined for SBS, SBR, EAM, CRM and EVA blends series. The results are summarized in Chapter IV. However, the mixing condition developed for AC/EAM blending system in air could be modified by mixing in nitrogen. The mixing in the nitrogen atmosphere minimized the chance for the binders to be oxidized during mixing. Without severe oxidization, the binders could be further mixed at 380°F for obtaining fully cured asphalt/ EAM binders.

- The optimum amounts determined based on rheological properties and economical concerns for all of the modified asphalt binders. The results are summarized in Chapter IV.

- The softening points and melting points of SBS (AC-5 and 10), SBR (AC-2.5, 5, 10, and 20), Elvaloy® AM (AC-2.5, 5, and 10), CRM (AC-5, 10, and 20), and EVA (AC-5 and 10) modified asphalt blends were determined using thermal mechanical analysis (TMA). The increase of the softening points of EVA modified binders is the highest (more than 25°C) among the modifiers which were used in this projects. The results of the softening and melting points of the binders are summarized in Chapter IV.

- Gel permeation chromatography (GPC) was used to examine the molecular weight information of SBS, SEBS, EAM modified asphalt binders as well as modifiers and asphalt binders. Gel Permeation Chromatography (GPC) was also used to examine the molecular weight information of aged asphalt binders. However, SBR, CRM, and EVA modified binders could not be tested because of their insolubility in the solvent (THF) used for a current GPC system.

- Fourier-Transform Infrared Spectroscopy (FTIR) has been used to analyze polymers as well as aged and unaged polymer modified asphalt binders. FTIR has been used to analyze polymers (SBS, SEBS, SBR, Elvaloy® AM, and EVA) as well as the modified AC-2.5, AC-5, AC-10, and AC-20 binders.

- The viscosity of all the binders mixed with modifiers (AC-5/SBS, AC-5/SEBS, AC-10/SBS, AC-10/SEBS, AC-2.5/SBR, AC-5/SBR, AC2.5/EAM, AC-5/EAM AC-5/CRM, AC-10/CRM, AC-20/CRM, AC-5/EVA and AC-10/EVA blends) were measured at various polymer contents and temperatures using a Brookfield viscometer. Most of the binders with the optimum amounts of the modifiers passed the SHRP specification.

- Both the SHRP and MDOT specifications were reviewed and comments were made. The rheological properties (G*/sinδ) of unaged binders were used to determine the high temperature SHRP specification. Aged binders were analyzed using the Bending Beam Rheometer to determine the low temperature SHRP performance grade. Although the SHRP PG also depends on the other properties, it has been shown that the m-value is the major factor that has controlled the low PG in every case. SBR was the most promising candidate for asphalt modification based on the processing condition, rheological properties (high and low temperature), and economical concerns.

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II. Basic Morphology and Microstructure of Polymer/Fiber-Asphalt-Aggregate Mixtures

The main objective of this study is to reveal the morphology and microstructure of straight and modified binder-aggregate mixtures and their failure mechanisms. Microstructural and morphological information of mixtures is extremely important in predicting pavement performance based on the physical and chemical data of binders and aggregates. This task can be broken into four tests: morphology analysis, fracture tests, void analysis, and binder/aggregate bonding analysis. The identification of morphological change in the asphalt mixture and how these changes affect the locus of fracture and failure mode when the mixture is subject to a combination of stresses and environmental factors is a critical element necessary to evaluate and predict PMA performance.

2.1. Morphology Analysis - Binder and Polymer Phase

The main objective of this study is to reveal the morphology and microstructure of straight and modified binder-aggregate mixtures and their failure mechanisms. Microstructural and morphological information of the mixtures is extremely important in predicting pavement performance based on the physical and chemical nature of binders and aggregates. The identification of morphological changes in asphalt mixtures and how these changes affect the locus of failure and failure mode when the mixture is subject to a combination of stresses and environmental factors is a critical element necessary to evaluate and predict PMA performance.

2.1.1. Specific Objectives

- To study the network morphology and microstructure of pure asphalt binders and characterize the effects of processing conditions and aging.
- To study the changes in the microstructure and morphology of polymer modified asphalt binders and the effect of polymer modification on the aging behavior of the binders.
- To characterize the phase morphology of the polymer modifiers in the asphalt binders.

2.1.2. Accomplishments

2.1.2.1 Development of Test Methods

Binder Morphology

The study of binder morphology was best achieved using an Environmental Scanning Electron Microscope (ESEM) to view thin asphalt binder films (1/5000 inch thickness) [5].

Asphalt binder thin films were prepared by using a hot press compression molding process. Sections of the thin films were then placed in the ESEM and observed under an electron beam.

Polymer Phase Morphology

The polymer phase morphology was observed using the Confocal Laser Scanning Microscope (LSM, Zeiss 10) which works on the principle of fluorescence [7]. The unsaturated bonds in the polymer phase fluoresce at certain frequencies of exciting light. This fluorescence is then observed with the help of suitable filters. The advantage of the confocal LSM is that it allows the light to be focused beneath the surface of the asphalt binder film, thus giving a depth profile. This allows the direct observation of the polymer phase distribution in the bulk of the binder instead of only the surface where the morphology can be affected by any number of factors including the processing method, storage, etc. The ESEM technique used for binder morphology was also used to determine the polymer phase morphology of the particulate crumb rubber. ESEM imaging of SBR modified binders at low temperature (5°C) also showed the morphology of the SBR phase [11].

2.1.2.2. Network Morphology of Straight and Polymer Modified Asphalt Binders

A 3-dimensional entangled network structure was observed in asphalt binder thin films after exposure to the electron beam in the Environmental Scanning Electron Microscope (ESEM) [4]. This network structure is seen in both unmodified and polymer modified asphalt binders. Figure 2.1(a) shows the typical network structure seen in fresh binders. The network structure is stable and is revealed as the low molecular weight oils in the asphalt binder thin films are displaced by the localized heating caused by the electron beam, either by volatilization or by rapid diffusive processes. The speed at which the network becomes visible in the ESEM depends on the strength of the electron beam. The energy of the electron beam can be varied by changing the working distance from the sample, pressure, type of gas used and condenser setting in the ESEM. It was observed that the network forms faster when the electron beam is stronger and slower when the beam is weaker. This supports the theory that the network formation kinetics are controlled by the localized heating caused by the electron beam.

The network structure, when allowed to relax by removing the binder film from under the electron beam, gradually disappears as the surrounding oils and low molecular weight fractions diffuse into the area. Subsequent exposure to the electron beam at the same location makes an identical network structure reappear. Figure 2.1(b) shows the results of subsequent electron beam exposure at the same location on an asphalt binder thin film. This supports the theory that the network is a real structure within the asphalt binder and not an artifact created by electron beam etching. When the asphalt binder films are subjected to tensile loads or pre-strained in a particular direction, the network strands are seen to align themselves in the direction of the load [6]. Figure II.1(c) shows the network structure seen in pre-stretched binder films. The direction of the arrow indicates the direction of stretching. The in-situ deformation of the network structure in the ESEM clearly shows a stable three dimensional structure. This leads to further evidence that the network is the inherent structure of asphalt. It is believed that the network strands or fibrils are composed of the higher molecular weight asphaltenes.

Microstructural studies on asphalt binders from different sources with asphaltene contents of 8.8%, 15.5% and 20.4% show that the network fibrils become more refined and the network density increases with increasing asphaltene content [12]. This supports the theory that the network is comprised of the high molecular weight asphaltene fractions and surrounded by the lower molecular weight oils and resins. The kinetics of network formation or revelation are also dependent on the asphaltene content. The lower asphaltene content binder networks form rapidly and also disappear rapidly on beam removal. The higher asphaltene content binder networks take longer time to form and disappear after beam removal.

The network structure is seen to become coarse when the asphalt is aged [6]. Figure II.1(d) shows the typical network structure seen in a highly aged asphalt binder sample. This was seen in binders aged in the TFO-PAV as well as in binders processed at high temperatures (380°F). This has proven to be a very reliable qualitative test to identify aged binders. All polymers (SBS, SEBS, SBR, Elvaloy® AM and CRM) when added to the asphalt binder, were generally seen to slow the aging process. This performance was judged based on the coarseness of the network strands seen after TFO-PAV aging. Addition of SBS, SEBS, SBR and CRM to the asphalt binder does not cause a visible or remarkable change in the network structure itself. 0%(w/w) Elvaloy® AM modified binders which are processed at higher temperatures (380°F) appear similar to the aged binders. The 1%EAM binders however do not show any signs of aging.

2.1.2.3. Polymer Phase Morphology

The phase morphology of SBS, SEBS and SBR latex was determined using Confocal Laser Scanning Microscopy [7, 8]. SBS modifier was seen to form discrete, well-dispersed spherical phases of 0.5-2μm diameter while SEBS was seen to form well-dispersed spherical phases 1-3μm in diameter as well as block-like particles about 5μm width and 20μm length. Both polymers were excited by Blue (488nm) light and fluoresced in the Red (590-620nm) region. Figure II.2(a) shows the typical polymer phase morphology in SEBS modified asphalt binders.

SBR latex at 1wt.% concentration is seen to form fine spherical 3-5μm particles while at higher concentrations (3-5wt.%) it disperses in the asphalt binder in the form of thin linearly aligned strands ~1-2μm in diameter and ~100-300μm in length [8]. Figure II.2(b) shows the typical polymer phase morphology in SBR modified asphalt binders. The number of strands and their entanglement is directly proportional to the amount of SBR latex added to the binder. SBR also fluoresces in the Red spectrum with Blue excitation. SBR latex modified binder films, when viewed in the ESEM at low temperatures (5°C) also showed similar strands of SBR on the surface. Figure II.2(c) shows the strands like structure seen on SBR binder films at low temperatures in the ESEM .

The phase morphology of Crumb Rubber (GF-80) could not be determined using the LSM technique since there is no significant fluorescence from the rubber particles. The crumb rubber particles retain their form even after hot blending with binder and this allows the use of ESEM imaging to observe the rubber particles [11]. The crumb rubber particles were seen to remain as 75μm size particles (unprocessed crumb rubber particles are 75μm size) and the binder network fibrils are seen to have good contacts with the surface of the rubber. A new surface treated crumb rubber (XP-81) was also evaluated. This crumb rubber shows slightly higher interaction between the binder network and the rubber particle. Figure II.2(d) shows the interaction between the network structure and the rubber particles in crumb rubber modified asphalt binders.

The phase morphology of Elvaloy could not be determined by using the LSM or the ESEM [10, 11]. Table II.1 shows the details of the various binders used, processing conditions and the salient features of the binder and polymer phase morphology.

2.2. *Void Morphology and Analysis*

It has been shown that an optimum range of void content exists for asphalt surfaced pavements. The addition of polymer modifiers to asphalt may alter the optimum level. A morphological investigation to study the effects of voids using an image analysis of thin plane sections was done to determine the void size, distribution and density. The effects of voids on initiation of failure cracks and propagation were studied.

2.2.1. Specific Objectives

- To determine the total void content of polymer modified asphalt concrete
- To identify and study the various types of voids present in asphalt concrete
- To characterize the void shapes, sizes and distribution in polymer modified asphalt concrete

2.2.2. Accomplishments

2.2.2.1. Development of Test Methods

Thin Plane Section Image Analysis

A two filter fluorescence emission system was developed in conjunction with optical microscopy for image analysis of thin plane asphalt concrete sections [14]. Void analysis samples were prepared from 15mm thick sections cut from Marshall samples. These thick sections were vacuum impregnated with fluorescent epoxy (Struers Epofix/Epodye system). This allowed the fluorescent epoxy to fill all the inter-connected air-voids in the asphalt concrete sections. Thin plane sections (30μm thickness) were then cut, polished and analyzed using optical microscopy and image analysis system. An average of 80 samplings were done on a single plane section and 2-4 plane sections are analyzed for each composition.

Void Casting Method

An alternate method was developed to achieve better void analysis results [10]. This method involved vacuum impregnation of fluorescent epoxy in thick sections cut from Marshall samples. The impregnated samples were then heated and soaked in trichloroethylene to extract the binder. The voids cast in epoxy were recovered and the volume of each void is calculated individually. This method yielded highly satisfactory results for void size and distribution but is manually intensive.

2.2.2.2. Results from Thin Plane Section Image Analysis

This method provides understanding of the three different types of voids found in asphalt concrete; Interfacial voids, Binder phase voids and Isolated voids [2]. Binder phase voids are small in size and completely surrounded by the asphalt binder. Interfacial voids are large irregular shaped air-voids found near the surface of the aggregates. Isolated voids are air-voids trapped between aggregates where the binder does not penetrate. These different types of voids were characterized. Figure II.3 shows (a) binder phase void, (b) interfacial void, (c) isolated void. The image analysis system uses statistical mean circle diameters and aspect rations of voids in a thin plane section to calculate the net air-void content. This method, however, does not give a consistent and accurate measure of the actual net air-void content in asphalt concrete since the void distribution and void shapes in asphalt concrete samples are non-uniform. A quantitative two-dimensional analysis of such voids thus does not yield good results for the sampling size used. SBS and SEBS modified asphalt concrete was tested using this method.

2.2.2.3. Results from Void Casting Method

This method gives a more accurate measure of the net air-void content in asphalt concrete. It also allows the visualization of complete voids (interfacial voids and binder phase voids only) in three dimensions. This is a better method to characterize void shapes and sizes than the earlier method which only characterizes the uneven voids found in asphalt concrete, in two dimensions. The void content and distribution in asphalt concrete was characterized for SBR latex and Elvaloy AM modified binders using the epoxy impregnation method and the results were found to be dependent on the viscosity of the asphalt binder at the processing temperatures used [10, 11].

Two major types of voids, binder phase voids and interfacial voids were characterized. Binder phase voids are generally small with void volume below 10 cu. mm. They are beneficial to the properties of asphalt concrete since they allow for expansion of the binder with temperature. The interfacial voids are large, irregular and not beneficial since they provide starting points for fracture in asphalt concrete. Freeze-thaw cycling seen during winter in the environment can lead to stripping of aggregates if a large number of interfacial voids are present.

In unmodified asphalt concrete samples the void distribution shows roughly 81% interfacial voids while the content increases to about 85% with SBR modification. Figure II.4 shows the void size and distribution plots for AC-5/0%SBR and AC-5/5%SBR. EAM, which has a higher processing temperature was found to have about 90% interfacial voids without any EAM added and about 95% interfacial voids with 2% EAM. The reason for this increase in interfacial voids with polymer addition could be the increased viscosity in polymer modified mixes. Higher viscosity of the polymer modified binders leads to incomplete wetting of the aggregate surfaces and an increase in the number of interfacial voids. The proper selection of processing temperatures to get binder viscosity at which good wet-out is achieved and optimization of the aggregate gradation is thus necessary to get a beneficial void morphology. Table II.2 shows the void analysis results for SBS, SEBS modified asphalt concrete using the image analysis method, and for SBR and EAM modified asphalt concrete by using the void casting method.

2.3. *Binder/Aggregate Interface Analysis*

2.3.1. Specific Objectives

- To develop a reliable and meaningful test method to investigate the aggregate/binder interface properties, such as adhesion.
- To determine the alteration in adhesion due to polymer modification as a function of modifier type and concentration, and thus, to establish mechanical performance finger printing of all available polymer modified binder systems.

- To identify temperature dependent adhesion failure modes and mechanisms in terms of polymer modification.
- To investigate parameters influencing adhesion in terms of polymer modification.

2.3.2. Accomplishments

2.3.2.1. Development of Test Methods

Three test methods were initially developed for the aggregate/binder adhesion studies, specifically in quantification of the adhesion behavior, by modifying the existing standard or widely used techniques in the adhesion and adhesive communities, namely, lap-shear, cross-lap tension and blister peel test [2,3,4,5,15]. Unique test fixture for each method was built to handle asphalt binders. The first two tests were then carried out on the MTS test frame. The Lap-shear test gives a measurement of the adhesive bond strength between two flat parallel plates having an overlap adhesive joint in shear (Mode II) when pulled apart under tensile loads, while the cross-lap tension provides direct tensile adhesion strength between two bonded plates (Mode I). On the other hand, the blister peel test was designed to measure the adhesive strength in terms of the energy of interfacial adhesion, so-called the adhesive fracture toughness which is defined by the critical strain energy release rate, a material constant independent to test methods. However, most of the adhesion studies in phase II was carried out by the lap-shear test method alone since some initial cross-lap tension results were almost identical to those of the lap-shear test and because of technical difficulties of the blister peel test on asphalt binders [6].

The lap-shear test sample consists of a pair of aggregate sections, 1x1" in area and a thin film of asphalt binder prepared by a picture frame compression mold in a hot-press, up to about 0.005 inch thick. The specimen was then mounted in the special fixture for the MTS testing. A cross-head speed of 2.5mm/min was used. All tests were done with duplicate samples to ensure reproducibility.

Test results showed that the lap-shear and cross-lap tension tests can clearly identify the effects of polymer modification, effects of temperature, and interfacial failure modes and mechanisms. From the lap-shear test, the load-displacement responses from which various properties, such as initial stiffness, ultimate strength, and toughness, were determined, were monitored. Three toughness terms, so-called elastic strain energy, tenacity and toughness were introduced [8,10] for more meaningful analysis of the results. However, these three terms showed almost identical trend in polymer concentration dependency in all binder systems at all temperatures.

Extensive fracture surface analysis of the Lap-shear and Cross-lap tension samples was made to identify the failure modes and to characterize any changes in the surface morphology as a function of polymer concentration and temperature [4,15]. All tested samples were frozen immediately after testing to preserve the fracture surfaces and observations were made using an optical microscope.

2.3.2.2. Effects of Polymer Modification on Lap-Shear Performance

In phase II of the program, we have investigated two types of asphalt binders (viscosity graded AC-5 and AC-10) and five different polymer modifiers, namely, SBS[4,5,6,7], SEBS[4,5,6,7], SBR[8,9], EAM[10,13], and CRM[11,12] in either fresh or aged (TFO/PVA processed) state in terms of polymer concentration and service temperatures. Most significant findings during this phase are summarized as follows.

In general, from both Mode I cross-lap tension and Mode II lap-shear analyses, the effects of polymer modification on the adhesion behavior of asphalt binders in either fresh or aged state were strongly temperature dependent, i.e., a negative effect at higher temperatures and a positive effect at lower temperatures, normally 0°C or below. However, the degree of improvement was varied depending upon modifier types and concentration.

The failure mode of the asphalt binder/aggregate adhesion was changed from cohesive failure to adhesive failure as decreasing temperature. The transition was clearly observed from the lap-shear analysis (load-displacement responses and LS properties as a function of temperature) and agreed well with the fracture surface analysis. Polymer modification shifts the failure mode transition to lower temperature, thus improves the low temperature properties, such as strength and toughness.

The aged binders were generally stronger but more brittle than fresh ones due to the aging induced embrittlement processes, such as oxidation, volatilization of low molecular weight organics (aromatics/saturates), shifting of naphthene aromatics towards polar aromatics, and so on. However, it was suggested that polymers retarded the aging process which conformed to the previous rheological results and the binder network morphology study results. Generally, polymer modifiers improved the residual lap-shear properties of aged binders, especially with increasing polymer concentration and seemed to suppress the aging process.

Another very interesting trend observed in most of polymer modifiers was that the lap-shear strength and toughness were initially decreased at low concentrations of modifiers, but then increased back at high polymer concentration. It was suggested that the mode change of the adhesion properties as a function of polymer concentration were due to the two or more competing adhesion mechanisms, i.e., surface wetting controlled by surface tension and mechanical interlocking controlled by strength of binder. That is, with a small content of polymer, the binder loses its wettability because polymer absorbs low molecular oil phase more than raising strength of binder, but further increasing polymer content will eventually strengthen the binder, thus the mechanical interlocking strength.

In general, both polymer concentration and test temperature dependency of the EAM modified binders were similar to those of the other polymer modified asphalt binders including SBS, SEBS, and SBR. However, even though the strength of Elvaloy modified binders is equivalent to or slightly higher than those of others at the higher temperature from 10°C to -10°C, the value drops down to the lowest at -20°C partly due to the high T_g and associated brittleness of the thermoset epoxy on the adhesion strength, or due to the high temperature processing resulting in aging or oxidation as described in the last report from the ESEM network morphology study.

The effect of CRM modification on lap-shear properties and behavior was not much different to any of other polymer modifiers even though the CRM concentration scale is much higher than that of the other modifiers. However, because of the particle size (~74 micron) and high concentration, the effect is more pronounced with AC-10 binders unlike all others.

The overall effects of polymer modification on the binder/aggregate adhesion have been evaluated systematically. Table II.3 lists overall lap-shear properties, so-called lap-shear strength and elastic strain energy as a toughness term. Each figure represents the average of two measurements. For each modifier, an optimum concentration which is shaded in Table II.3, was determined by the average lap-shear performance in terms of strength and toughness of both fresh and aged binders, especially, emphasizing low temperature performance on toughness. It is of interest to note that the optimum polymer content in AC-10 was always higher than that of AC-5 for all polymer modifier types. This indicates that the asphalt composition also controls the binder/aggregate adhesion mechanisms. In other word, it is important to study the effects of asphalt binder sources on polymer modification. In all cases, polymer modifiers improved the performance, especially, at the lower temperatures where the failure mode transition occurred, as shown in Figure II.5. More improvement was observed from AC-5 binders than from AC-10 binders (Figure II.6). In general, polymer modifiers shift the cohesive-adhesive failure mode transition temperature to lower temperature, and thus improve low temperature performance (Figure II.7).

2.3.2.3. Other Parameters Influencing Adhesion

During the phase II of this program we have also investigated other variables and parameters that control or influence the binder/aggregate adhesion in terms of polymer modification. Most significant findings are summarized as follows.

Effects of Substrate Rock Type Compositional analysis of the aggregate mix used in asphalt concrete in Michigan, which was performed by petrographic examination with major physical and mechanical property variation, indicated that the aggregate mix consisted of 28% Granitic rocks, 19% Basaltic rocks, 23% Quartzite, 10% Greenstones, 11% Sandstones, and 9% Limestones/Dolomite [2].

In general, the lap-shear adhesion behavior of other rock substrate, namely, quartzite and greenstone, was very similar to that of graphite rock system in terms of polymer concentration and temperature dependency. However, the interfacial adhesion properties including ultimate strength, peak displacement, and stiffness of both quartzite and greenstone systems at low temperature of -10°C were approximately 70 % greater than those of granite rock system [6].

Effects of Coated Substrate with SBR When the substrate was coated with SBR latex solution the lap-shear adhesion analyses showed (i) the coating improved the lap-shear strength and adhesive toughness substantially, (ii) the improvement was most pronounced at -10°C for AC-5 asphalt, and (iii) the thinner coating was more effective in promoting adhesion properties [8,9]. The effects of coating thickness, type of rock substrate, SBR content in binder, and the other types of coating material, such as anti-stripping compound were studied. Interestingly enough, the same or even better improvement on adhesion properties for the binder with 5wt% SBR was obtained by a thin SBR coating of the substrate and the effect was extremely dependent on thickness. The optimum thickness was found to be about 5 to 10 micron. The failure surface analysis of the SBR coated substrate system, especially tested at -10°C, indicated combination of binder-SBR coating adhesive mode and SBR coating-rock substrate adhesive mode. However, the adhesion performance of the anti-stripping compound coated system was very poor, even compared to the uncoated system [10]. In most cases, the failure was adhesive, but at the compound-asphalt binder interface, not at the rock surface and compound interface, i.e., the adhesion between asphalt binder and the compound was inferior than that between the rock surface and the compound.

The economic feasibility of the coating approach was also assessed. The average asphalt film thickness was about 11 micron. From these calculations it was found that the film thickness of a polymer coating on the aggregate, equivalent to 5% polymer concentration in the binder, would be approximately 0.5 micron [10].

Effects of Polymer Modification on Performance of Mixture of Aged and Fresh Binders To assess the possibilities of rejuvenating aged binders by mixing with fresh binders, the mechanical performance of the four different mixture systems, such as, 0%(A)+0%(F), 1%(a)+1wt%(F), 6%(A)+6%(F), and 0%(A)+6%(F) was evaluated with lap-shear tests [9]. All mixtures showed some considerable performance improvement with polymer modified mixture systems, especially for the low temperature adhesion properties. However, from the comparison of the mixture data with 100% aged or 100% fresh binder data, the enhanced properties in the mixtures of the polymer modified binders might just come from the superior aging resistance of the polymer modified system, not necessarily from the fresh part of the system. From the ESEM network analysis and lap-shear adhesion measurement of mixed (fresh+aged) binders, especially, 0wt% (aged) + 6wt% SBS (Fresh) mixture, the aging process in a straight asphalt binder is probably irreversible.

Effects of Storage Time at Processing Temperature In order to simulate the actual pavement construction practice the effect of storage time at the processing temperature on the adhesion behavior has been investigated [11,12,13]. Lap-shear test results showed that the high temperature (375°F) storage deteriorated asphalt binder properties regardless of polymer modification. As increasing storage time, both strength, whether cohesive or adhesive, and toughness were decreased. The AC-10/10 wt% CRM modified binder significantly lost its adhesive strength and toughness at -10°C after even 5 hrs storage time, to the level lower than that of the straight, unmodified binder. This result was somewhat unexpected since CRM was found to retard the aging process from binder network morphological study. From additional storage experiment of AC-5/CRM modified binders, it was also confirmed that as increasing storage time, both strength, whether cohesive or adhesive, and toughness of binders decreased significantly. From the optical microscopic examination, the low adhesive strength was simply due to poor wetting of binders onto the rock substrate which was mostly caused by thermal degradation and/or loss of low molecular weight oil phase as the rubber particles absorbed.

Another issues raised on Elvaloy AM modified systems were (i) possible oxidation of binders prepared under normal mixing conditions used at MSU, i.e., mixing at 380°F for 2 hrs in air, and (ii) time required for full reaction or cross-linking of polymer. Thus, it was necessary to study the effects of reaction time (storage time) and N_2 environment on adhesion and to compare with network structure results [13]. As expected, in the case of AC-5/2 wt% Elvaloy AM binders, the lap-shear properties were improved after 24 hrs curing under N_2 environment. This is consistent with the network morphology study results. Therefore, it can be concluded that the

Elvaloy AM modified binders need to be cured for longer time and under air-sealed or N_2 purged environment. However, this may cause some conflict in real pavement process.

Surface Treated CRM The effects of surface treatment on crumb rubber particles on performance of CRM modified asphalt binders were investigated by determining stability of binders at the high temperature storage condition [13]. Network morphology and lap-shear performance were monitored as a function of storage time. A new type of crumb rubber, CRM XP-81, which was surface-treated to provide better properties, was evaluated. Surprisingly, the lap-shear properties of the surface treated CRM after 24 hrs storage, especially at -10°C, were significantly improved from those of conventional CRM binders. This must be something to do with differences in aging mechanisms and/or swelling behavior between those CRM binders.

2.4. *Fracture Tests*

The failure mechanisms of asphalt mixtures are functions of binder properties, aggregate properties, binder-aggregate adhesion and voids (concentration, size and distribution). For modified asphalt mixtures, the failure mechanisms are also functions of the modifier chemistry, morphology and distribution of the modifier.

2.4.1. Specific Objectives

- To study the fracture process and the effect of polymer modification on the fracture morphology of asphalt concrete.
- Develop a methodology to determine the fracture toughness of asphalt concrete and evaluate the effect of polymer modification on fracture toughness

2.4.2. Accomplishments

2.4.2.1. Development of Test Methods

In-situ ESEM Tensile Tests

The in-situ ESEM test was performed on 1.5mm thick sections of asphalt concrete cut from Marshall samples. The sections were polished and mounted on notched polycarbonate backing. The notch in the polycarbonate backing provided a reference point and also served to locate the fracture in it's vicinity. The samples were mounted in a tensile loading stage that went in the ESEM. The sample was then stressed and the fracture process was observed in the ESEM.

Cracks were viewed at high magnifications to identify the failure processes taking place in the sample [14].

Fracture Toughness of Asphalt Concrete

The J-integral fracture toughness provides a path independent measure of the fracture toughness [20]. For non-isotropic, non uniform materials like asphalt concrete which have high plastic deformation zones, the J-contour integral method provides a more reasonable measure of fracture toughness than other methods like K_{IC} (stress intensity factor) and G_{IC} (Strain energy release rate). This method is based on the principles of elastic-plastic fracture mechanics. The critical value of the J-contour integral (J_{IC}) was determined by performing the 3-point bending beam test on beams with notches of various lengths. Samples were prepared using the California Kneading Compactor. Beams of dimensions 2 x 2 x 8 (inch) were cut and notched in the center from 40% to 60% of the beam width. The load vs. mid-point deflection curves are plotted for different notch lengths. The area under the load-deflection curve till the failure (peak) point is calculated and this energy (U) divided by the beam width (U/b) is plotted against the notch length. The slope of the linear relationship between energy per unit length and notch length gives the critical value of the J-integral. Figure II.8 shows a graphical representation of the J_{IC} calculation process. All samples were tested in the UTS temperature control chamber at -10°C using liquid nitrogen as a coolant.

$J_{IC} = -1/b \, dU/da$

where,

JIC = Critical J-contour integral fracture toughness (lb-in/in^2)
b = Beam width (in.)
U = Energy to failure (lb-in)
a = Notch length (in)

2.4.2.2. Deformation and Fracture Behavior of Polymer Modified Asphalt Concretes

The in-situ tensile test performed in the ESEM on asphalt concrete sections is an excellent method to identify the fracture morphology and behavior of asphalt concrete. The network structure seen in asphalt binder thin films is also seen in asphalt concrete samples during the tensile fracture tests. The network strands seen in the binder play an important role during the fracture process of asphalt concrete. Polymer modified asphalt concrete shows a vastly different fracture morphology than unmodified asphalt concrete. These changes include a reduction in adhesive (interfacial) failure, a corresponding increase in cohesive (binder phase) failure and the onset of crack bridging mechanisms like high amounts of fibril formation. The fracture process was seen to progress in three stages - void formation, void growth and finally crack propagation.

Unmodified asphalt concrete. It has a tendency for the fracture to proceed along the aggregate boundaries [4]. The failure was observed to be both adhesive and cohesive. The mechanism of cohesive failure started with void formation in the binder phase. These voids grew and interconnected, leaving a few fine strands of asphalt binder (called fibrils) which acted as crack bridges. These fibrils were about 6-7 microns in diameter and began to neck after being sufficiently strained. Fibril rupture occurred at about 2 micron neck diameter and 50-100 micron length. Only a few fibrils were observed across the fracture surface in unmodified concrete samples.

SBS modified asphalt concrete. The fracture morphology was strongly affected by the addition of SBS [4]. The most noticeable feature was an increase in the number of fibrils formed and their deformation behavior. The fibrils were thinner, longer and appeared to be interconnected. They were more elastic and had higher elongation at break. Most fibrils were stable up to elongation of 130 microns. The number of fibrils forming across the crack increased in direct proportion to the concentration of the polymer added. There did not seem to be any apparent morphological changes in the fibrils due to increasing polymer concentration.

SEBS modified asphalt concrete. The morphology seen in SEBS modified AC-5 samples was similar to that of SBS modified AC-5. The fibril formation was not as dense as that seen in SBS [4,5]. The elongation at break was approximately 70-130 microns. Failures were mostly cohesive and gross adhesive failure was only seen in a few instances. Compared to unmodified AC-5, SEBS modified AC-5 showed higher fibril formation and elongation.

Elvaloy AM modified asphalt concrete. Elvaloy AM modified AC-5 binders appeared to have a much higher stiffness compared to the other previously studied polymer modified systems [9]. Fracture was observed to predominantly occur near the binder-aggregate interface rather than in the binder phase. The modified binder formed coarse bridges across the crack face, but very low fibril densities were observed. The number of fibrils formed were fewer than seen in the unmodified material and decreased rapidly with increasing polymer concentration. The individual binder fibrils were about 7-8 microns in diameter at the base and about 2 microns at the neck at the point of failure. EAM concentration did not visibly affect the morphology at this level. From the change in fibril density and fracture morphology, Elvaloy AM modified binders appeared to have reduced viscoelastic behavior.

SBR latex modified asphalt concrete. With the addition of SBR latex, binder morphology underwent a vast change. The micrographs showed a high density of tough fibrils and large crack widths [9]. The binder remained soft and could sustain high plastic deformation. The aspect ratio and appearance of the binder fibrils changed with longer, thinner strands connecting the two faces. The fibril density obtained with SBR was the highest amongst all the polymer modified binders studied. The deformation was also different in that the entire fibril elongates instead of necking. SBS, SEBS, EAM and unmodified binders normally showed fibril rupture at a crack width of 50μm to 300μm. SBR fibrils remained stable even when the crack width was on the order of millimeters and macroscopic observations indicated that some fibrils extended to approximately 25-50 mm before rupture. The fibril density was seen to be directly proportional to the concentration of SBR latex in the binder. Most fibrils had an extremely high aspect ratio, remaining stable even up to diameters of 700 nm. Fibrils were also seen to be clearly attached to the aggregates at their ends. This type of morphology is likely to prove beneficial in terms of crack inhibition and crack healing in asphalt concrete.

Crumb Rubber modified asphalt concrete. With the addition crumb rubber, the asphalt binder fibrils were observed to have much higher elongation at break (~600 microns) and the fibril density showed a slight increase as compared to unmodified AC-5. The fracture surfaces appeared to be covered with asphalt and no bare aggregate surfaces were observed [13].

Figure II.9 shows ESEM micrographs of (a) adhesive failure seen in unmodified asphalt concrete at low temperatures, (b) typical failure process in unmodified asphalt concrete at room temperature, (c) typical fracture morphology of SBR modified asphalt concrete, (d) details of the binder network in the asphalt concrete fibrils seen during fracture. Table II.4 summarizes the observations made during the ESEM fracture tests for all types of polymer modifiers.

2.4.2.3. Fracture Toughness of Polymer Modified Asphalt Concretes

The fracture toughness of asphalt concrete was determined using the 3-point bending beam test using beams notched to different depths. This method was found to be reproducible and consistent.

Aggregate gradation is an important factor to be considered in fracture toughness measurement. The repeatability and accuracy of the data obtained improves significantly with a reduction in the aggregate size. It was found that by using an aggregate gradation, where 99% of the maximum aggregate size was 25% or smaller than the minimum beam dimension, the repeatability increased significantly [7, 8]. Table II.5 shows the aggregate gradation used in the beam samples for fracture toughness testing. The J_{IC} fracture toughness was evaluated for all polymers and can be seen in Table II.6.

2.5. *Durability Tests*

2.5.1. Specific Objectives

- To determine the effect of freeze-thaw cycling in the presence of salt and water on the binder/aggregate adhesion properties and on the fracture properties of asphalt concrete.

2.5.2. Accomplishments

2.5.2.1. Experimental Approaches

Thermal-Saltwater Exposure Cycles For simulation of environmental conditions, test samples of asphalt binder and asphalt concrete were subjected to freeze-thaw cycling with intermittent conditioning in a 10 wt.% salt (NaCl) solution. A total of 100 thermal cycles were programmed [13].

Durability Cycling Conditions -
1) from 23 °C to 0 °C; Rate = -5 °C/min
2) from 0 °C to -30 °C; Rate = -1 °C/min
3) -30 °C dwell for 1 hour
4) from -30 °C to 20 °C; Rate = 10 °C/min
5) 20 °C dwell for 1 hour

Saltwater Saturation Samples were taken out from the temperature cycle chamber when they are at 20°C dwell and then conditioned in a salt solution at 23°C for 2 hours. Approximately, 20 thermal cycles to give a ratio of 10 thermal cycles for every an hour of conditioning.
Total number of thermal cycles = 100
Total hours of salt-solution conditioning = 10 hours

Test Specimens Lap-shear and ESEM tensile fracture specimens were employed in the thermal-saltwater cycle experiment. Lap-shear samples prepared by the standard procedure described in previous reports were cycled under a slight cramping force using small paper clamps in order to avoid possible separation due to thermal fatigue. Thin strap sheet form of tensile fracture samples made from Marshall concrete samples were cycled between thermal chamber and saltwater bath directly. After exposure, all samples were conditioned at room temperature and room humidity for one day or so and tested at the same condition.

In-situ ESEM tensile tests The samples from the durability cycling were fractured in the ESEM tensile stage and the morphology was studied [13].

2.5.2.2. Adhesion Properties and Behavior

Effects of thermal-salt water exposure cycles on adhesion properties and behavior of polymer modified asphalt binders have been determined by the lap-shear performance [13]. Both fresh mixed and aged AC-5 and AC-10 binders modified with SEBS and CRM were studied at two different temperatures, 0°C and -10°C. Surprisingly enough, there was no dramatic property degradation or catastrophic failure due to the cycle for both fresh and aged binders regardless of polymer modification.

2.5.2.3. Fracture Morphology and Behavior

The fracture morphology of unmodified asphalt concrete samples undergoing thermal-cycling durability tests showed a slight coarsening of the binder. The polymer modified asphalt concrete samples did not show any change in the morphology from that of fresh samples. This indicates that the polymer modified asphalt can enhance the durability of asphalt concrete to some extent [13].

Summary of the Results

Various test methods and procedures have been newly developed for characterization of asphalt binders and asphalt concretes in terms of basic morphology, microstructure, fracture behavior, aggregate/asphalt binder adhesion, and durability. It has been proved from the phase II results that these methods and procedures are reliable and meaningful in evaluating polymer modification of asphalt systems as well as in determining material parameters that can be used in predicting performance in actual applications. From the results optimization of the polymer modified asphalt concrete can be achieved by attaining the ultimate goal of improved pavement performance. The development of the complete test methodology is one of the major achievements made in the phase II program. These methods and procedures are now available for MDOT and the other interested parties and can also be incorporated into the existing standard tests and specifications in the asphalt industry.

Overall, it should be concluded that the polymer modification improved the performance and properties of asphalt binders and concretes from the analyses of five modifiers (SBS, SEBS, SBR, Elvaloy AM, and CRM) studied in phase II in that: (1) the binder/aggregate adhesion strength and toughness increased considerably with adding polymer modifiers, especially at lower temperatures where the failure mode transition occurred, (2) polymer modified asphalt binder concretes showed more ductile deformation and fracture processes by more intense fibrillation formation, and (3) polymer modification seemed to prevent or retard the aging process from binder network morphology studies and lap-shear adhesion analyses.

The study of binder microstructure has led to a fundamental understanding of the nature of asphalt binders. The proprieties and nature of the network structure is found to control the properties of the asphalt binder and asphalt concrete. The ESEM technique developed during this study provides a good qualitative tool for characterizing asphalt binders, aging and asphaltene content. The study of polymer phase morphology also leads to an understanding of the different mechanisms with which polymers enhance the asphalt binder properties and fracture morphology of asphalt concrete. Polymer modification of binders was seen to conclusively retard the aging process in asphalt concrete.

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III. Basic Structural and Engineering Properties of Polymer/Fiber-Asphalt-Aggregate Mixtures

Throughout the State of Michigan, several types of distress can be found on asphalt surfaced pavements. These include thermal cracking, block cracking, aging, fatigue cracking, rutting, raveling and stripping, and reflective cracking. The distress mechanism varies from one type of distress to another and it is influenced by the structural properties of the pavement layers and the roadbed soil, construction practices, traffic load and volume, and environmental conditions. Although each of these factors has a specific role on pavement performance, the asphalt courses play the major role and they represent the most expensive element of the pavement structure. The main objective of this subtask is to assess the engineering properties (such as compressive and tensile strengths, creep and plastic characteristics, fatigue life, resilient modulus, viscoelastic properties, and the stability of the AC mixtures) of asphalt mixtures exposed to various combinations of low and high temperatures, moisture conditions, and static and cyclic loads.

Part 1. Structural, Engineering, and Physical Properties of Mixtures

3.1 Materials Used

The materials used throughout this study are presented below.

3.1.1 Aggregates

The coarse and fine aggregates used in the asphalt mixtures were obtained from Spartan Asphalt and were stored at the storage facility of Michigan State University (MSU) in four different piles according to the aggregates sizes. The aggregates were then transferred to the MSU Pavement Research Center of Excellence (PRCE) laboratories in small quantities where they were sieved, washed, dried, and stored. Fly ash supplied by the Michigan Department of Transportation (MDOT) was used as the mineral filler for the asphalt mix design.

3.1.2 Asphalt Cement

Three viscosity graded asphalt cements were used in this study AC-2.5 (see Table III.3), AC-5, AC-10 and AC-20. These asphalts were supplied by Amoco in 5 gallon containers. Upon opening a container the asphalt cement was stored in a freezer to prevent the aging which could occur at room temperature.

3.1.3 Polymers

Five types of polymers were selected for modifying the asphalt cements. These are:

- Styrene-Butadiene-Styrene (SBS)
- Styrene-Ethylene-Butylene-Styrene (SEBS)
- Styrene-Butadiene-Rubber (SBR latex)
- Elvaloy® AM (EAM)
- Crumb Rubber (CRM)

SBS, SEBS and SBR latex are classified according to their functions as network thermoplastics, as they behave like resins and form a network inside the asphalts. The EAM acts as a reacting polymer, as it bounds molecularly with the asphalt and forms an elastic network within the asphalt.

3.2 *Physical Properties of Aggregates*

Various physical properties of the aggregates were evaluated. The results are presented below:

3.2.1 Specific Gravity

The specific gravity of the aggregates was determined using the ASTM D127 for the coarse aggregate and ASTM D 128 for the fine aggregate. The individual aggregate sizes were tested in a triplicate samples and the bulk and the apparent specific gravity was determined. The bulk specific gravity of the saturated surface dried samples (SSD) were also determined in this test. The bulk specific gravity of the fly ash material was tested by MDOT using the standard AASHTO procedures. Table III.1 shows the specific gravity of the individual aggregates which represents the average of triplicate samples. The specific gravity of the coarse aggregates (-1/2" to +#4 sieve) and the fine aggregates (-#4 sieve to +#200 sieve) was averaged based on the proportions of each sieve size in the proposed aggregate gradation.

3.2.2 Absorption Capacity

The absorption capacity of the aggregates is defined as the ratio of the weight of water required to saturate all the permeable voids in the aggregates while keeping their surface dry to their oven-dry weight. The absorption capacity of the aggregates was determined from the specific gravity test data (ASTM D127 for the coarse aggregate and ASTM D128 for the fine aggregate). The absorption capacity of each individual aggregates is listed in Table III.1. It can be seen that the absorption capacity varies from 1.78 percent for the fine aggregates of plus size #200 to 0.60 percent for the coarse aggregate passing on the 1/2" size sieve. The average absorption capacity of the aggregates was found to be 1.10 percent.

3.2.3 Durability

Durability of the coarse aggregates was evaluated using the Los Angeles Abrasion Test based on Michigan Test Procedure MTM 102-78. A blend of about 5000 gram of the coarse aggregates was made. The blend was tested for 500 revolutions in the Los Angeles Abrasion Machine. The percent loss by weight of the aggregates was 24.20 percent which satisfied the MDOT specifications.

3.2.4 Viscosity

The viscosity of the straight and the polymer modified asphalt binders was measured using the Brookfield viscometer. The results for the AC-5 and AC-10 are presented in Figure III.1. It can be seen that the SBS modified binders have higher viscosity than straight binders. For the mixtures with the straight asphalt binders, both the mixing and the compaction temperatures were selected as 290°F based on MDOT recommendations. For the mixes with the SBS modified binders, both the mixing and compaction temperatures were selected as 350°F. The viscosity of the modified binders at this temperature are within the range used for the straight asphalts and within the range of temperatures recommended by the industry. It was noticed that the SBS modified mixtures were easy to handle at this temperature level.

3.3 Marshall Mix Design

3.3.1 Aggregate Gradation

The aggregate gradation used throughout this study was selected based on a trial and error procedure. Seven aggregate gradations (G1 through G7) were made and the resulting asphalt mixes were tested using the Marshall mix design procedure. The G7 gradation shown in Figure III.2 and Table III.2 satisfies the MDOT specifications of voids in mineral aggregate (VMA) and the MDOT criteria for asphalt mix.

3.3.2 Mix Design

A mix design of the straight and the modified asphalt mixtures was conducted using the standard Marshall Mix design procedure. The aggregate gradation G7 was used for this mix design. All Marshall samples were compacted and tested in the following order:

1. Bulk specific gravity (ASTM D 2726)
2. Stability and flow test (ASTM D 1559)
3. Maximum theoretical specific gravity (ASTM D 2041).

The optimum asphalt content was determined based on MDOT specifications. These include:

1. A target air voids of 3.5 percent based on the traffic volume.
2. A minimum of 16 percent VMA.
3. A minimum Marshall stability of 1200 pounds and Marshall flow in the range of 8 to 16.
4. An asphalt content between 5 and 8 percent by weight of the total mix.

Based on the above specifications, the optimum binder contents for straight and polymer modified asphalt mixtures were determined and are summarized in Table III.3.

3.4 Test Types

Two types of tests were conducted to evaluate the structural properties of straight and polymer modified asphalt mixtures. These includes; Indirect Tensile Cyclic Load Test (ITCT) and Indirect Tensile Strength Test (ITST). For all tests, Marshall size samples (4-inch diameter & about 2.5-inch thick) were used. The test procedures are presented below:

3.4.1 Indirect Tensile Cyclic Load Test

Indirect Tensile Cyclic load tests were conducted to evaluate various properties of the asphalt mixtures. First, the sample was placed on the 0.5 inch wide strip on the loading device and a 30-pound sustained load was applied. When the sample came to rest, a cyclic load of 170-pounds was applied. The deformation of the sample was measured in three directions using LVDT's. Each loading cycle consisted of 0.1 sec load-unload period and 0.4 sec rest period. Figure III.3 shows the sinusoidal load cycles applied to the sample and a typical measured deformation. Figure III.4 displays a typical behavior of an asphalt mixture subjected to cyclic loading. It can be seen that the total strain can be divided into 3 components; elastic, viscoelastic and plastic.

Part of the measured deformation which was recovered immediately upon unloading is called the elastic deformation. Another portion that was recovered after a longer period of time is the viscoelastic deformation. The third portion is plastic (permanent) in nature. This plastic deformation accumulates as the number of load cycles increases and it ultimately causes failure.

Several trial tests were conducted to determine the magnitude of the cyclic, the total peak load and the sustained load. When a cyclic load of 300 pounds and a sustained load of 50 pounds were applied, the sample failed after few cycles in shear failure. After several trial tests, the magnitudes of the cyclic and sustained load were selected as 170 and 30 pounds respectively. These made the total peak load 200 pounds and the minimum load 30 pounds.

The Indirect Tensile Cyclic Load test was used to determine the fatigue life, the resilient modulus, the plastic deformation and the deformation rate of the straight and polymer modified asphalt mixtures.

Resilient Modulus

Resilient modulus is an essential measure of the stiffness of a particular asphalt mixture under cyclic loading. The resilient modulus of the asphalt mixture was calculated at test temperature of 23, 77 and 140°F using the following equation [1]:

$$M_R = (0.253680*H + 3.9702876*V - 0.0142874*A)/D$$

where $D = 1.105791(H^2 + V^2 + A^2) - (h-0.0627461*V + 0.319145*A^2)$;

$H = D_H*L/P$;

$V = D_V*L/P$;

$A = D_L/P$; and

M_R= resilient modulus;

D_H= horizontal resilient or total deformation of the specimen along the horizontal diameter (inches);

D_V= vertical resilient or total deformation of the specimen along the vertical diameter (inches);

D_L= longitudinal deformation along the longitudinal axis (thickness) of the specimen (inches);

P= the magnitude of the applied load (pounds);

L= sample thickness (inches).

Fatigue Life

Fatigue cracking is one of the major load-related distress modes experienced in asphalt concrete pavements. In the laboratory, the fatigue responses of the straight and the modified asphalt mixtures were studied under stress controlled tests using an indirect tensile test device. The test frequency was set at 2 cycles per second (2 Hz). Each loading cycle consisted of 0.1 sec of loading-unloading period and 0.4 sec of relaxation time. All tests were conducted at a temperature of 77°F. For all tests, the fatigue life of a sample was defined as the number of load cycles that caused fracture in the sample. Due to time constraint, the tests for some samples were terminated at 1,000,000 cycles and the fatigue life was considered as unlimited.

Plastic Deformation

From the results of the indirect tensile cyclic test, vertical plastic deformation versus the number of load cycles was obtained. This represents the resistance of a material to the permanent deformation which leads to rutting. The number of cycles that is required to develop a certain level of the plastic deformation is considered to be the basis for the relative performance of the polymer modified and unmodified asphalt concrete mixtures. These three levels of plastic deformation are 0.03, 0.05, and 0.07 inch.

Deformation Rate

Deformation rate (inch/cycle) is defined as the magnitude of the horizontal plastic deformation per load cycle. This represents the rate at which the damage (permanent strain) is induced into the sample. This permanent strain is ultimately responsible for initiating fatigue cracks. It should be noticed that this deformation is caused by the tensile stress that is induced into the sample and it simulates the tensile strain that is developed at the bottom of the asphalt layer of the pavement due to traffic loading. This tensile strain causes the fatigue cracks in the asphalt layer when it exceeds the material capacity. Higher deformation rates, cause shorter and lower fatigue life.

3.4.2 Indirect Tensile Strength Test

Indirect tensile strength test employs an indirect method of measuring the tensile properties. For this test, the same set up as the indirect tensile cyclic test was used and a ramp loading was applied to the sample at a rate of 2 inch per minute until failure. During the test, the magnitude of the load and the sample deformation were measured. The data were used to calculate:

Tensile Strength	which is the maximum tensile stress applied to the sample during the test. Higher tensile strength indicates better resistance to cracking.
Total modulus	which is an indication of the stiffness of the material. Higher total modulus indicates higher deformation resistance.
Fracture toughness	which is the total energy (lb-inch) required to cause complete failure of the sample. This is equivalent to the area under the load-deformation curve at failure. Higher toughness indicates a material that is more resistant to cracking.

The indirect tensile strength tests were conducted at test temperatures of 23, 77 and 140°F. The Marshall samples were placed in the temperature chamber for 4 to 5 hours and then tested within one minute. For each sample, the indirect tensile strength (ITS) was calculated for each sample using the following equation [1]:

$$\text{ITS (psi)} = 0.156 * P / L$$

where

L = thickness of the sample (inch); and

P = maximum load at failure (pounds).

3.5 *Experiment Program Matrix*

To accomplish the objectives of this study, several materials and test methods were used. Prior to commencement of the tests, an experiment design matrix was established. The experiment matrices for Indirect Tensile Strength Test (ITT) and Indirect Tensile Cyclic Test (ITCT) are shown in Figures III.5 and III.6 respectively. Each cell in the matrix represents a triplicate. There are three test temperatures, 23°F (-5° C), 77°F (25°C) and 140°F (60°C), three types of asphalt grades (AC-5, AC-10 and AC-20), and five types of polymers (SBS, SEBS, SBR, EAM and CRM) with different polymer content. For each asphalt grade, three types of mixes are included as in Figures III.5 and III.6. These are;

Straight asphalt - virgin asphalt that will be mixed with the aggregates at 290°F

Polymer modified asphalt (PMA) - an asphalt that was mixed with polymers according to the established mixing protocol for two hours at 350°F or 380°F depending on the type of polymer used, after one hour of melting at temperature of 275°F.

Processed asphalt - an asphalt that was processed in the exact conditions (temperature and time of mixing) as the polymer modified asphalt except that this was mixed without the addition of any polymers. Thus, during the mixing processes, this asphalt was subjected to the same aging conditions as the polymer modified asphalt. The reason for making this type of asphalt is to examine the effect of aging that occurs during the polymer mixing process on the engineering properties of the mixtures.

The samples made from the above mentioned asphalts were cured for 12 hours or more at room temperature. For oven aging, the samples were placed in an oven for 7 days at 140°F and then cured for 9 to 12 hours at room temperature.

3.6 Samples Designation Numbers

1. The first digit is the **Test Type**:
   - Marshall Mix Design = 1
   - Indirect Cyclic Tensile = 2
   - Indirect Tensile = 3
2. The second digit indicates **Test Temperature**:
   - Temperature of 140°F = 1
   - Temperature of 77°F = 2
   - Temperature of 23°F = 4
3. The third digit indicates the **Asphalt Type**:
   - AC-5 = 2
   - AC-10 = 3
   - AC-20 = 4

4. The fourth digit indicates the **Asphalt Additive**:

Straight Asphalt = 0
Asphalt + SBS polymer = 1
Asphalt + SEBS polymer = 2
Asphalt + SBR polymer = 3
Asphalt + EAM polymer = 4
Asphalt + CRM polymer = 5

5. The fifth digit indicates the **Polymer Contents**:
   Polymer content of 0% = 0
   Polymer content of 1% = 1
   Polymer content of 2% = 2
   Polymer content of 3% = 3
   Polymer content of 4% = 4
   Polymer content of 5% = 5
   Polymer content of 6% = 6
   Polymer content of 7% = 7
   Polymer content of 10% = 10
   Polymer content of 15% = 15
6. The sixth digit indicates the **Aging**:
   Processed and PMA samples = 1
   Oven aged samples (7 days, 140°F) = 2
   Straight samples = 5
7. The seventh digit indicates the **Sample Number (SN)** by order of test
   SN = 1 to 3.

Part 2. The Engineering Properties of Conventional and Modified Binder-Aggregate Mixtures.

The purposes of this study are to determine whether or not the performance of compacted asphalt mixtures can be improved by using polymer modified asphalts. An improvement in the tensile strength implies an improved fatigue life. On the other hand, an improved tensile strength and extensibility (flexibility) at low temperatures implies lower temperature cracking potential.

3.7 Indirect Tensile Strength Tests

Indirect Tensile Strength Tests (ITST) were conducted on several asphalt mixtures at different test temperatures. These include:

1. Straight, processed, and polymer modified AC-5 asphalt mixtures at test temperatures of 77 and 140°F.
2. Oven aged straight, processed, and polymer modified AC-5 asphalt mixtures at a test temperature of 77°F.
3. Straight, processed, and polymer modified AC-10 and AC-20 asphalt mixtures at test temperatures of 23, 77 and 140°F.
4. Oven aged straight, processed, and polymer modified AC-10 and AC-20 asphalt mixtures at test temperatures of 23, 77 and 140°F.

For each test, the load and the vertical deformation were measured. The indirect tensile strength, the toughness, the compressive strength and the total modulus for these mixtures were calculated and the results are presented below. Unfortunately the supply of AC-5 binder was exhausted before the testing program was completed. Although new AC-5 was obtained, the physical and chemical properties and the composition of the new binder were different from the original one. Since such properties and composition influenced the test results and in order to compare the results without introducing new variables, the tests for normally cured and oven aged AC-5 straight and polymer modified asphalt (PMA) mixtures at the test temperature of 23°F and oven aged AC-5 PMA mixtures at the test temperature of 140°F were not included.

3.7.1 Optimum Polymer Content

As mentioned above, the ITSTs were conducted at 77°F using different polymer contents in the asphalt mix. It was found that for each polymer type, increasing the polymer content from zero to an optimum value caused an increase in the indirect tensile strength and the toughness of the PMA mixtures. This behavior was due to the improvement of the rheological properties of the asphalt cement with the addition of polymers until a certain "optimum" polymer content, after which the improvement was minimal. A summary of the ITSTs results at the test temperature of

77°F for AC-5 and AC-10 PMA mixtures is shown in Tables III.4 and III.5 respectively. Discussion of the test results is presented below by polymer type.

Styrene Butadiene Styrene (SBS)

Figures III.7 and III.8 show the indirect tensile strength and the toughness of AC-5 and AC-10 PMA mixtures at different SBS polymer contents. It can be seen that AC-5/SBS processed asphalt mixtures show an increase of 9 percent in the average value of tensile strength, while AC-10/SBS processed show an increase of 70 percent. This increase is due to the age hardening of the asphalt mixtures occurred during processing at high temperature and subsequently mixing with the aggregates. Aging occurs due to the loss of the volatile components or evaporation of lower molecular weight materials (oils and resins) during the high temperature processing due to the oxidation/polymerization of asphalt molecules at the surface. Both these mechanisms results in an increase in the viscosity of the binder and subsequently an increase in the strength of the laboratory samples. It seems that the percent increase in the indirect tensile strength of processed AC-10/SBS asphalt mixtures is more as compared to processed AC-5/SBS asphalt mixtures with respect to the straight one. It is because the AC-10 has more asphaltenes (higher molecular weight materials) and less lower molecular weight materials than AC-5. Therefore, for the same mixing time and temperature, the evaporation of lower molecular weight materials causes higher asphaltene-oils ratio for AC-10 mixtures than AC-5 mixtures and results in stiffer mixture.

It can be seen from the figures that the indirect tensile strength and the toughness increases as the polymer content is increased. It is interesting to notice that each AC mixture shows almost the same tensile strength and the toughness at 3 and 5 percent of polymer content and there is a slight decrease in the average value of the tensile strength at 4 percent polymer content. However, this decrease is not dramatic. Moreover, a significant drop in tensile strength can be seen at 7 percent polymer content.

Visual inspection of the failed Marshall samples revealed that the SBS PMA mixtures showed fibrils of the asphalt binder itself or the asphalt-polymer blend bridging the cracks in the sample. No bridging was observed for the straight and processed asphalt mixtures.

Both AC-5 and AC-10 asphalt mixtures modified with SBS show an optimum polymer content of 5 percent. The increases in the average value of tensile strength at 5 percent polymer content, with respect to the straight one, are approximately 55 and 85 percent for AC-5/SBS and AC-10/SBS respectively.

Styrene Ethylene Butylene Styrene (SEBS)

Figure III.9 shows the indirect tensile strength of AC-5 and AC-10 asphalt mixtures modified with SEBS polymer system. Similar trend can be seen as in the SBS polymer system. However, AC-10 asphalt mixtures modified with SEBS polymer do not show any decrease in the average value of tensile strength at 4 percent polymer content. Five percent polymer content shows the maximum indirect tensile strength for both AC-5 and AC-10/SEBS polymer modified asphalt mixtures. The increases in the average values of the tensile strength at 5 percent polymer content for SEBS polymer system are approximately 70 and 110 percent for AC-5 and AC-10 PMA mixtures, respectively. It should be noticed here that for AC-10/SEBS PMA mixtures, approximately 70 percent increase in the tensile strength is due to the age hardening of the mixture during mixing of the polymer with asphalt binder. Similar trend can be seen in the toughness of these mixtures as shown in Figure III.10, except that AC-10/SEBS polymer modified mixtures do not show any significant increase in the average toughness values.

Styrene Butadiene Rubber (SBR Latex)

Figures III.11 and III.12 show the indirect tensile strengths and the toughness of AC-5 and AC-10 asphalt mixtures modified with SBR polymer. Essentially there is no significant difference in the average values of the tensile strength and the toughness between the straight and the SBR modified asphalt mixtures. It might be explained by the processing difficulties of the SBR modified mixtures. The mixing procedure of the SBR/latex with asphalt binder was established in the other study of this project for the investigation of the chemical and thermodynamic properties of polymer modified asphalts. The procedure calls for an optimum mixing time of the SBR latex with asphalt of 30 minutes. During mixing the SBR/asphalt binders with aggregates, a strainy and non-homogenous structure was observed. Moreover, a difficulty of mixing with aggregates was experienced at 4 and 5 percent SBR contents. Although the mixing temperature was 350°F, the AC-10/SBR blend was very sticky and behaves like a jell rather than liquid. It should be noted that these observations were in agreement with the viscosity measurements made during the fundamental chemical properties investigation of this project. The measurements showed that asphalts modified with high contents of SBR were extremely viscous and did not pass the SHRP viscosity specification. Moreover, in the mixing bowl, the mixing of the SBR modified binder with aggregate was somewhat difficult at SBR contents of 4 percent or higher. The SBR modified binders tended to stick to the mixing impeller along with the fine aggregates which was believed to have caused some segregation in the mix.

Although there is no significant increase in the tensile strength and the toughness of AC-5 and AC-10/SBR polymer modified asphalt mixtures, by taking into consideration of the mixing problems encountered at higher SBR content, optimum SBR polymer contents of 2 and 3 percent for AC-5 and AC-10, respectively, were selected.

Elvaloy® AM (EAM)

Figures III.13 and III.14 show the indirect tensile strength and the toughness of AC-5 and AC-10/EAM PMA mixtures, respectively. Based on the indirect tensile strength, it can be seen that at the optimum polymer content of 1 and 2 percents, the tensile strength and the toughness increases by approximately 110 and 135 percent for AC-5 and AC-10/EAM PMA mixtures relative to the straight mixtures respectively. It should be noticed here that about 87 and 110 percent of the strength gain is due to age hardening of the PMA mixtures under high mixing temperature of 380°F and extended mixing time of two hours. This aging of the AC-10/EAM processed asphalt was also confirmed by ESEM network morphology. It was observed that the morphology features of the network resembles that of the aged asphalt binders, that is, rougher and corrugated strand surfaces to some degree, even though the fibril diameter was not coarsened. The slight increase in the average value of the tensile strength of the EAM polymer modified asphalt mixtures is due to the effect of crosslinking on the adhesion strength of the mixture. There is no significant difference between the average values of the toughness of the AC-5 and AC-10 asphalt mixture modified with EAM system with respect to EAM processed mixtures. It seems that the EAM polymer itself does not significantly improve the toughness properties of the asphalt mixtures. The increase in toughness is only due to aging and hardening during the mixing process.

Crumb Rubber (CRM)

Figure III.15 and III.16 show the indirect tensile strength and the toughness of AC-10 asphalt mixtures modified with crumb rubber (CRM). Initially, there is no significant difference between processed AC-10/CRM mix and 5 percent CRM/AC-10 mix. The tensile strength and the toughness dramatically increases to 105 percent at the polymer content of 10 percent and then decreases at CRM content of 15 percent. The optimum polymer content for these mixtures can be seen as 10 percent. The strength gain due to age hardening during high temperature (350°F) mixing process was found to be 29 percent. It seems that most of the tensile strength and the toughness gain in the AC-10/CRM mixtures is due to the CRM itself. Similar to the other polymers, the strength gain in CRM is also due to the improvement in the rheological properties of CRM asphalt binders. However, it was noticed that at higher percentages of CRM (15 and 20 percent) CRM asphalt blends became more viscous and 20 percent CRM did not pass the SHRP viscosity specification. This causes a decrease in the indirect tensile strength and the toughness of AC-10 mixtures modified with 15 percent CRM content. It was also visually observed during the mixing process, CRM asphalt blend got more viscous and difficult to mix at 15 percent CRM content as compared to lower percentages of CRM. Moreover, the CRM particles could be seen scattered in the blend. While mixing with the aggregates, the mixture seemed segregated, which ultimately resulted in the reduction of the tensile strength and the toughness of AC-10/CRM mixtures.

Finally a summary of the mixing time & temperature and optimum polymer content for all polymer systems used in this study are listed Table III.6. These optimum polymer contents are used to compare the engineering properties of straight and polymer modified asphalt mixtures at different test temperatures and curing conditions.

3.7.2 Comparison at High Temperature (140°F)

For each polymer and AC grade, the optimum polymer contents were used to compare the engineering properties of straight and polymer modified asphalt mixtures at test temperature of 140°F. The test of results of the straight and PMA AC-5, AC-10 and AC-20 mixtures are summarized in Tables III.7 through III.12 and plotted in Figures III.17 through III.20.

Table III.12 shows the percent increase or decrease in the ITST results of the PMA mixtures with respect to the processed one. Figure III.17 shows the effect of polymer type on the indirect tensile strength and toughness of asphalt mixtures at test temperature of 140°F. The average values of the tensile strength is considerably higher for the AC-5 PMA mixtures than the straight and the processed one, except the EAM modified AC-5 mixtures which show a decrease of 11 percent as compared to the processed one. There is no considerable increase in the average values of the toughness of AC-5 PMA mixtures as compared to the processed one. However, EAM modified AC-5 mixtures show an increase of 45 percent over the processed one. SEBS modified AC-5 mixtures seems to be more effective than the other AC-5 PMA mixtures. The tensile strength and toughness increase by 71 and 26 percent, respectively. It can also be seen from Figure III.17 that the average values of the tensile strength and toughness of processed AC-10 and AC-20 mixtures are greater than the straight mixtures. This is because of the age hardening of AC mixtures during processing for an extending period of time (1/2 to 2 hours depending on polymer type). AC-10 mixtures modified with SBR show an increase of 33 percent in the average values of the tensile strength over the processed mixtures followed by EAM modified AC-10 mixtures with an increase of 17 percent. SBS, SEBS and CRM show no significant increase in the tensile strength. AC-20 mixtures modified with EAM exhibits higher tensile strength as compared to the other PMA mixtures with an increase of 40 percent. SBR and SEBS modified AC-20 mixtures show an increase of 30 and 27 percent respectively, in the average values of tensile strength, while SBS modified mixtures show no significant increase. The average toughness values of AC-10 PMA mixtures decreases (17 to 32 percent) as compared to the processed one, except, the EAM modified AC-10 mixtures, which show an increase of 36 percent. However, AC-20 PMA mixtures show considerable increase in the averages values of the toughness. EAM modified AC-20 mixtures show a considerable increase in the toughness with an increase of 59 percent over the processed one followed by SBR and SBS with increases of 28 and 22 percent, respectively.

Figure III.18 shows the effect of polymers on the vertical deformation at failure and total modulus of the straight and PMA mixtures at test temperature of 140°F. The vertical deformation of the PMA mixtures is less as compared to the straight and processed ones. However, EAM and SBS modified AC-5 mixtures show increases of 55 and 10 percent, respectively, in the average values of vertical deformation. The higher toughness values (Figure III.17) is the result of higher vertical deformation. The moduli are also lower for these mixtures as compared to the processed mixtures. The vertical deformation for SEBS and SBR modified AC-5 mixtures show decreases of 29 and 22 percent, respectively with respect to the processed one. This is because of the increase in the total moduli values with the addition of polymers. The increases in the moduli values are 145 and 100 percent for SEBS and SBR systems respectively. In the case of AC-10, the PMA mixtures with SBS, SEBS and SBR show decreases of 10, 25 and 24 percent respectively in the vertical deformation at failure, while CRM mixtures show an increase of 12 percent. AC-20 PMA mixtures do not have any significant difference in the vertical deformation and total modulus values, except the EAM system which shows an increase of 14 percent in the vertical deformation at failure. The increase in the total modulus values and the decrease in the vertical deformation at failure indicate higher resistance to rutting.

Figure III.19 shows the effect of polymers on the tensile strength and the toughness of oven aged AC-10 and AC-20 mixtures at 140°F. The tensile strength and the toughness are considerably higher for the polymer modified mixtures than the straight ones. EAM and SEBS systems seem to have more effect at 140°F as compared to other polymers. Moreover, it can be seen that the SBR modified mixtures show lower tensile strength and toughness after oven aging than before aging. Considerable increases in the toughness values were found for SBS and EAM modified AC-20 mixtures than the straight mixtures (140 to 160 percent). Figure III.20 shows the effect of polymers on the vertical deformation at failure and the total modulus of the oven aged AC mixtures at 140°F. The vertical deformation of AC-20 mixtures modified with SBS show considerable increase of 14 percent which results in an increase in the toughness. However, the other AC mixtures show a decrease in the average values of the vertical deformation (11 to 28 percent), subsequently, the modulus is also higher for PMA mixtures as compared to the straight ones. Moreover, EAM modified AC-20 mix shows the highest modulus (an increase of about 220 percent) among all the polymer used in this study.

3.7.3 Comparison at Room Temperature (77°F)

Table III.4, III.5 and III.13 provides a summary of the ITST results at the test temperature of 77°F. The percent increase and decrease in the ITST results of PMA mixtures with respect to the processed mixtures are shown in Table III.14.

Figure III.21 shows the effect of polymers on the tensile strength and the toughness of the straight and the PMA mixtures at test temperature of 77°F. The EAM system shows higher tensile strength and toughness values, but it should be noted here that most of the increase is due to the aging and hardening during processing. There is no significant increase in the tensile strength and the toughness of EAM modified AC mixtures. SBS and SEBS systems seem to be the most effective polymers at a test temperature of 77°F. Increases of approximately 38 to 53 percent can be seen in the average values of the tensile strength of SBS and SEBS modified AC mixtures with respect to the processed one. The CRM modified AC-10 mixtures show an increase of 60 and 45 percent in the tensile strength and toughness respectively, than the processed mixtures. AC-5 mixture modified with SBR and AC-10 mixture modified with SBS show increases of 36 and 38 percent in the toughness. These increases are due to increases in the vertical deformation at failure. A significant increase of 54 percent in tensile strength of AC-20 mixture with 5 percent SBS and SEBS can also be seen from the figure.

A summary of the results for the oven aged PMA mixtures at test temperature of 77°F is shown in Tables III.15 through III.17. Figure III.22 shows the effect of polymers on the vertical deformation and the total modulus of PMA mixtures at test temperature of 77°F. The moduli of AC-5 PMA mixtures increase by approximately 30 to 125 percent. SBS modified AC-5 mixtures show the maximum value. There is no significant increase in modulus values for EAM modified AC mixtures. Moreover, no significant difference is found in the vertical deformation at failure between the processed and the PMA mixtures. However, AC-5 modified with SBS and AC-10 with SBR show decreases of 23 and 19 percent, respectively. The considerable increases in the tensile strength and toughness of AC-5/SBR, AC-10/SBS, AC-10/CRM and AC-20/PMA mixtures clearly indicate better resistance to fatigue cracking and rut potential than the processed mixtures.

Figure III.23 shows the effect of oven aging on the tensile strength and the toughness of the PMA mixtures at the test temperature of 77°F. There is no significant difference in the tensile strength and the toughness after oven aging. However, EAM modified PMA mixtures show a slight decrease in the tensile strength and the toughness. Moreover, the modulus of AC-5 and AC-20 PMA mixtures is not significantly affected by oven aging. There is a considerable increase found in the modulus values of AC-10 PMA mixtures after oven aging as shown in Figure III.24. It is also clear from this figure that the vertical deformation decreases considerably because of oven aging.

3.7.4 Comparison at Low Temperature (23°F)

A summary of the indirect tensile strength test results is tabulated in Tables III.18 through III.21 and are plotted in Figures III.25 through III.28. Table III.22 shows the percent increase or decrease of the ITST results of PMA mixtures with respect to the processed mixtures.

Figures III.25 shows the effect of polymers on the tensile strength and the toughness of AC-10 and AC-20 PMA mixtures at 23°F. There are 2 to 15 percent increases in the average value of tensile strength of the polymer modified mixtures from the processed mixtures. However, there is no significant difference in the average toughness values of AC-10 and AC-20 mixtures modified with 5%SBS and 5%SEBS polymer. AC-10 mixtures modified with 3%SBR and 10%CRM show increases of 30 and 53 percent, respectively. Moreover, no significant difference is found between the straight and the PMA AC-10 and AC-20 mixtures. Figure III.26 shows the effect of the polymers on the vertical deformation at failure and the total modulus at the test temperature of 23°F. There is no significant difference in the total modulus and vertical deformation. However, AC-10 mixtures modified with 3%SBR and 10%CRM show respectively increases of approximately 35 and 40 percent in the vertical deformation with respect to the processed one. The increase in the vertical deformation of SBR and CRM modified AC-10 mixtures causes the increases in toughness. This indicates that SBR modified AC-10 mixtures show high resistance to thermal cracking. In general, the total moduli of AC-10 and AC-20 PMA mixtures slightly decrease as compared to the processed mixtures.

Figure III.27 shows the effect of polymers on the tensile strength and the toughness of oven aged AC-10 and AC-20 PMA mixtures at 23°F. Similar trend can be seen in the unaged AC mixtures. There are only 10 to 25 percent increases in the tensile strength and 14 to 32 percent increases in the toughness values. AC-10 mixtures modified with 3%EAM show higher tensile strength and toughness values than the other PMA mixtures. Figure III.28 shows the effect of polymers on the vertical deformation at failure and the total modulus of the oven aged PMA mixtures at the test temperature of 23°F. AC-10 mixtures modified with 3%SBR show higher modulus values than the other mixtures, however, the increase is not significant. Moreover, there is no substantial difference in the modulus values of AC-10 and AC-20 PMA mixtures at low temperature. On the other hand, EAM and SBS modified AC mixtures show higher vertical deformation to failure (6 to 12 percent) as compared to the straight mix. The higher deformation at failure of SBR and CRM asphalt mixtures at low temperature indicates less potential of low temperature cracking.

3.8 *Indirect Tensile Cyclic Load Tests*

Indirect Tensile Cyclic Load tests (ITCT) were conducted on several asphalt mixtures at different temperatures. These include:

1. straight, processed and polymer modified AC-5 asphalt mixtures at a test temperature of 77°F.
2. straight, processed and SBS and SEBS modified AC-5 mixtures at a test temperature of 23°F.
3. oven aged straight, processed and polymer modified AC-10 asphalt mixtures at test temperatures of 23, 77 and 140°F.
4. straight, processed and polymer modified AC-20 asphalt mixtures at test temperatures of 77°F.
5. AC-20 straight mixtures at test temperature of 23°F.

For each test, the applied load and the deformations in all three directions were measured. After each test was terminated, the fatigue life, the resilient modulus, and the plastic deformation rates were calculated and the results are listed in Tables III.23 through III.30 and are plotted in Figures III.29 through III.59.

3.8.1 Fatigue Life Criteria

Fatigue cracking is one of the major load-related distresses occurring in asphalt concrete pavements. Fatigue cracks are series of interconnecting cracks caused by the fatigue failure of asphalt surface or stabilized granular base under repeated traffic loading [2]. The fracture occurs when the induced cumulative plastic strain exceeds certain maximum value. Fatigue cracks initiates at the bottom of the asphalt concrete layer, where the tensile stress and strains are maximum. These cracks propagate upward and interconnect with increasing load repetitions. Fatigue cracks are typically accelerated by environmental factors (such as temperature change, rainfall, moisture and freeze-thaw) and they form a pattern resembling chicken wire or skin of an alligator [2]. A significant amount of efforts has been made to predict the fatigue life of asphalt concrete pavements by laboratory testing under simulated environmental conditions. In the laboratory, the number of cycles to failure is a basic criteria which indicates how well a particular asphalt mixture will perform relative to fatigue cracking. In order to study the fatigue cracking resistance of asphalt concrete, a cyclic load is applied to a Marshall size sample and the number of cycles to failure is determined. Figure III.4 shows the general stress strain behavior of an asphalt mixtures subjected to a cyclic load [4]. The material response in the form of strain consists of three components:

a) elastic strain which is stress and temperature dependent and is recovered immediately after the load is released.
b) viscoelastic strain which is time, stress and temperature dependent and is completely recoverable with time.
c) plastic or permanent strain which is stress and temperature dependent.

Traditionally, the stress and strain amplitude data are plotted against the number of load cycles to failure and these curves are called S-N curves. For asphalt mixtures, the fatigue life increases with decreasing the tensile stress and the strain amplitudes until the limiting values are reached. In general the stress and strains below fatigue life causes elastic strains. It should be noted here that the plastic strain or permanent deformation is responsible for the fatigue damage and consequently results in fatigue failure of the pavement. A perfectly elastic material will never fail in fatigue regardless of the number of load applications [5].

In the laboratory, the fatigue life of the test samples is defined according to an established criterion. Many criteria have been reported in the literature, non of which is universally accepted. These criteria include [5, 6, 7]:

1) The number of load cycles at which 50 percent drop in the resilient modulus values occur.
2) The number of load cycles at which the horizontal plastic deformation (HPD) reaches 0.1 inch.
3) The number of load cycles at which the slope of the deformation ratio (the ratio of the horizontal to vertical plastic deformations) increases rapidly.
4) The number of the load repetition at which the vertical permanent deformation reaches between 0.28 and 0.36 inches.

5) The number of load cycles at which the commutative HPD along the horizontal diameter of a compatible specimen tested to failure using the indirect tensile test mode reaches a value equal to 95 percent of the total horizontal deformation at failure.

For most of the polymer modified samples, the drop in the resilient modulus does not reach 50% even at failure shown in Figure III.29. This implies the polymer modified samples maintained high values of modulus until fatigue failure occurs. Therefore, the first criterion is not applicable. The second and third criteria show similar results as shown in Figure III.30 and III.31. In this study, the slope of HPD curve show more consistent results as shown in Figure III.32.

In this study, it was hypothesized that the fatigue life are initiated in the test sample in the form of undetectable (by visual observation) microcracks. With increasing number of load repetitions, they grow to macrocracks that can be visually detected. Once the microcracks are initiated, the tensile HPD starts to increase sharply as a result of stress concentration at the crack tip. Therefore, the fatigue failure of the test sample can be defined as the number of cycles at which macrocracks are initiated. This initiation causes an increase in the rate of the accumulation of the HPD. Based on the above definition and observations, the following procedure was established for the determination of the fatigue lives of the test samples. From the test results, the HPD is plotted as a function of the number of load repetitions as shown in Figure III.33. From this, the normalized slope of HPD is calculated by simply dividing all the data points by the first reasonable data (within the accuracy point of the LVDT i.e 10^{-4} inch) plastic deformation value. This division practically normalizes the plastic deformation data relative to the first reasonable plastic deformation value. The normalized data are then plotted on a semi logarithmic paper as a function of the number of load repetitions as shown in Figure III.32. This curve shows the incremental rate of accumulation of the HPD as a function of the number of load repetitions to failure. The slope of this curve decreases first, reaches a valley, and then starts to increase. The decrease in the normalized slope shows that the rate of accumulation of horizontal deformation is low at the beginning of the test. When cracks are initiated, the rate of HPD increases which results in the increase of the normalized slope. Therefore, in this study, the fatigue life is defined as the number of load cycles at which the slope of the HPD just starts to increase, as shown Figure III.32 point "A". Hence, using the above established procedure, the numbers of fatigue life for the asphalt mixtures shown in Figure III.32 are 30,000 and 25,000 load cycles for the triplicate samples of AC-5/3%SBS, # 2 and 3, respectively. This criteria for the fatigue life was used throughout this study to compare the various PMA mixtures.

3.8.2 ITCT at Room Temperature (77°F)

3.8.2.1 Fatigue Life

Indirect tensile cyclic load tests were conducted at temperature of 77°F to determine the fatigue life of AC straight and PMA mixtures. Figure III.34 shows the effect of mixing temperature and time on the fatigue life of AC-5 and AC-10 mixtures. It can be seen that the average fatigue life of the processed AC-5 asphalt is higher than the straight asphalt mixtures. It increases from 2,033 cycles to 5,000 cycles for SBS/SEBS, to 3,500 for SBR and CRM processing and to 25,000 cycles for the EAM processing condition. The increase in fatigue life is due to the aging of the asphalt mixtures (see section 3.7) occurred during processing at high temperature and subsequently mixing with the aggregates. This aging increases in the stiffness of the asphalt concrete mixtures. It can also be seen that mixing temperature has more influence on aging of the mixtures than the mixing time since the EAM has the same mixing time as that for SBS and SEBS but higher mixing temperature. Similar trend can also be seen for AC-10 processed mixtures. The effect of polymer content on the fatigue life of PMA mixtures is discussed below:

Figure III.35 shows the effect of polymer content on the fatigue life of AC-5 PMA mixtures at the test temperature of 77°F. It can be seen that the fatigue life increases as the polymer content increases and the optimum polymer contents are 5, 5, and 4 percent for SBS, SEBS and SBR, respectively. It should be noted here that the fatigue life of the EAM mixtures is higher than one million load cycles (i.e. the sample did not experience fatigue failure at 1,000,000 load repetitions and the tests were stopped due to time constraint). Hence, the fatigue life of EAM mixtures is considered as unlimited (U). One interesting point should be noted is that the SBS and SEBS systems showed the same optimum polymer contents in the cyclic load test as those obtained from the ITST. The SBR system, however, shows a different polymer content.

Examination of Figure III.35 indicates that the fatigue lives of AC-5 mixtures with 5%SBS, 5%SEBS and 4%SBR increase by factors of 13, 10 and 3 relative to the processed mixtures. It can also be seen that the EAM system shows higher fatigue life than all the polymer used in this study.

Figure III.36 shows the effect of polymer content on the fatigue life of AC-10 PMA mixtures. The EAM mixtures show the maximum fatigue life i.e., more than million load cycles. Moreover, a decrease in average values of fatigue life can be seen at polymer contents of 4 percent for both SBS and SEBS systems. Unlike AC-5/SBR polymer modified mixtures, AC-10/SBR system shows the optimum polymer content of 3 percent. The average value of the fatigue life of the SBR modified mixtures is lower than all the other polymer mixtures. It is because of the mixing and segregation problems as discussed before in section 3.7.

3.8.2.2 Resilient Modulus

The resilient modulus is an essential measurement of the stiffness of a particular asphalt mix under cyclic loading. The higher the resilient modulus, the less the strain developed in the material for certain stress level and the better the permanent deformation resistance. The resilient modulus was calculated at 500th load cycles. The results for AC-5 and AC-10 PMA mixtures are plotted in Figures III.37 and III.38, respectively.

Figure III.37 shows the effect of the polymer content on the resilient modulus of AC-5 PMA mixtures at 77°F. It can be seen that the addition of polymers increases the resilient modulus of AC-5 mixtures over the straight mixtures. It should be noted here that most of the increase is due to the aging of the mixtures during mixing at a high temperature and an extended period of time. The percent increases in the average value of resilient modulus due to processing are found to be approximately 32 to 73 percent. SBR modified AC-5 mixtures with shorter mixing time of 30 minutes at 350°F show lower values than EAM mixtures with a mixing time of two hours at 380°F. The increases in average values of the resilient modulus due to polymer itself are found to be 12 to 42 percent. As compared to other systems, the EAM system shows the lowest and the SEBS system shows the maximum percent increase in the resilient modulus.

Similar trend can be seen in AC-10 PMA mixtures as shown in Figure III.38, except that the SBR system shows the maximum percent increase (31 percent) in the average values of the resilient modulus than the other polymer systems. It is interesting to note here that, there is no significant difference in the resilient modulus between the processed and the PMA mixtures, however, considerable improvement in the fatigue life can be seen. This indicates that the polymer modification has improved the plastic part of the total modulus which results in the improvement of the fatigue life and the resistance to rutting.

3.8.2.3 Deformation Rate

This represents the rate at which a damage (permanent strain) is introduced to the sample. The higher the deformation rate (inch/cycle), the sooner the cracks initiation, and the lower the fatigue life.

Substantially, low deformation rates of the PMA mixtures over the processed mixtures can be seen in Figures III.39 through III.42. It is evident from Figure III.39 that, by adding 5% SEBS to the AC-5, for instance, reduces the deformation rate 45 times as compared to the processed mixtures. AC-5 mixtures with 3%SBR show the least reduction in the deformation rate (3.25 times) as compared to the other systems. Similar trend can be seen for AC-10 PMA mixtures. Considerable reduction in the deformation rate of PMA mixtures implies that high numbers of load repetitions are required to develop the same plastic deformation in the PMA mixtures as compared to the straight or the processed ones. This confirms that the result of less strain levels in the asphalt lead to higher fatigue cracking resistance as a result of adding polymers.

3.8.2.4 Plastic Deformation and Rutting Resistance

Figures III.43 and III.44 show the effect of the polymer content on the plastic deformation resistance of AC-5 and AC-10 PMA mixtures, respectively at a test temperature of 77°F. This resistance is presented in terms of the number of load cycles required to attain a certain level of vertical plastic deformation. It is clear from the figures that polymer modified mixtures show higher number of load cycles to attain the assigned level of vertical plastic deformation than the straight and the processed mixtures. For example, 5%SBS, 5%SEBS and 3%SBR modified AC-5 mixtures show 11, 14 and 5 times more number of load cycles to attain 0.05″ of vertical plastic deformation. This indicates that PMA mixtures are more resistant to rutting as compared to straight mixtures. The EAM modified AC mixtures did not fail and the vertical plastic deformation for these mixtures were lower than 0.01 inch even at 300,000 cycles. This implies that EAM modified AC mixtures are more resistant to rutting as compared to the other PMA mixtures.

3.8.3 Comparison at High Temperature (140°F)

3.8.3.1 Resilient Modulus

Indirect Cyclic Tests were conducted at the test temperature of 140°F to study the resilient behavior of the straight and polymer modified AC-10 mixtures. The resilient modulus was calculated at 100th load cycles. Figure III.45 shows the resilient modulus of triplicate samples of normally cured straight and polymer modified AC-10 asphalt mixtures. It should be noted that the optimum polymer content was selected for comparison of the resilient modulus values. The straight and 3%SBR modified AC-10 failed before 100 load cycles and hence, the resilient modulus was not calculated. The resilient moduli for 5%SBS, 5%SEBS and 2%EAM are almost the same and greater then the straight AC-10 mixture. This shows that, all the other polymer systems except SBR, improve the resilient properties of the AC-10 polymer modified mixtures at 140°F.

Figure III.46 shows the resilient modulus of oven aged AC-10 polymer asphalt mixtures at 140°F. It should also be noted that only one sample with 3%SBR reached the 100 load cycles and the other two samples failed before 100 load cycles. Hence, the resilient modulus was not calculated for those two samples. It can be seen that the resilient modulus for 5%SEBS is greater than 5%SBS and 2%EAM. Moreover, the samples showed higher resilient moduli after oven aging.

3.8.3.2 Horizontal Plastic Deformation

The Indirect Tensile Cyclic Load tests (ITCT) were conducted at high temperature of 140°F to study the plastic behavior of the straight and polymer modified AC-10 asphalt mixtures. Figures III.47 and III.48 show the effect of the polymer type on the resistance to HPD of the polymer modified AC-10 asphalt mixtures at high temperature of 140°F. It should be noted that the straight and 3%SBR AC-10 and AC-20 asphalt mixtures failed before 100th load. It can be seen that the accumulative plastic deformation of AC-10/2%EAM at high temperature is lower than other polymer systems, while the oven aged AC-10/5%SEBS sample shows less plastic deformation. This clearly indicates that polymer modification improves the plastic properties of AC-10 mixtures at high temperature of 140°F.

3.8.3.3 Deformation Rate

Figure III.49 shows the deformation rate (in/cycle) of AC-10 PMA mixtures at a test temperature of 140°F. It can be seen that the deformation rates for EAM and SEBS modified AC-10 mixtures are less than those of SBR and SBS mixes at 140°F. This implies that these polymer systems improve the resistance to the plastic deformation at high temperature of 140°F.

3.8.4 Comparison at Low Temperature (23°F)

3.8.4.1 Resilient Modulus

Figure III.50 shows the resilient modulus of triplicate samples of normally cured straight and polymer modified AC-5 asphalt mixtures at the test temperature of 23°F. The resilient modulus was calculated at 500 load cycles. It can be seen that there are some variations in the resilient modulus values within the triplicate samples of the same mix exit. However, there is no significant difference between the average values of the resilient modulus of AC-5 straight and the polymer modified mixtures.

Figure III.51 shows the resilient modulus for the triplicate samples at test temperature of 23°F. There is not much difference between straight and polymer modified mixtures except that the 5%SBS shows a slight increase in the average moduli values. The average resilient moduli values for the straight and modified mixtures show no significant difference. Moreover, the oven aged samples show slightly lower moduli values than the unaged samples. The AC-5/SBS processed mixtures show approximately 18 to 26 percent less resilient modulus value than the straight and polymer modified AC-10 asphalt mixtures.

Figure III.52 shows the effect of temperature on the resilient modulus of the straight and the polymer modified AC-10 asphalt mixtures. It is clear that the resilient modulus decreases as the temperature increases. There is not much difference between the average values of the resilient modulus for straight and polymer modified mixtures at 23°F (Figure III.52a), except the 2%EAM mixture which shows an increase of 20 percent. At 77°F considerable increase can be seen from the straight one. EAM polymer system shows the maximum increase of approximately 90 percent followed by SBR (65 percent), SEBS (65 percent) and SBS (50 percent). The resilient modulus is almost the same for all type of polymers used in this study. At 140°F, straight samples failed before 100 load cycles and the resilient modulus cannot be calculated, hence, it is obvious that the polymer modified mixtures shows improvement at 140°F. The same trend can be seen in Figure III.52b for the oven aged polymer modified AC-10 asphalt mixtures.

3.8.4.2 Deformation Rate

Figure III.53 shows the deformation rate (in/cycle) for AC-10 straight and polymer modified asphalt mixtures at the test temperatures of 23°F. The deformation rate is considerably lower for polymer modified asphalt mixtures than the straight ones. Moreover, AC-10 mixtures modified with 2%EAM shows lowest deformation rate as compared to the other PMA mixtures. This indicates that the polymer modified asphalt mixtures have higher resistance to fatigue cracking due to repetitive traffic loading than the straight asphalt mixtures at the low temperature of 23°F.

3.8.5 Comparison at Room Temperature (77°F)

3.8.5.1 Resilient Modulus

Figure III.54 shows the resilient modulus values of the triplicate samples of AC-10 PMA mixtures at 77°F. The resilient modulus was calculated at 500th load cycles. It is clear that the resilient modulus of the polymer modified mixtures is greater than that of the straight AC-10. Moreover, EAM polymer shows the highest modulus value among all the polymer systems. However, it should be noted that most of the increase in resilient modulus is due to age hardening during mixing process as mentioned earlier.

Figure III.54b shows the effect of oven aging on the resilient modulus of the straight and polymer modified AC-10 mixtures. It seems that there is not much effect on the resilient modulus of straight and polymer modified mixtures due to the aging, except for the EAM mixtures which show slightly lower modulus values. The SEBS polymer system show slightly higher values after the oven aging.

Figure III.55 shows the comparison of the resilient modulus of PMA mixtures at the test temperature of 77°F. There are considerable increases in the average values of PMA mixtures than the straight AC mixtures. However, no significant difference in resilient modulus is found among the PMA mixtures. 3%SBR/AC-5, 10%CRM/AC-10 and 2%EAM/AC-20 show slightly lower modulus values as compared to other mixtures. Moreover, there is no significant difference between the straight AC-20 and AC-10 PMA mixtures at 77°F. The increase in the resilient modulus of the PMA mixtures indicates higher resistance to rutting and fatigue cracking as compared to the straight AC mixtures.

3.8.5.2 Fatigue Life

Figure III.56 shows the comparison of the fatigue life of the polymer modified asphalt mixtures at the test temperature of 77°F. Substantial increase in the average values of fatigue life can be seen with the addition of polymers. The EAM modified mixtures show more than million load cycles. These mixtures did not fail even after the million load repetitions and the test had to be terminated. Regarding the fatigue life, the EAM polymer system seems to be the best followed by the SBS polymer system as compared to all the polymers used in this study. Moreover, CRM modified AC mixtures were least effective in the resistance to the fatigue cracking even though it showed considerable improvement in the indirect tensile strength.

3.8.5.3 Plastic Deformation

Figure III.57 shows the deformation resistance of the PMA mixtures at the test temperature of 77°F. The number of the load cycles to develop 0.05" of vertical plastic deformation was selected to compare the PMA mixtures for rutting resistance. It can be seen that AC-5 and AC-10 modified with 5%SEBS show maximum numbers of cycles to develop 0.05" of the vertical plastic deformation. The AC-20 mixtures with 5% SBS and SEBS are not shown in the figure. It is because these mixtures were either failed or the test was terminated due to the time constraint. Moreover, EAM modified AC mixtures did not fail even after million load repetitions. Hence, the ITCT for EAM modified AC mixtures were conducted only up to 300,000 cycles. According to this established policy, the EAM modified AC mixtures showed less than 0.02" of vertical plastic deformation at 300,000 cycles. Hence, the EAM polymer system show more resistance to rut potential as compared to the other PMA mixtures followed by the SEBS polymer system.

Figure III.58 shows the effect of polymers on the resistance to the horizontal plastic deformation of AC-5 and AC-10 PMA mixtures. It can be seen that for a given horizontal plastic deformation, the number of the load cycles is higher for the PMA mixtures as compared to the straight ones. The EAM and the SEBS polymer systems are the most effective polymers in reducing the fatigue cracking of AC mixtures. This clearly indicates that PMA mixtures are more resistant to fatigue cracking than the straight one.

3.8.5.4 Deformation Rate

Figure III.59 shows the deformation rate of polymer modified AC-5 and AC-10 mixtures. It is clear that the deformation rate is lower for PMA mixtures than the straight ones. EAM and SEBS polymer systems seems to be the best among all the polymers used. SBR polymer system shows much higher deformation rate than the other polymers. This shows that SBR modified AC mixtures are more susceptible to fatigue cracking than the other PMA mixtures.

3.9 BENEFITS AND COST

Based on the laboratory data the benefits cost ratio (B/C) was calculated for polymer modified asphalt mixtures as shown in Table III.30. The cost of the straight asphalt mixtures was obtained from MDOT for the year 1996. Based on this data the cost per ton of AC mixtures was 29.64 dollars. The cost of PMA mixtures was calculated and was 10 to 16 percent more than the straight mixtures. The mixing and processing cost was not added in this estimate. It can be seen from Figure III.60 that the EAM polymer shows considerable high B/C of 14.9. It should be noted here that EAM modified AC mixtures did not fail even at 1,000,000 load cycles. Hence, for

B/C calculations the fatigue life of EAM asphalt mixtures was assumed to be 1,000,000 load cycles. It is clear from the figure that there is no significant difference in B/C of SBS, SEBS and SBR polymer systems (4.5 to 6.5). This B/C is based on laboratory test data of AC10 PMA mixtures at test temperature of 77° F. However, the better assessment of B/C can be possible after the field data is available.

Summary of the Results

Resilient Modulus:

- Polymer modification improved the resilient properties of asphalt mixtures at 77 and 140°F, while the resilient modulus of AC-10 PMA mixtures decreased at 23°F with respect to straight mixtures.
- Resilient modulus of the AC-10 PMA mixtures was higher than straight AC-20 asphalt mixtures at 140°F.
- Oven-aged AC-10 PMA mixtures showed higher resilient modulus than unaged asphalt mixtures at 140°F.
- At 77°F, there was no significant difference between the average values of the resilient modulus of unaged and oven-aged AC-10 polymer modified mixtures. Mixtures modified with 2% EAM showed slightly lower values of resilient modulus after oven aging. After oven aging a considerable increase in resilient modulus was found in AC-10 PMA mixtures with respect to oven aged straight AC-10 mixtures.
- The oven-aged AC-10 mixtures showed slightly lower resilient modulus than the unaged AC-10 mixtures at 23°F.

Fatigue Life:

- Fatigue life of PMA mixtures was considerably higher than the straight AC mixtures. EAM system showed highest fatigue life among all the polymers, followed by SEBS system. The increase in fatigue life is due to the increase in resilient modulus and resistance to horizontal plastic deformation with polymer modification.

Plastic deformation:

- Polymer modification improved the resistance to both vertical and horizontal plastic deformation at 23, 77 and 140°F which indicated more resistance to rutting and fatigue cracking.
- Oven aged and unaged straight AC-10, straight AC-20, and AC-10 mixtures with 3%SBR, tested at 140° F, failed before 100 load cycles.
- Horizontal plastic deformations of unaged AC-10 with 2%EAM and oven aged AC-10 with 5%SEBS were less than the other AC-10 PMA mixtures at the test temperature of 140°F.
- Deformation rate showed that PMA mixtures improved the rutting resistance at 77 and 140°F. EAM polymer system had the lowest deformation rate as compared to the other polymer systems.

Indirect Tensile Strength and Toughness:

- Polymer modification improved the indirect tensile strength and the toughness of asphalt mixtures at 77 and 140°F, while no significant improvement was found at low temperature of 23°F.
- AC-10 and AC-20 with 2%EAM or 3% SBR were more effective than the other polymer modified systems at 140°F. The strength and the material toughness increased with the addition of the two polymers.
- At test temperature of 77°F, the indirect tensile strength and the toughness of SEBS and SBS polymer systems were higher than the other polymers. Moreover, AC-10 with CRM showed the maximum tensile strength and toughness.
- Indirect tensile strength was considerably high for oven-aged AC-10 polymer modified mixtures than straight AC-10 at 140°F, same was true for straight and polymer modified AC-20 mixtures.
- At 23°F, slight increases (1 to 15 percent) in the tensile strength of AC-10 and AC-20 polymer modified mixtures were found than the processed mixtures. However, considerable increases (10 to 50) percent could be seen in the toughness of AC-10 and AC-20 PMA mixtures.
- No significant difference between the average values of tensile strength and toughness of polymer modified AC-10 and AC-20 mixtures at 23°F was found.
- The vertical deformation at failure and the toughness of AC-10/3%SBR increased at low temperature. This implies that SBR modified AC mixtures improve the resistance to temperature cracking.

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6. Conclusions

The goal of polymer modification of asphalt is to increase the temperature range of both the elastic and viscous properties of the asphalt binders and mixes. Modification of the asphalt binder to enhance its performance at both high and low temperatures and under traffic loading is essential to the success of constructing superior pavements. It has been concluded that the addition of polymer to asphalt was beneficial to the high temperature properties of the asphalt blend. The high temperature properties are affected by polymer modification to a greater extent than the low temperature properties. Low temperature properties can best be improved by using a softer base asphalt for polymer modification. The softer asphalt will give better low temperature performance while the polymer will enhance the high temperature properties.

A fingerprinting protocol for the polymer modified asphalts was developed based on several characterization methods. The mixing conditions and optimum amounts were determined based on rheological properties. Based on the Strategic Highway Research Program (SHRP) specifications, performance grade enhancements were determined for SBS, SBR, EAM, CRM and EVA modified binders.

Several new test methods, methodologies and procedures have been developed for characterization of morphology of polymer modified asphalt binders and mixes, such as; identification of the binder morphology using an ESEM, characterization of the polymer phase morphology using the Confocal Laser Scanning Microscope, quantification of the void morphology methods by the Thin Plane Section Image Analysis and the Void Casting Method. Quantification of aggregate/binder adhesion and interfacial durability has also been developed. Most significantly, a 3-dimensional fibrillar entangled network structure was observed in asphalt binder thin films after exposure to the electron beam in the ESEM.

The main objective of characterizing the engineering properties of PMA's is to determine whether or not the benefit/cost ratio for asphalt pavement can be improved by using polymer modification. The engineering properties of PMA that relate to fatigue cracking (fatigue life), rutting (permanent deformation), and stability (tensile strength and toughness) of the asphalt mixes were evaluated using various laboratory test procedures. Economic analysis of the cost and benefits of PMA was conducted based on extrapolation of laboratory results to pavement performance. All of the modifiers showed benefits.

Based on the broad investigation during the project, it is found that polymer modification improves the properties of AC mixtures at low, intermediate and high temperatures. However, among the polymers used in this study, no such polymer is found which is effective both at extreme low and high temperatures. SBR and EAM improves the high temperature properties of AC-5 and AC-10 binder mixtures. SBR improves the low temperature engineering properties of AC-10 binder mixtures. Hence, SBR is most effective for resistance to rut and low temperature cracking and EAM and SEBS are better polymer systems for improving the fatigue life of AC mixtures. The binder properties were related to not only SHRP specifications but also the engineering properties of the mixes as summarized in the Table in next page.

Overall, the conculsions of Phase II research are;

- Polymer modified asphalts improved pavement performance based on laboratory results.
- Binder studies and engineering properties of all polymer modified binder mixes are consistent except for Elvaloy® AM.
- Road study should be done in Phase III.
- Further research is needed in accordance with road study.

These efforts should be coupled with an investigation of the effect of asphalt source on the properties of the modified asphalt. It would be most beneficial to use the same asphalt grade from different suppliers rather than using different asphalt grades from the same supplier (Amoco) which was done in Phase II. The use of multiple asphalt sources will allow MDOT to apply the research results with greater confidence to a wide variety of asphalt types.

Summary of Results of Phase II-Polymers in Bituminous Mixtures Directly Applicable to MDOT

Modifiers		**Fundamental Properties of Binders**			**Morphology and Microstructure of Binder-Mixes**			**Engineering Properties of Mixes and Benefits**[5]	
list of the modifiers	Nature of modifiers	Optimum Mixing Condition	Optimum Contents, % (w/w)	SHRP PG[1] specification	Features of Networks	Polymer Phase Morphology	Adhesion and Fracture Behavior	Indirect Tensile Strength	Indirect Tensile Cyclic Load
SBS (Shell)	Network thermo-plastics	350°F 2 hours high shear	3-5 (AC-5), 2 (AC-10)	70-22 (AC-5 with 5%)	no change in network morphology	discrete phase	good (LT[3]) good (HT[4])	180% increase of ITS at RT	130% increase of resilient modulus
SEBS (Shell)	Network thermo-plastics	350°F 30 minutes high shear	2-5 (AC-5), 2-4 (AC-10)	70-22 (AC-5 with 5%)	no change in network morphology	discrete phase	good (LT) good (HT)	200% increase of ITS at RT	150% increase of resilient modulus
SBR (Textile Rubber & Chemical)	Network thermo-plastics	350°F 30 minutes high shear	4 (AC-2.5), 3 (AC-5 and AC-10)	64-28 (AC-5 with 3%)	softer and plastic binders	string-like morphology	v. good (LT) good (HT)	150% increase of toughness	170% increase of resilient modulus
EAM (DuPont)	Reactive polymers	380°F 2 hours, air[2] high shear	3 (AC-2.5), 1.5 (AC-5), 1 (AC-10)	76-16 (AC-5 with 1.5%)	coarse and stiffened binders	react with asphalt phase	fair (LT) good (HT)	250% increase of ITS at RT	unlimited, highest fatigue life
CRM (Rouse Rubber)	Particles (~74 μm)	350°F 30 minutes low shear	10-15 (AC-5, 10, and 15)	70-22 (AC-10 with 10%)	no change but high viscosity	remains as particulate	good (LT) good (HT)	considerable ITS increase	least effective in fatigue life
EVA (Exxon)	Network thermo-plastics	350°F 2 hours high shear	5 (AC-5), 3 (AC-10)	64-22 (AC-5 with 3%)	N/A	N/A	N/A	N/A	N/A

1. SHRP PGs for straight AC binders: 58-28 (AC-2.5), 58-28 (AC-5), 64-22 (AC-10).
2. can be mixed in nitrogen atmosphere to avoid oxidation of the binder.
3. based on lap shear strength and elastic strain energy at low temperatures (-10 or -20°C).
4. based on lap shear strength and elastic strain energy at high temperatures (10 or 20°C).
5. based on the projection of laboratory study on high temperature engineering properties without field study.

7. Recommendation for Future Work

Based on the results of Phase II as well as literature reviews and discussions with other research teams, there is a need for additional studies. This project attempted to present a comprehensive investigation of polymer modified asphalt. As good as it was, there are still many areas than need to be investigated. One of the main areas that should be investigated is the effect of asphalt source on the properties of the modified asphalt. This study used four different asphalt grades from the same supplier. In order to generalize these results, the modifiers need to be tested with asphalts from different sources. It will be more beneficial to use the same asphalt grade from different suppliers than using different asphalt grades from the same supplier. The majority of the differences in properties between modified AC-2.5 and modified AC-20 are due simply to the differences in the base asphalt properties. The use of multiple asphalt sources will allow MDOT to apply the research results with greater confidence to a wide variety of asphalt types. It is more important to have different asphalt sources rather than different asphalt grades from the same source. The expertise gained during Phase II will allow the team to investigate this issue by using selected modifiers and compositions, thereby eliminating the need to do an exhaustive study of each polymer and asphalt combination. The same argument can be applied to the use of different aggregates. Since all test methods and procedures are developed successfully, it needs to expand type of polymer modifiers, such as cellulose or/and polyester fibers (possibly recycled) for polymer modification study. It is of interest to fully evaluate the surface-treated CRM modifier since the preliminary test results of the binder systems showed some promising performance after the high temperature storage at 350°F. Since all of the polymers studied were beneficial in enhancing different properties, a mixture of two or more modifiers may be even more effective in improving asphalt performance.

Another area to investigate is to develop a better model of how the asphalt and modifier interact to yield the properties seen in the blend. A first step is to determine what variables are important in determining neat asphalt properties. This study investigated molecular weight and asphaltene content. While it is still believed that these play an important role, the inability to correlate properties using only these factors indicates that other variables are also important.

The determination of failure mechanisms in the interface is important to the understanding of asphalt mixture properties. Michigan has a variety of weather types. Main failure modes of the roads in the state of Michigan are thermal cracking, stripping, raveling as well as fatigue cracking which develops in the interface (interphase) of asphalt binders and aggregates. Without investigation and understanding of these failure mechanisms, it is almost impossible to develop better pavement materials. The effect of polymer modification on asphalt pavements can not be measured simply by improvement in the binder properties. The effect of the polymer on failure modes and adhesion needs to be studied to obtain the complete picture of how polymer affects asphalt pavements. Results of studies conducted in our laboratory have shown that it may be possible to enhance pavement performance by altering the aggregate treatment methods to precoat aggregate with the modified polymer asphalt binder prior to formation of the asphalt concrete. It appears that such placement toughens the asphalt-aggregate bond which could lead to more placement toughens the asphalt-aggregate bond which could lead to more durable pavement performance. The identification of the fibrillar network morphology of the asphalt binder and its modification with polymer modification is a potentially revolutionary discovery that can have major consequences for improving asphalt binder and asphalt performance. It has been shown that when aggregate-asphalt binder failure takes place fibrils are formed which bridge the growing cracks. The ability to control the size and strength of the asphalt binder fibrils through polymer modification opens the door for establishing a direct relationship between asphalt binder morphology and pavement performance. Extra efforts are needed for pin-pointing the failure mode transition temperature in terms of polymer modifier types and concentration for more meaningful evaluation of polymer modification. Systematic studies to identify the process-microstructure-composition interrelations and to understand controlling mechanisms on performance and properties of polymer modified asphalt binders and composites.

The actual road tests for evaluation of the effect of polymer modification on asphalts will be done by using the same kinds of materials (i.e. polymer modifiers, asphalt binders, and aggregates) and by following the procedures (for asphalts-polymers mixing and binders-aggregates mixing) used in the laboratories as possible. A sensor detection in the road will provide actual measures of rutting, fatigue, and/or thermal cracking behavior of the pavement materials under the traffic and make the laboratory results more useful. During Phases I and II, the MSU research team has not been able to have a road test using the selected materials prepared with the mixing processing methods developed in the laboratory. This results in unclear conclusions about the improvement on engineering properties of asphalt binders and mixes modified with polymers. There is no laboratory equivalent of a real pavement test section.

Even though a change in the current SHRP low temperature tests and specification for polymer modified binders is not likely at this present time, MSU research teams raised several questions on the low temperature SHRP specification. MDOT may need to consider the suggestions made by MSU on this issue. It may be desirable to add a test such as direct tension to the SHRP specifications for use with polymer modified binders.

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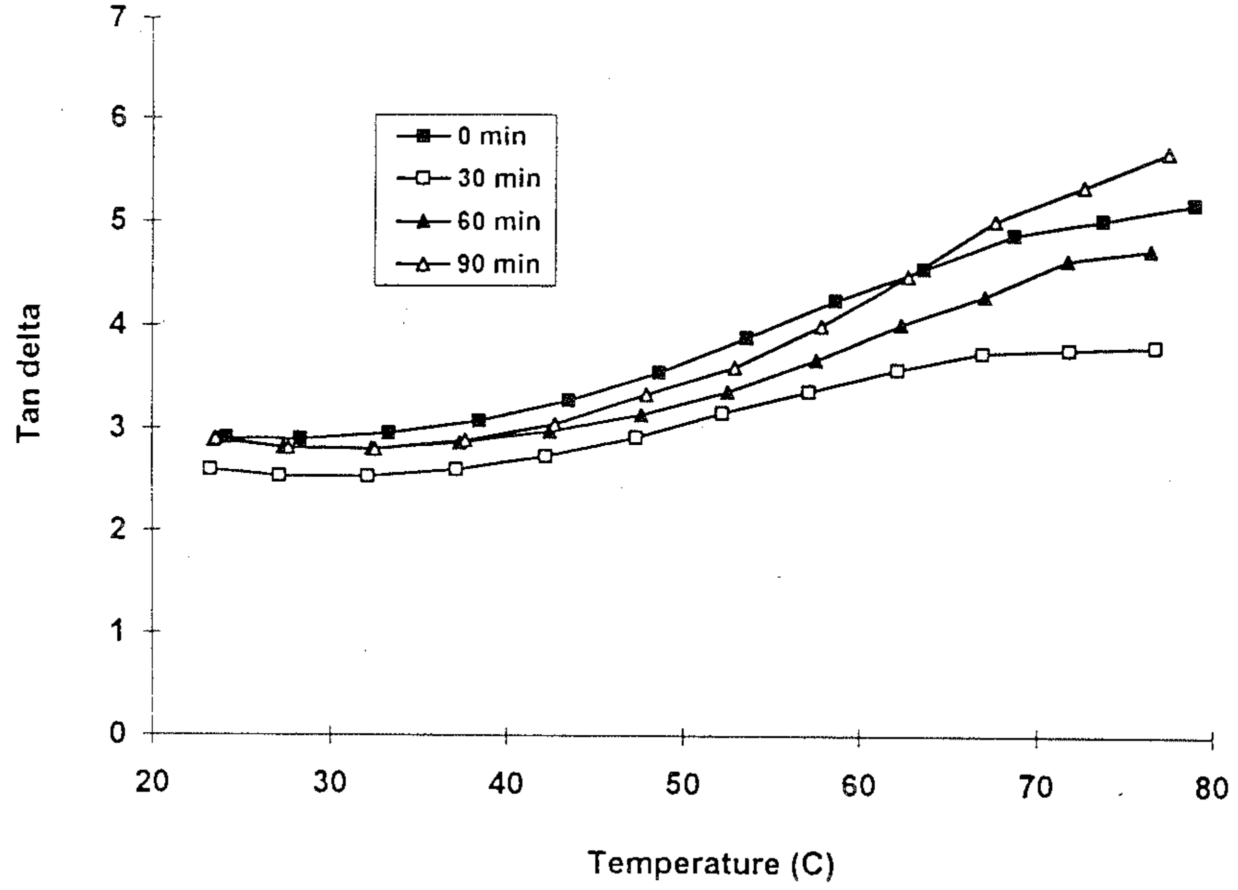
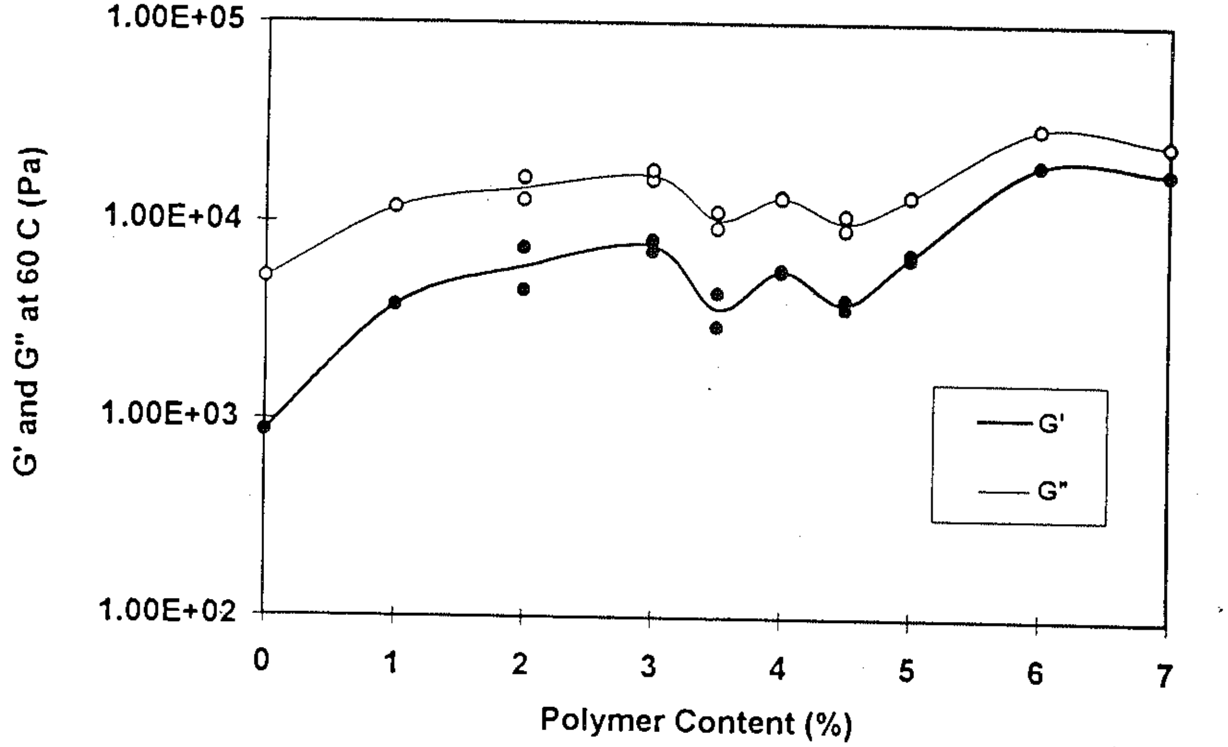


Figure 1.1 Tan delta curves of 5% (w/w) SBR modified AC-5 asphalt binders with different mixing times at 176°C.



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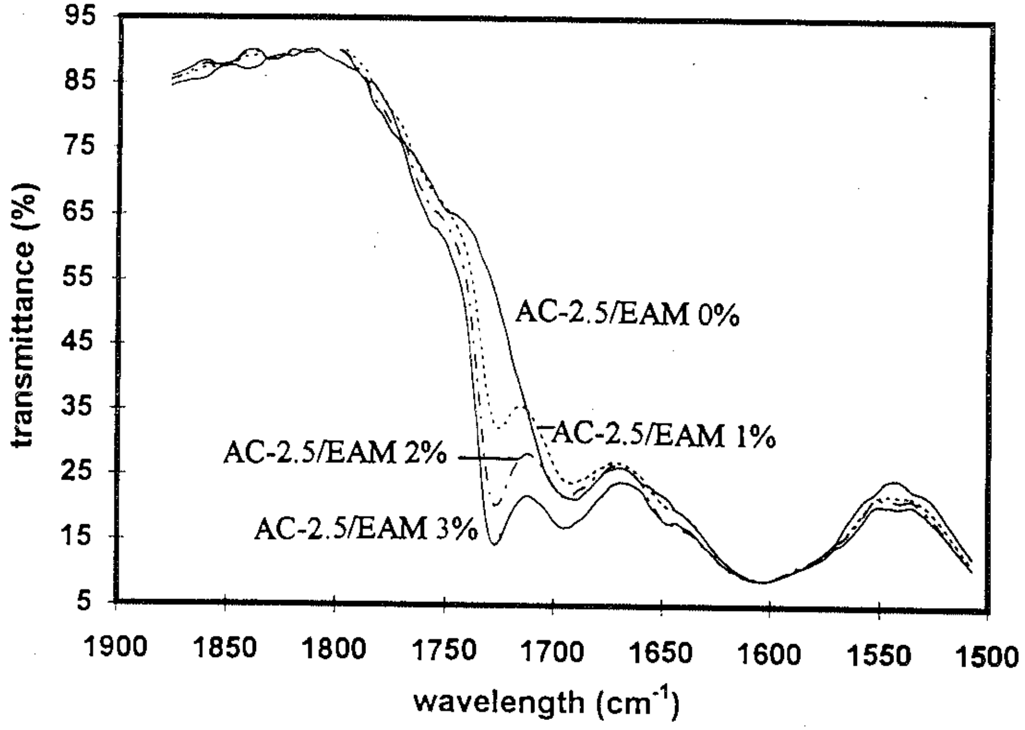

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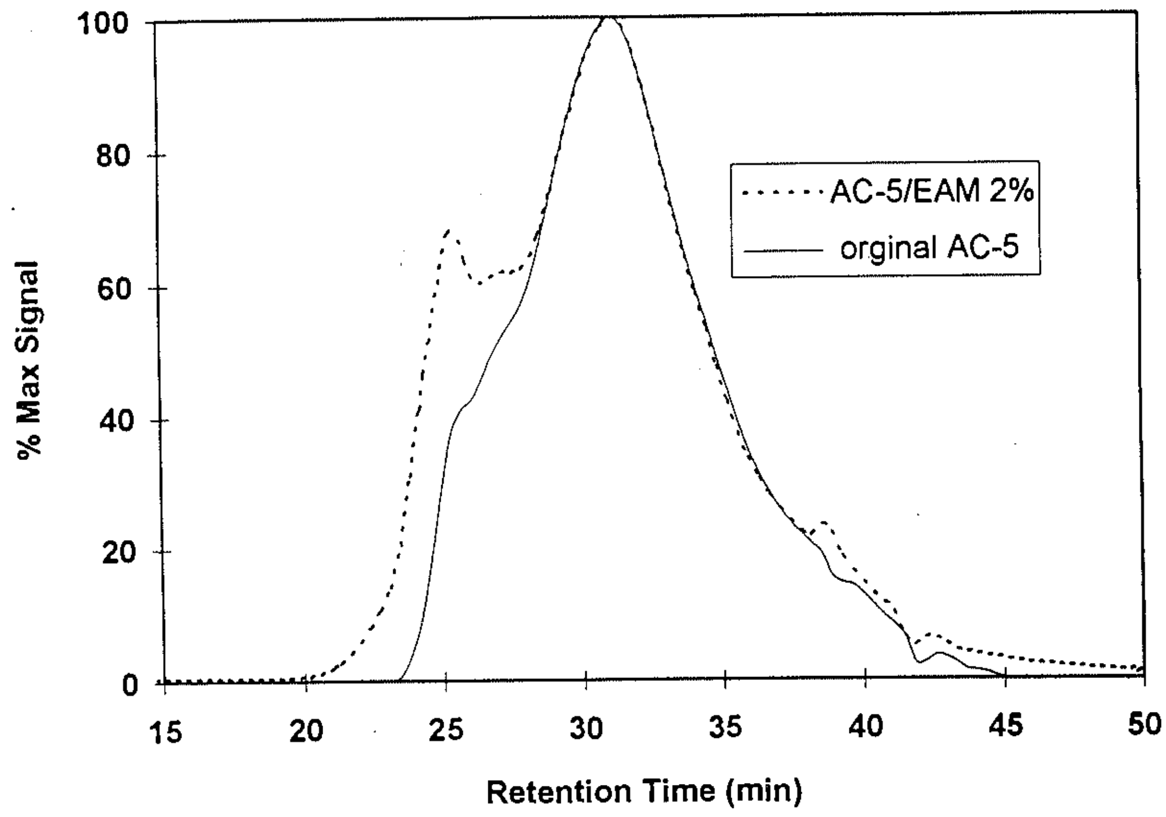

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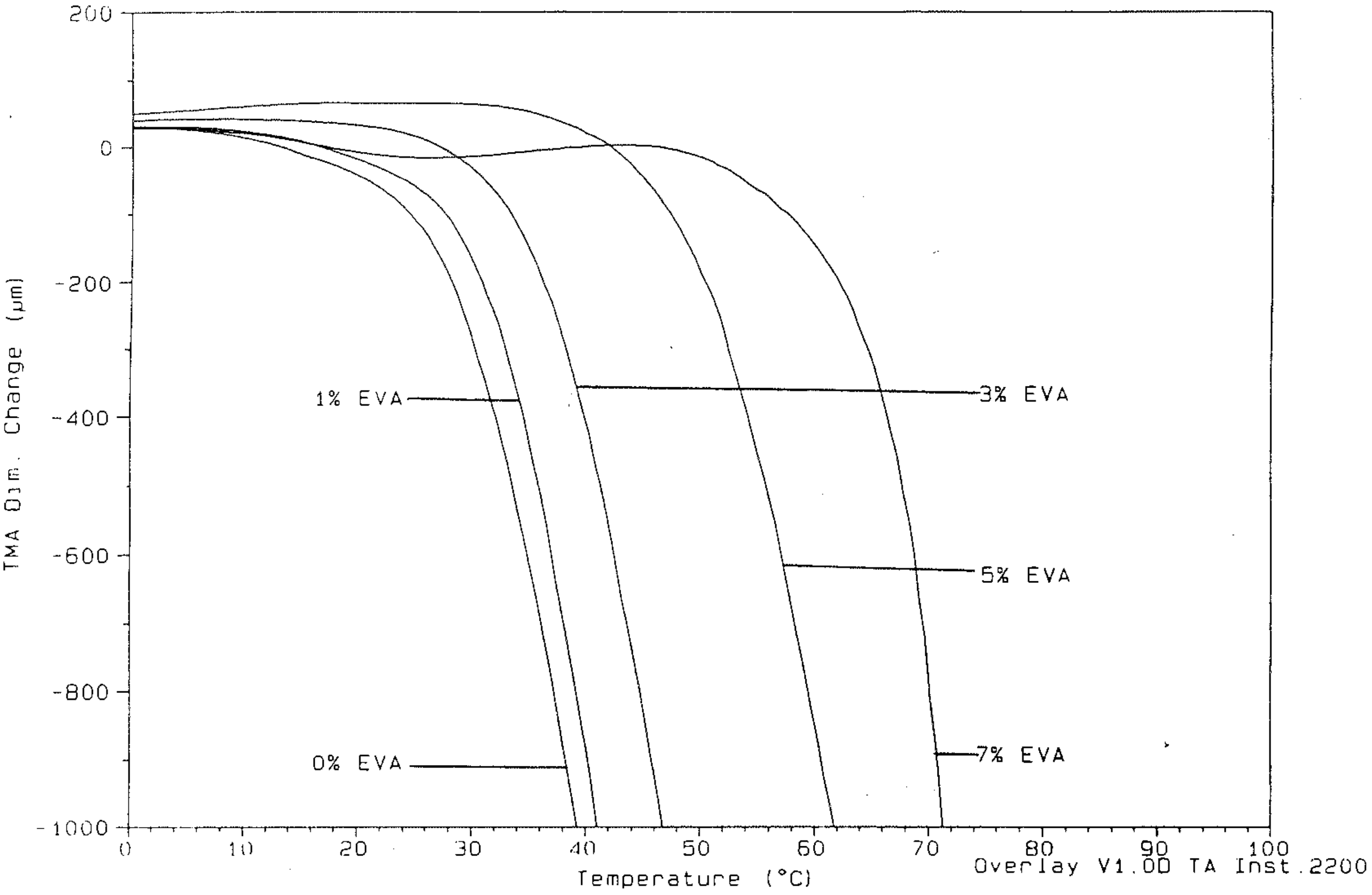

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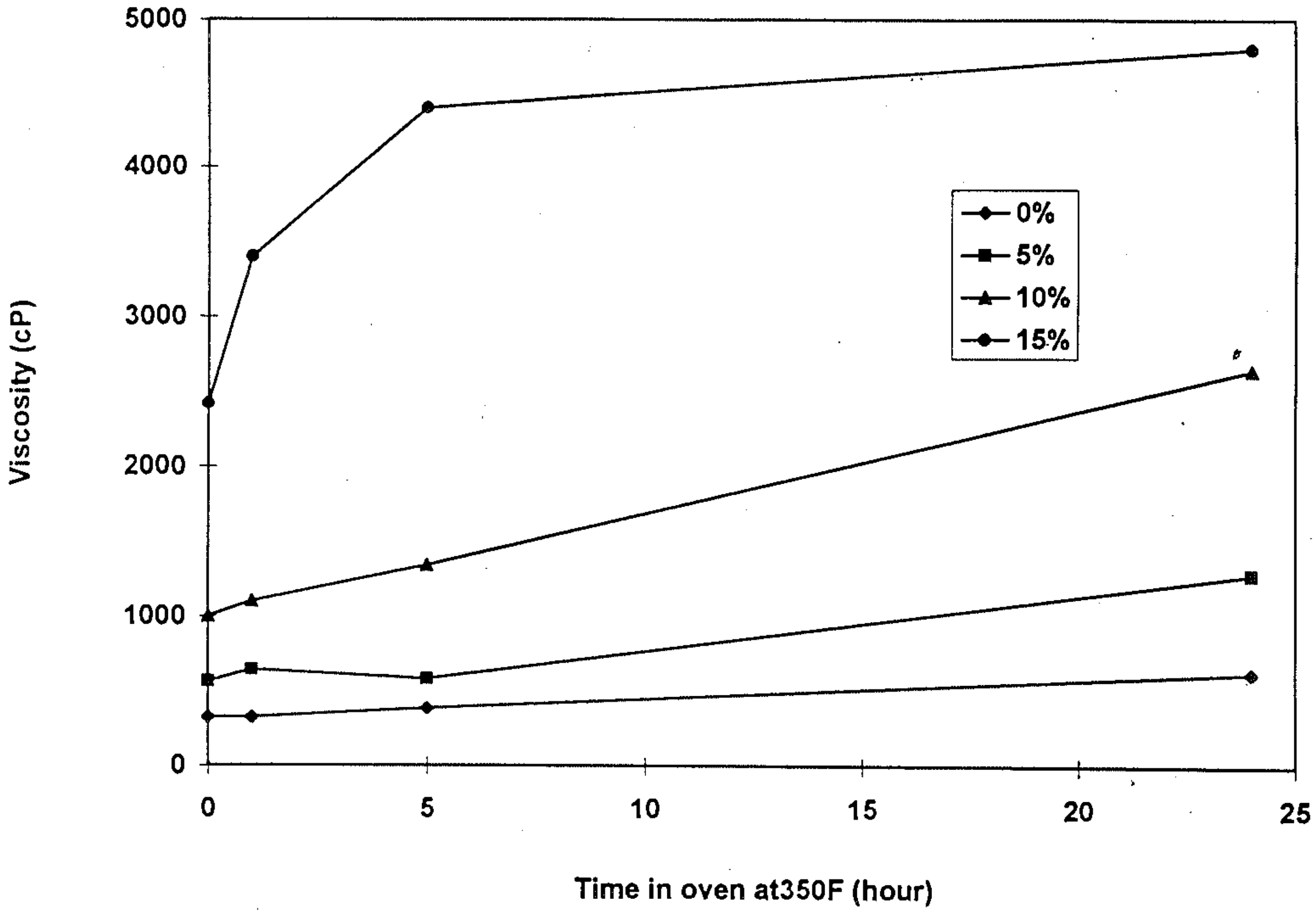
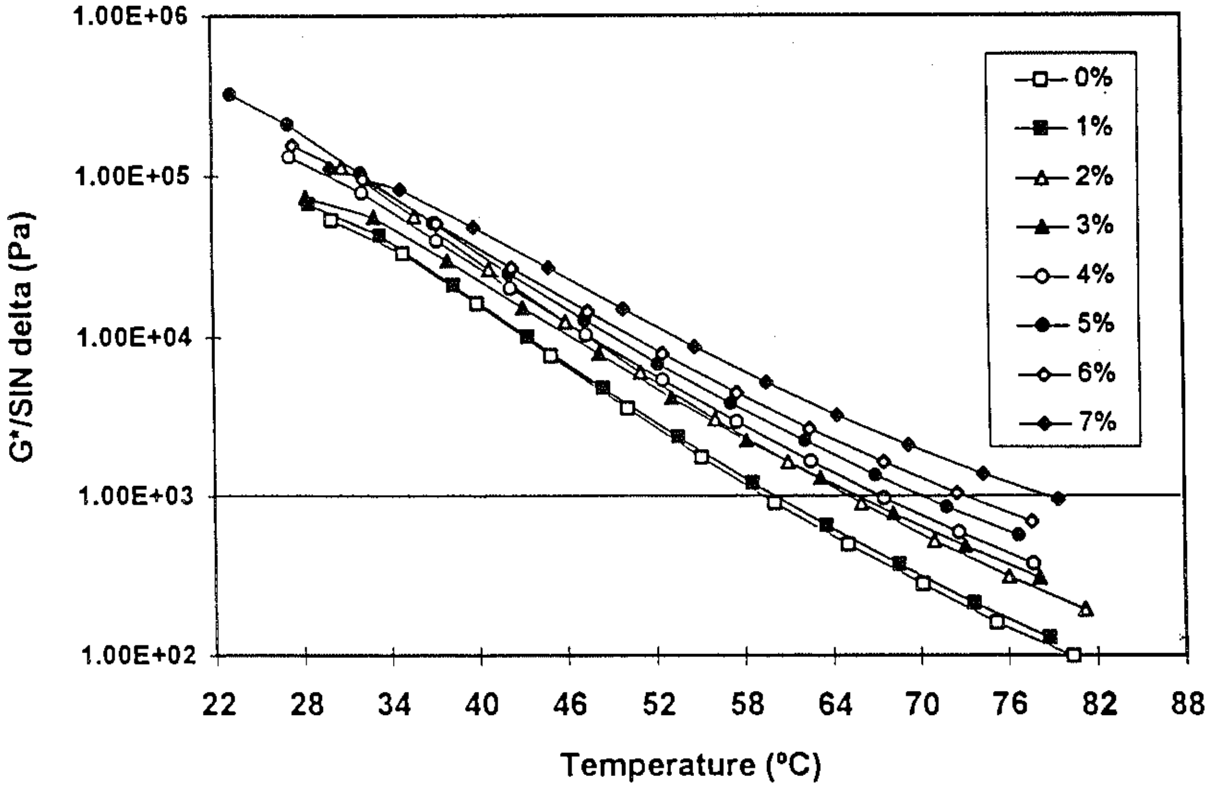


Figure I.6 Melt viscosity at 280°F of CRM modified AC-10 binders as a function of oven storage time (350°F).



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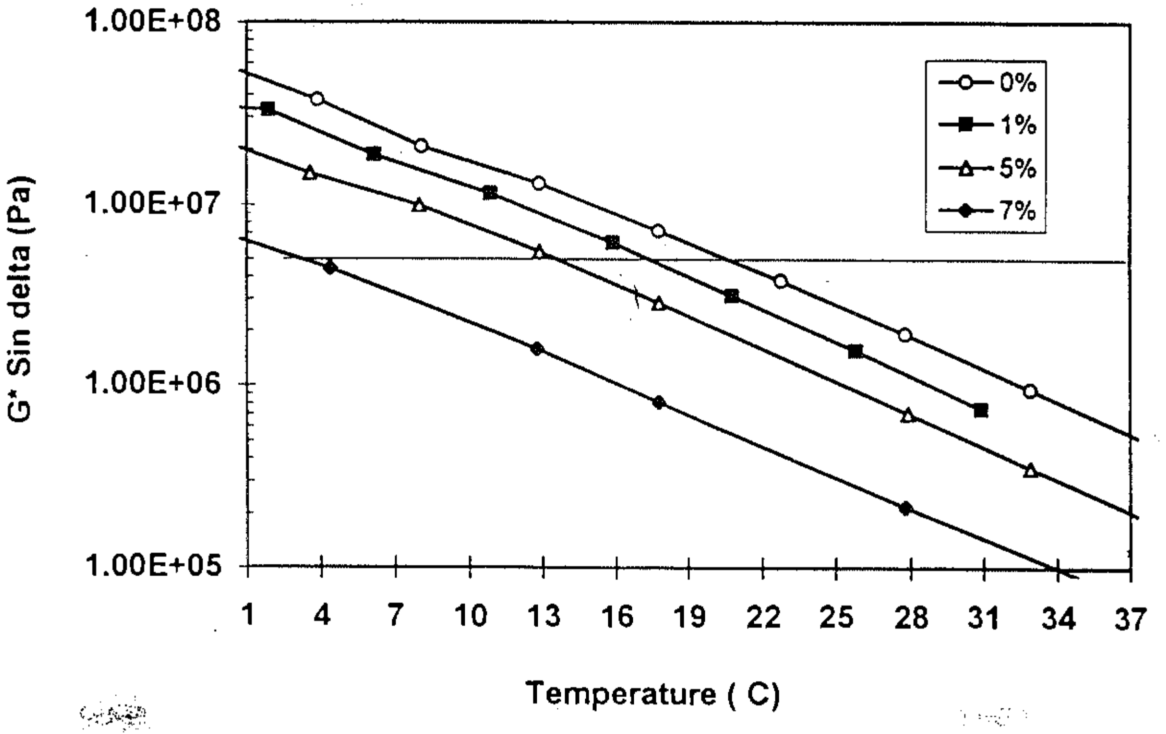

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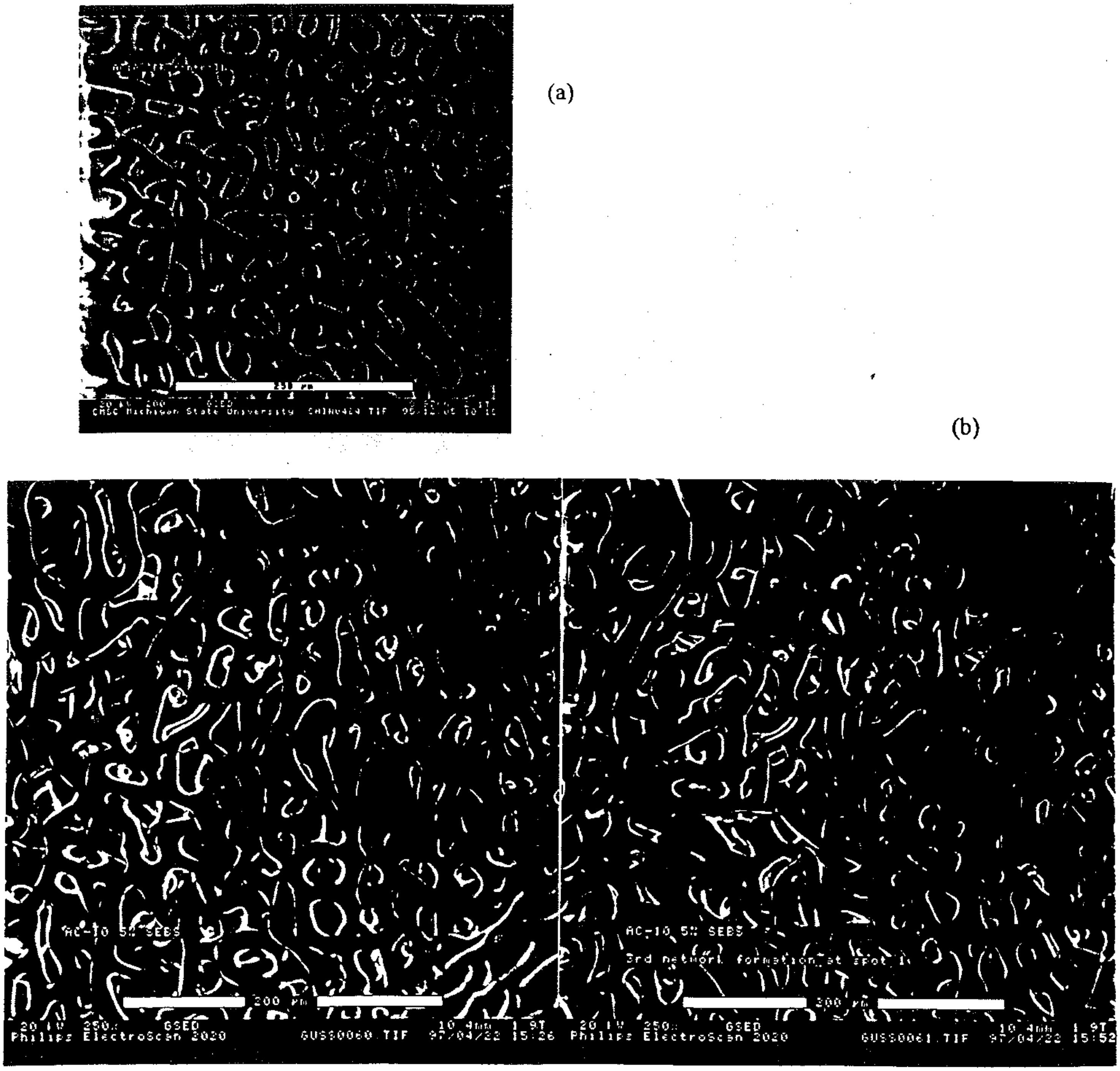
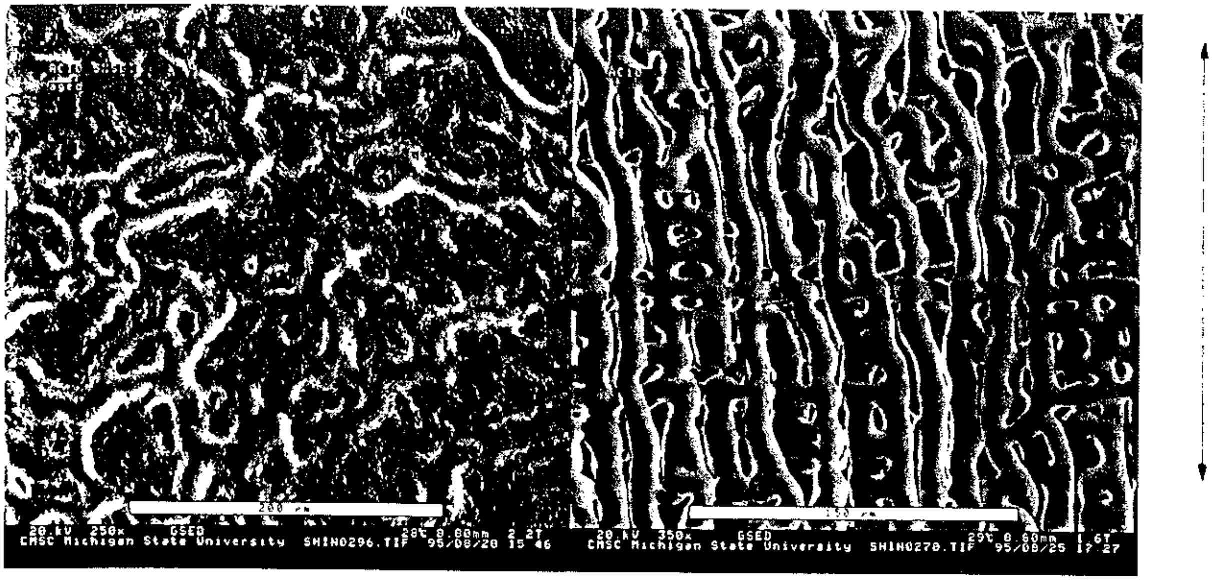
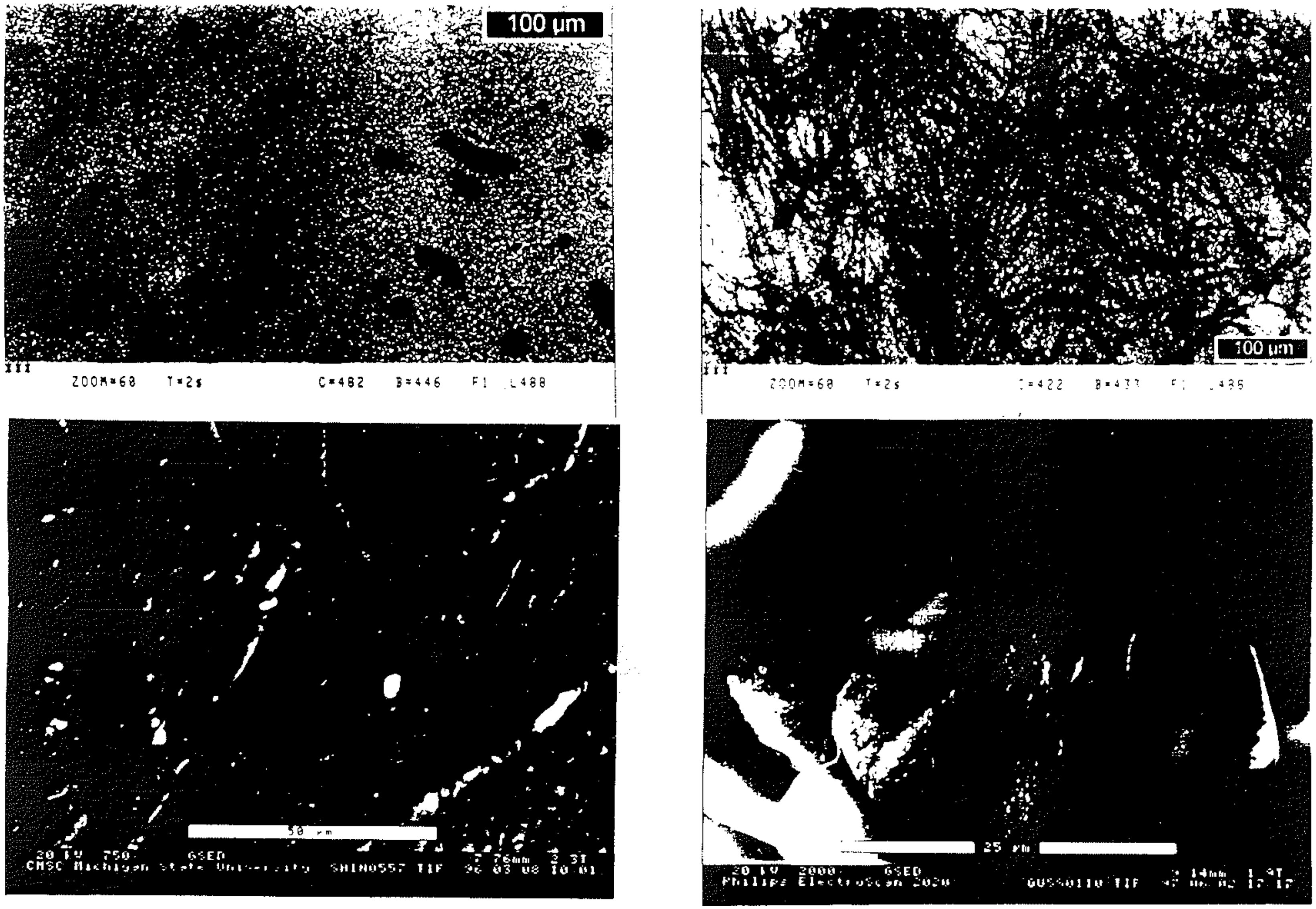


Figure II.1 ESEM micrographs of (a) typical network structure seen in fresh binders, (b) Network structure seen after three successive exposure-relaxation cycles in the ESEM in the same location on an asphalt binder film.



(c) (d)

Figure II.1 ESEM micrographs of - (c) typical network structure seen in highly aged asphalt binders. (d) Aligned network structure seen in pre-stretched binder films. Direction of arrow signifies direction of stretching



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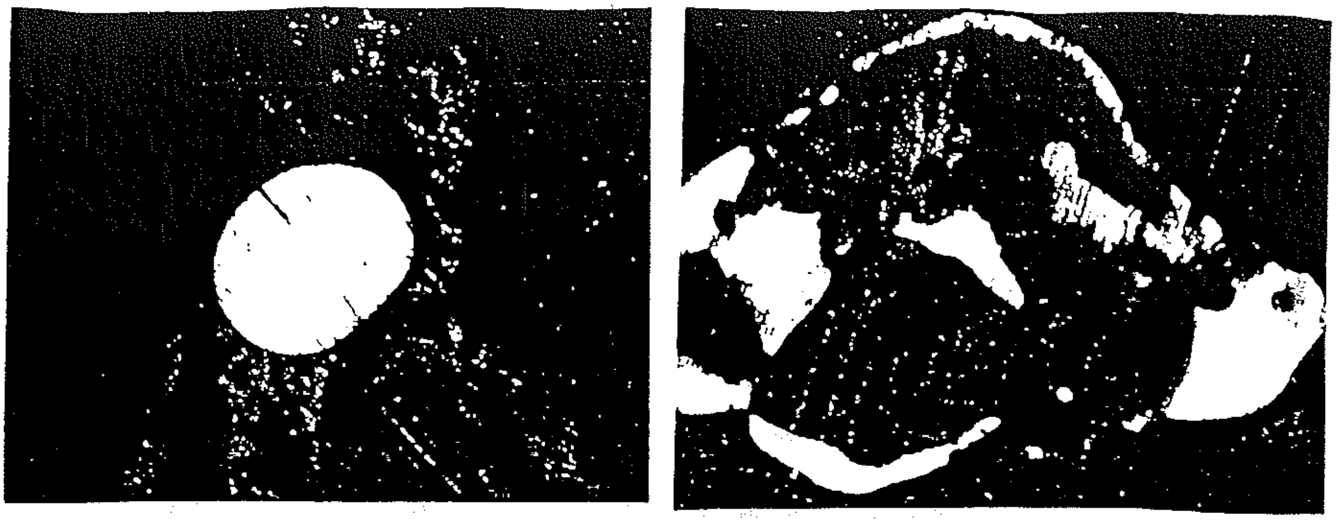
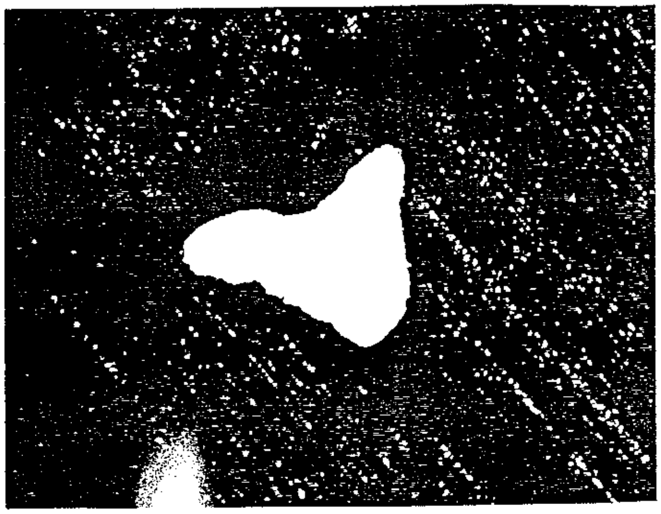


(a) Voids in the asphalt binder phase

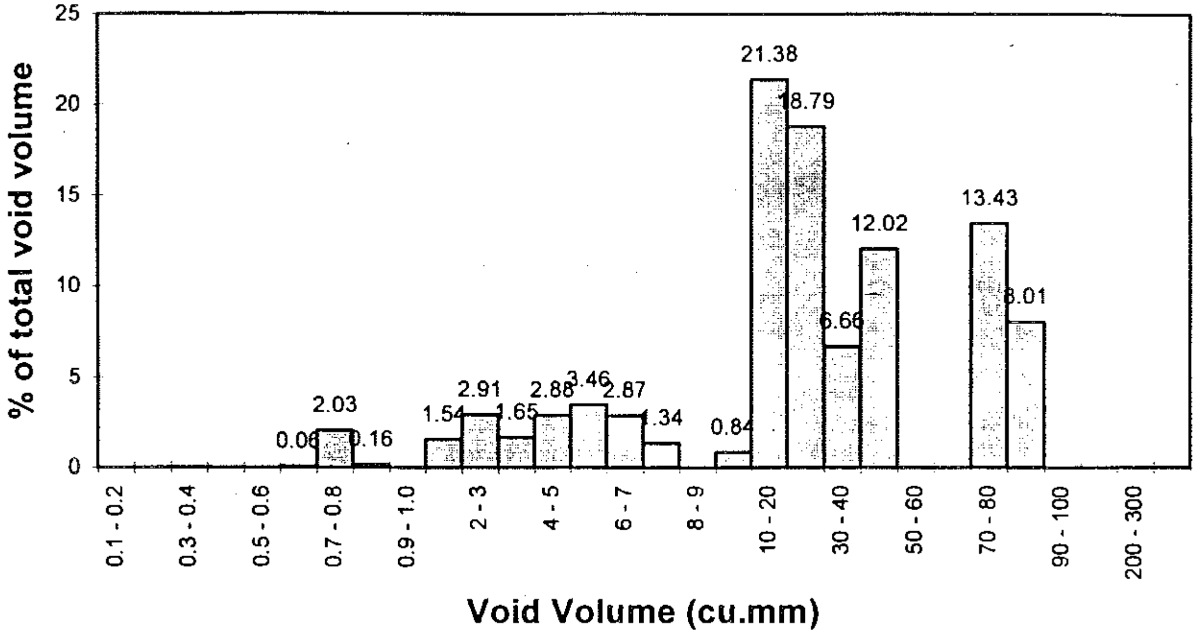
(b) Voids in binder and interface.



(c) Voids in entrapped area.

Figure II.3 Optical micrographs of the three types of voids seen in asphalt concrete (a) Binder phase voids, (b) Interfacial voids, (c) Isolated voids at 90X

Distribution of Void Volume in AC5-0%SBR (Net air void content = 4.21%)



Distribution of Void Volume in AC5-5%SBR (Net air-void content = 4.89%)

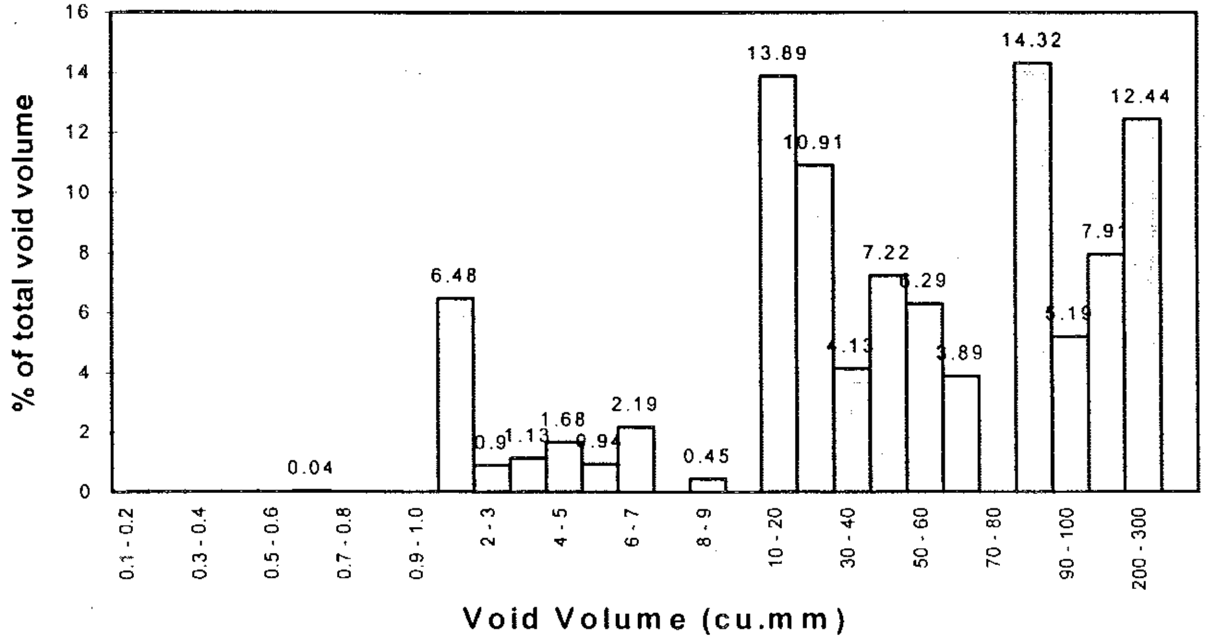


Figure II.4 Void size and distribution for AC5-0%SBR and AC5-5%SBR

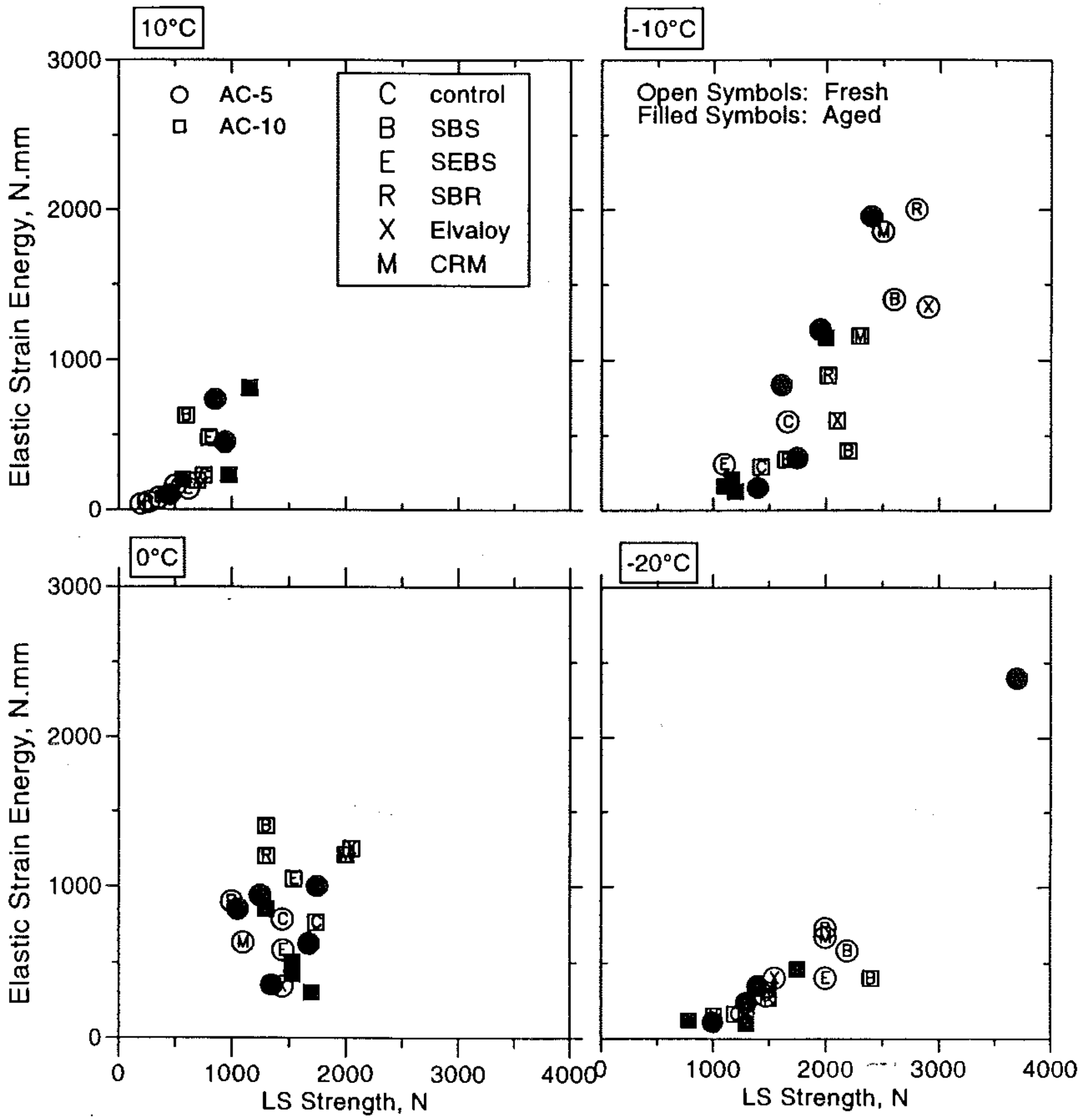


Figure II.5 **Lap-Shear Strength vs. Elastic Strain Energy Correlations of Various Polymer Modified Asphalt Binders with the Optimum Polymer Content Compared to the Control Binder Systems at Various Temperatures. Granitic Rock Substrate Used.**

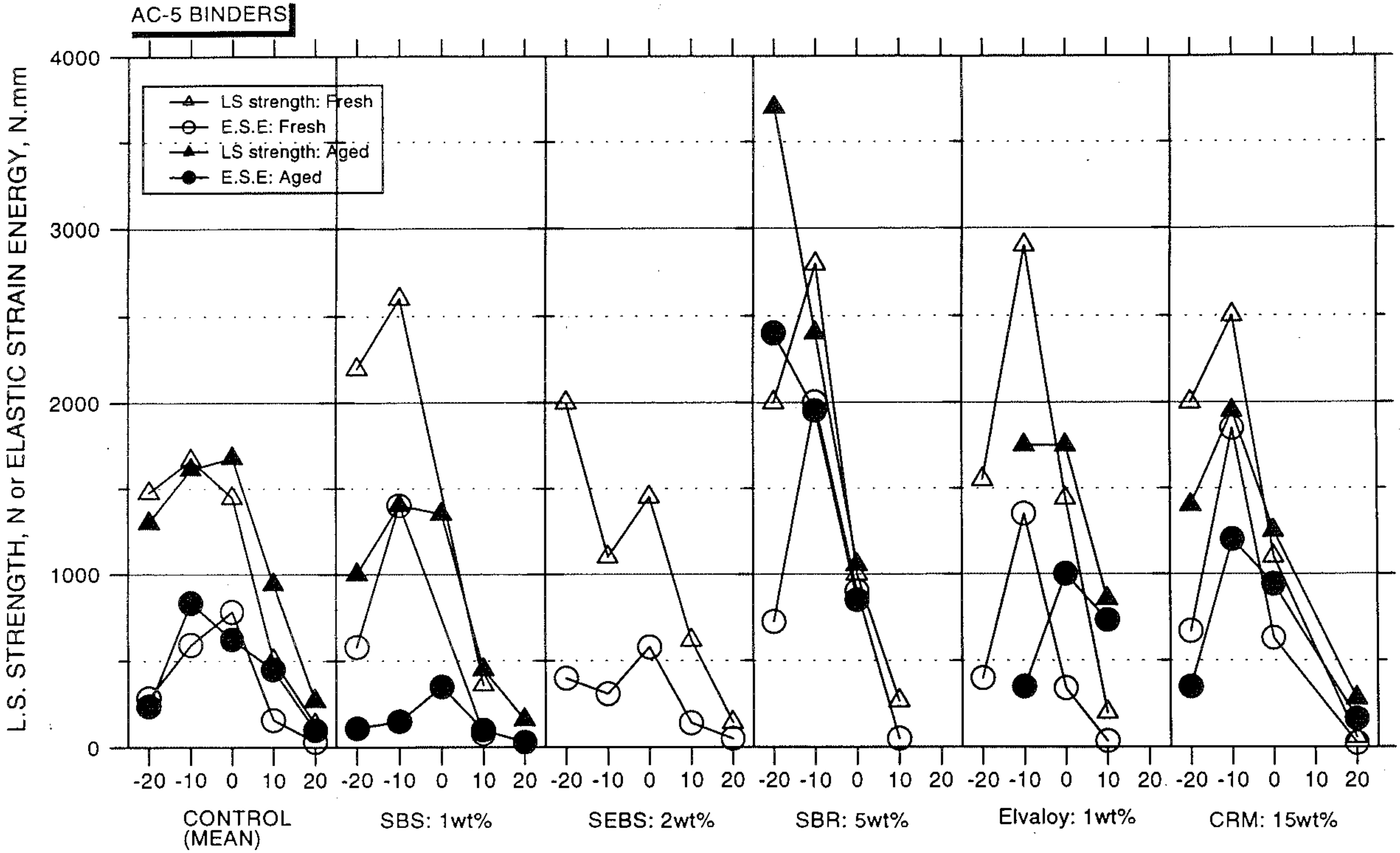


Figure II.6 **Lap-Shear Performance of Various Polymer Modified Asphalt Binders with the Optimum Polymer Content as a Function of Temperature. Granitic Rock Substrate Used.**

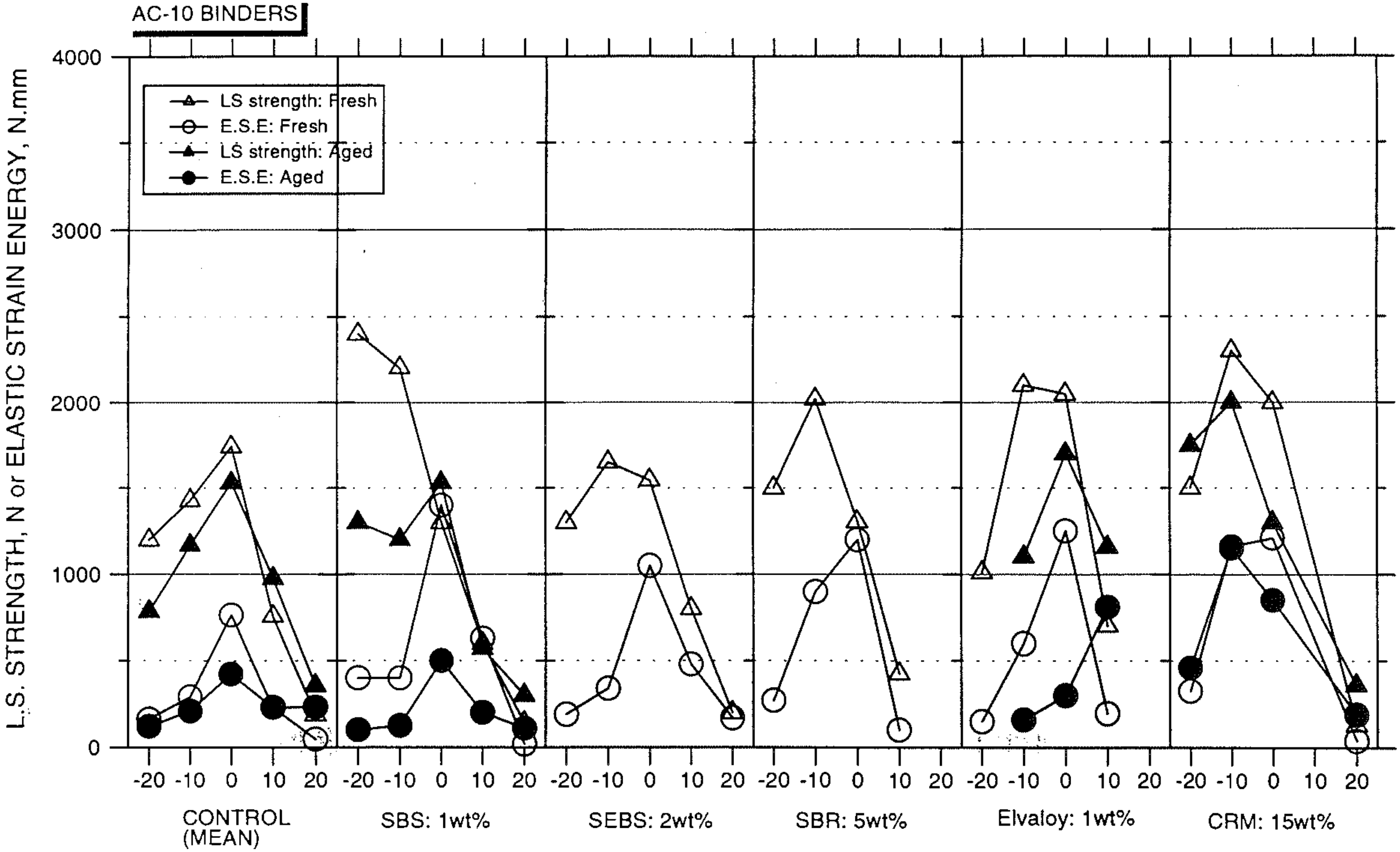


Figure II.6 **Continued.**

BINDER SYSTEM		wt %	20°C	10°C	0°C	-10°C	-20°C
AC-5/ SBS	FRESH	0	■	■	▨	□	□
		1	■	■	■	□	□
		2	■	■	■	□	□
		3	■	■	■	□	□
		4	■	■	■	□	□
		5	■	■	■	□	□
	AGED	1	■	■	■	□	□
		3	■	■	■	□	□
		6	■	■	■	□	□
AC-5/ SEBS	FRESH	0	■	■	▨	□	□
		1	■	■	■	□	□
		2	■	■	■	□	□
		3	■	■	■	□	□
		4	■	■	■	□	□
		5	■	■	■	□	□
		6	■	■	■	□	□
	AGED	3	■	■	□	□	□
AC-5/ SBR	FRESH	0	■	■	□	□	□
		1	■	■	□	□	□
		3	■	■	▨	□	□
		5	■	■	■	□	□
	AGED	0	■	■	□	□	□
		1	■	■	■	□	□
		3	■	■	■	■	□
		5	■	■	■	■	□
AC-5/ Elvaloy	FRESH	0	■	■	■	□	□
		1	■	■	■	▨	□
		2	■	■	■	□	□
		3	■	■	■	▨	□
	AGED	0	■	■	□	□	□
		1	■	■	□	□	□
		2	■	■	□	□	□
		3	■	■	□	□	□
AC-5/ CRM GF80A 74 μm	FRESH	0	■	■	▨	▨	□
		5	■	■	■	□	□
		10	■	■	■	▨	□
		15	■	■	■	▨	□
		20	■	■	■	■	□
	AGED	0	■	■	▨	□	□
		5	■	■	▨	□	□
		10	■	■	■	□	□
		15	■	■	■	▨	□
		20	■	■	■	■	□

BINDER SYSTEM		wt %	20°C	10°C	0°C	-10°C	-20°C
AC-10/ SBS	FRESH	0	■	■	▨	□	□
		2	■	■	■	□	□
		3	■	■	■	□	□
		4	■	■	■	□	□
		5	■	■	■	□	□
		6	■	■	■	□	□
	AGED	0	■	■	□	□	□
		2	■	■	□	□	□
		3	■	■	■	□	□
		5	■	■	■	□	□
		6	■	■	■	■	■
AC-10/ SEBS	FRESH	0	■	■	▨	□	□
		2	■	■	■	□	□
		3	■	■	■	□	□
		4	■	■	■	□	□
		5	■	■	■	□	□
		6	■	■	■	□	□
	AGED	3	■	■	■	■	■
AC-10 SBR	FRESH	0	■	■	■	□	□
		1	■	■	■	□	□
		3	■	■	■	□	□
		5	■	■	■	□	□
	AGED	0	■	■	□	□	□
AC-10/ Elvaloy	FRESH	0	■	■	▨	□	□
		1	■	■	▨	□	□
		2	■	■	■	□	□
		3	■	■	■	□	□
	AGED	0	■	■	□	□	□
		1	■	■	■	□	□
		2	■	■	■	□	□
		3	■	■	■	□	□
AC-10/ CRM GF80A 74 μm	FRESH	0	■	■	■	□	□
		5	■	■	■	□	□
		10	■	■	■	□	□
		15	■	■	■	▨	□
		20	■	■	■	▨	□
	AGED	0	■	■	▨	□	□
		5	■	■	▨	□	□
		10	■	■	■	□	□
			■	■	■	□	□
		20	■	■	■	■	□

Figure II.7 Overall Lap-Shear Failure Mode as a Function of Polymer Concentration and Temperature. Dark Shade: Cohesive, Lighter Shade: Mixed, and White: Adhesive Mode.

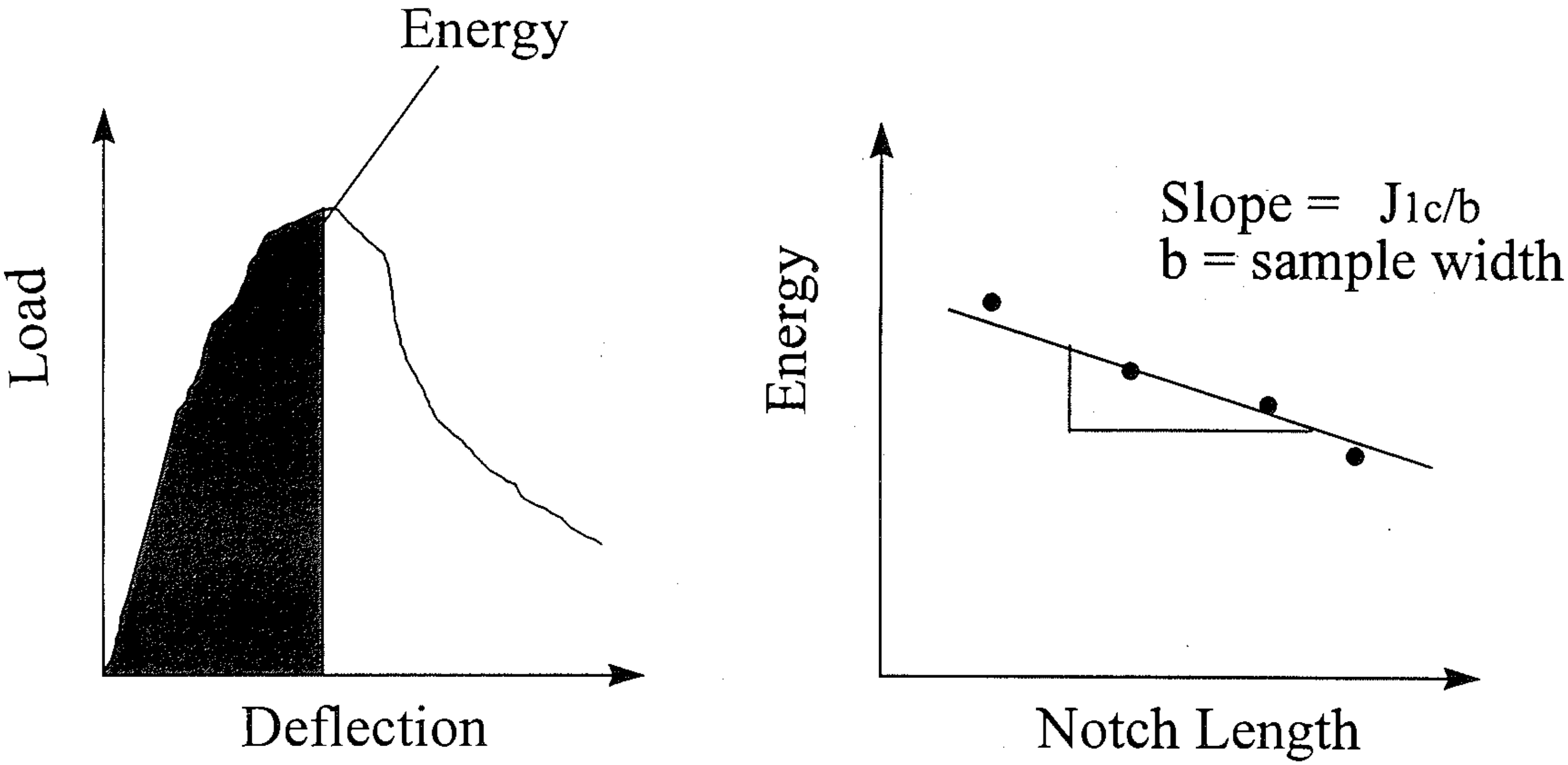
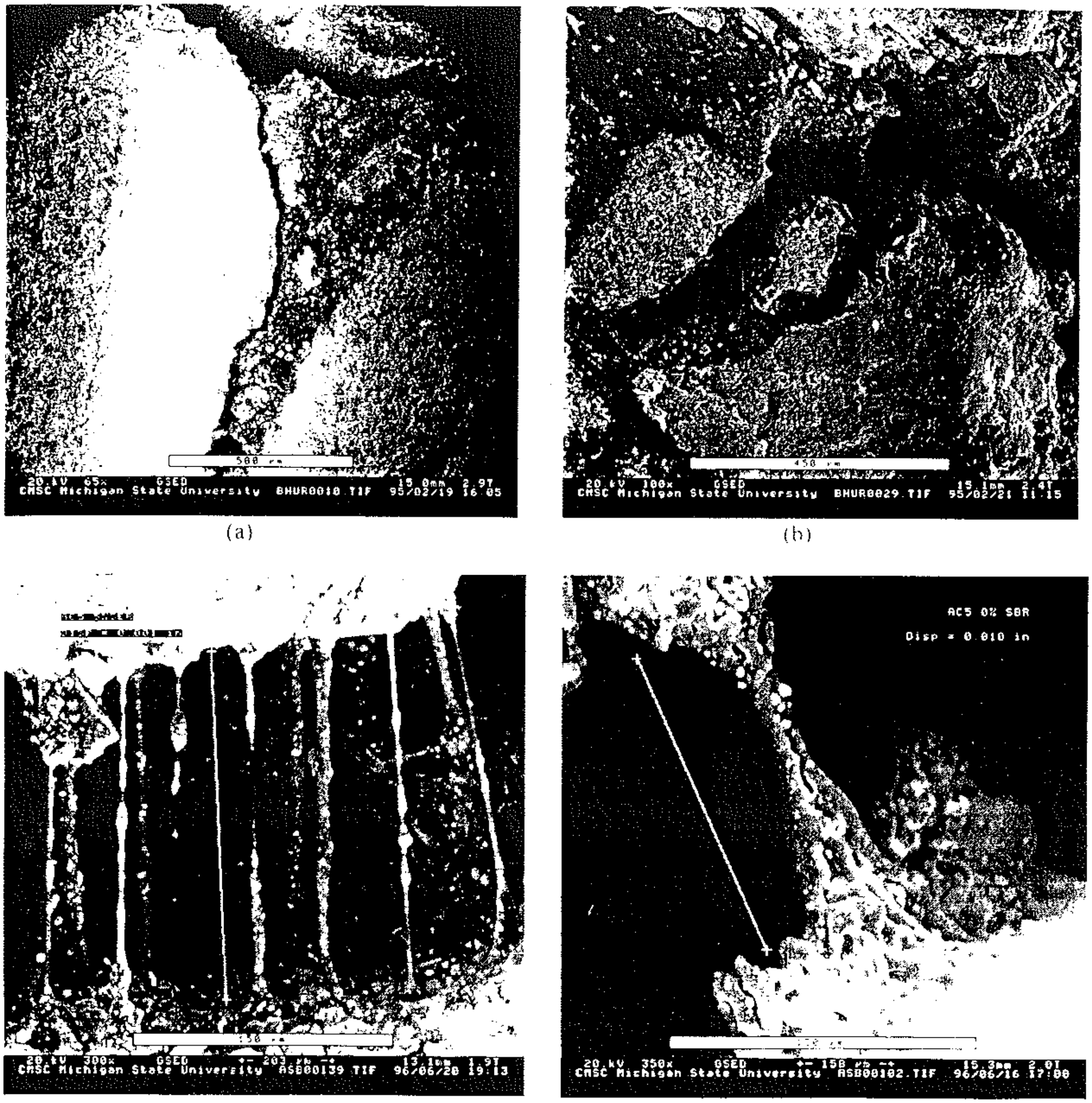


Figure II.8 Schematic representation of the J_{IC} calculation process



(a) (b)

(c) (d)

Figure II.9 ESEM micrographs showing (a) Adhesive failure in Unmodified asphalt concrete below 0°C, (b) Typical failure process in unmodified asphalt concrete at room temperature, (c) Typical fracture morphology of SBR modified asphalt concrete (d) Details of the binder network seen in asphalt fibrils during the fracture process

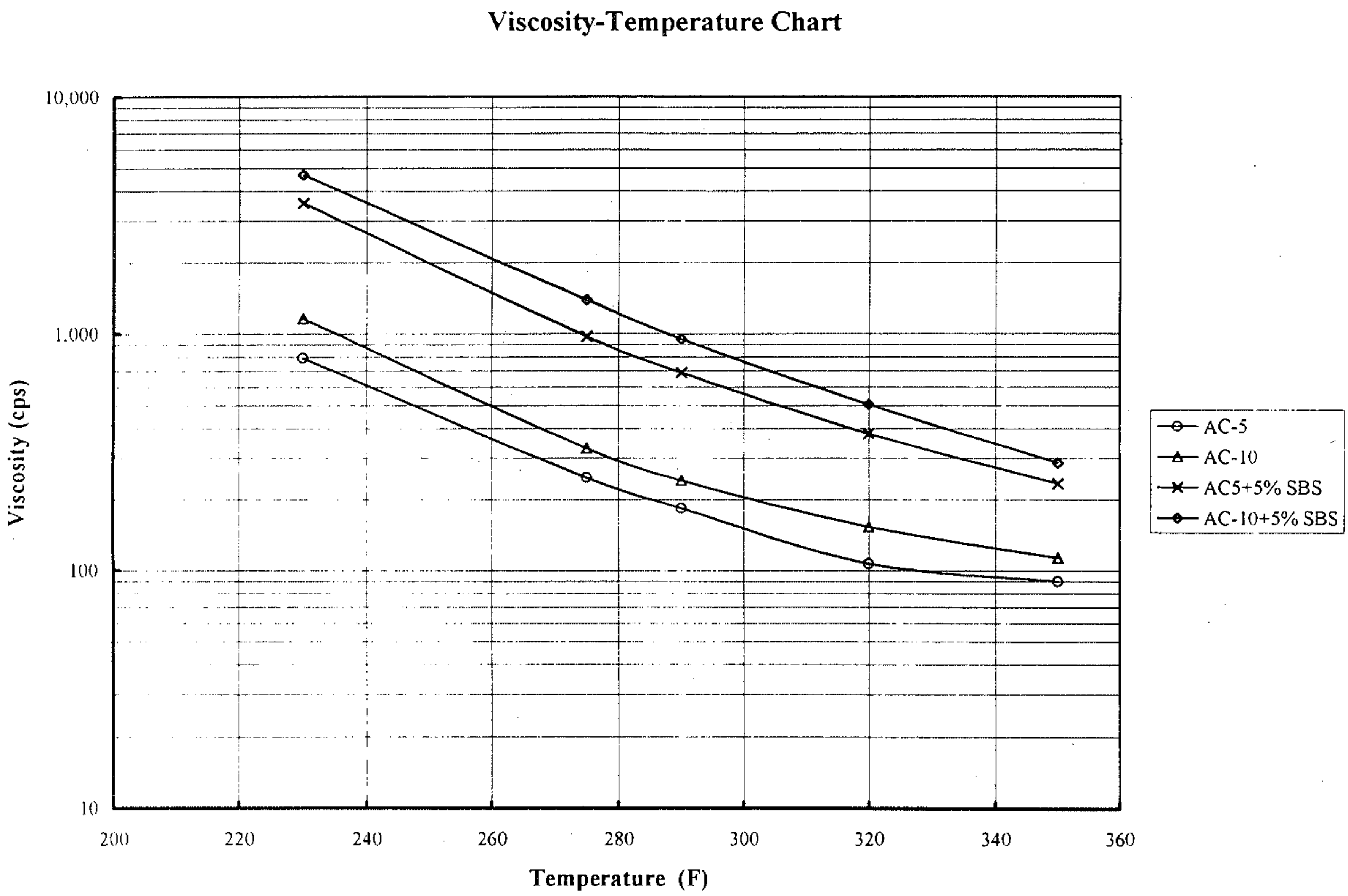
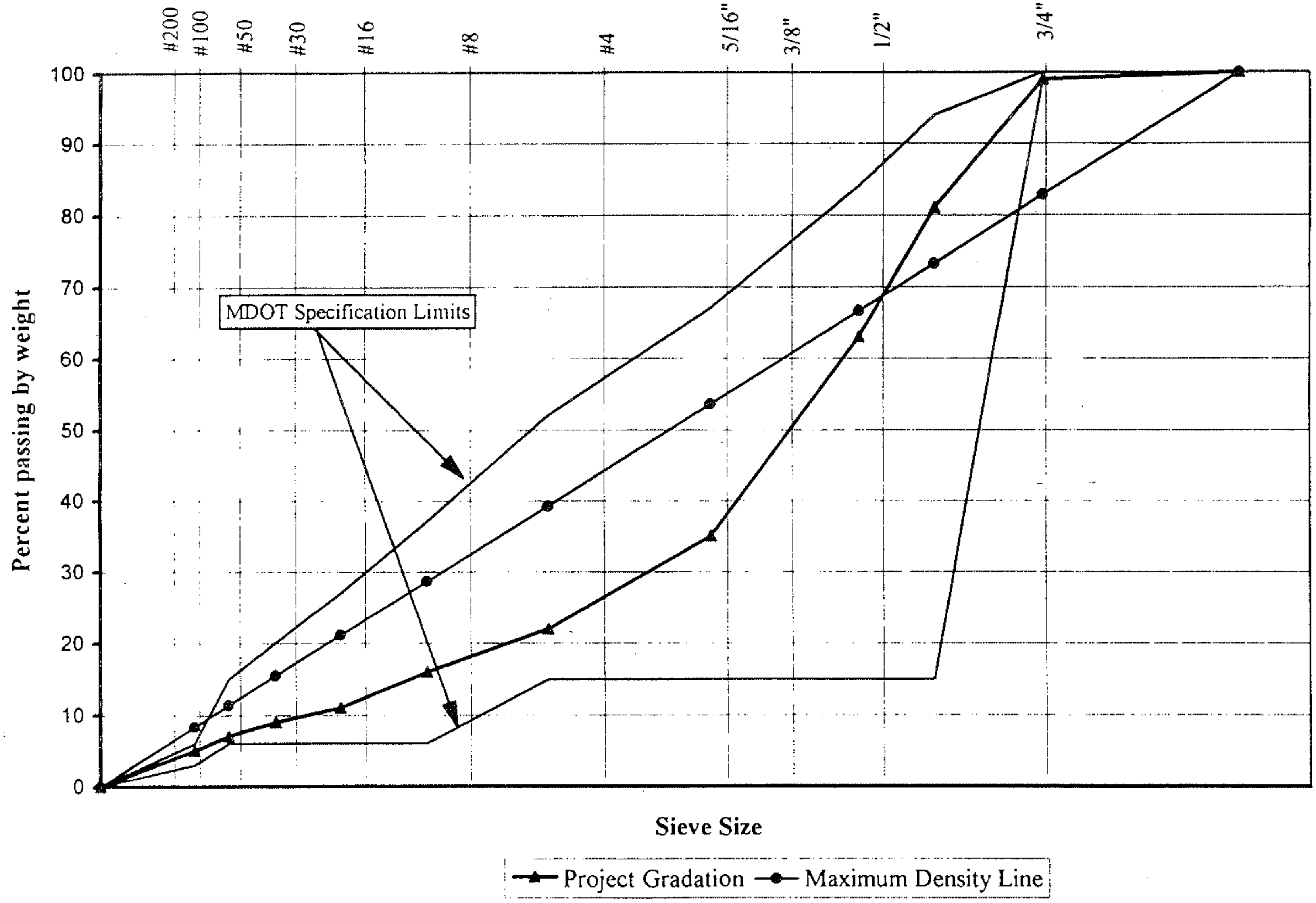


Figure III.1 Viscosity temperature chart for straight and polymer modified asphalt mixtures.



Aggregate Gradation G7

Figure III.2 Aggregate gradation (G7) curve.

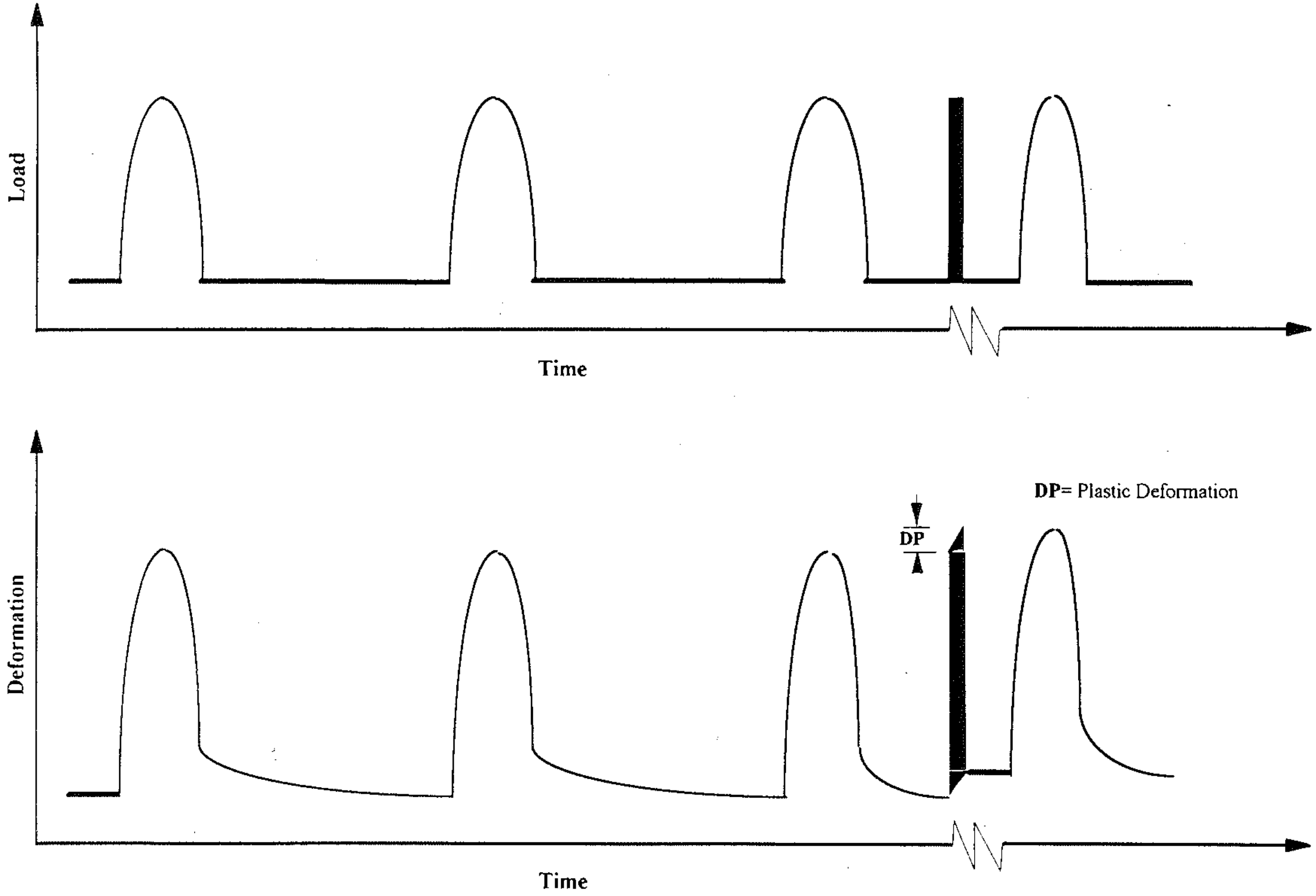


Figure III.3 Typical load deformation cycles with 0.1 second loading time and 0.4 seconds relaxation period.

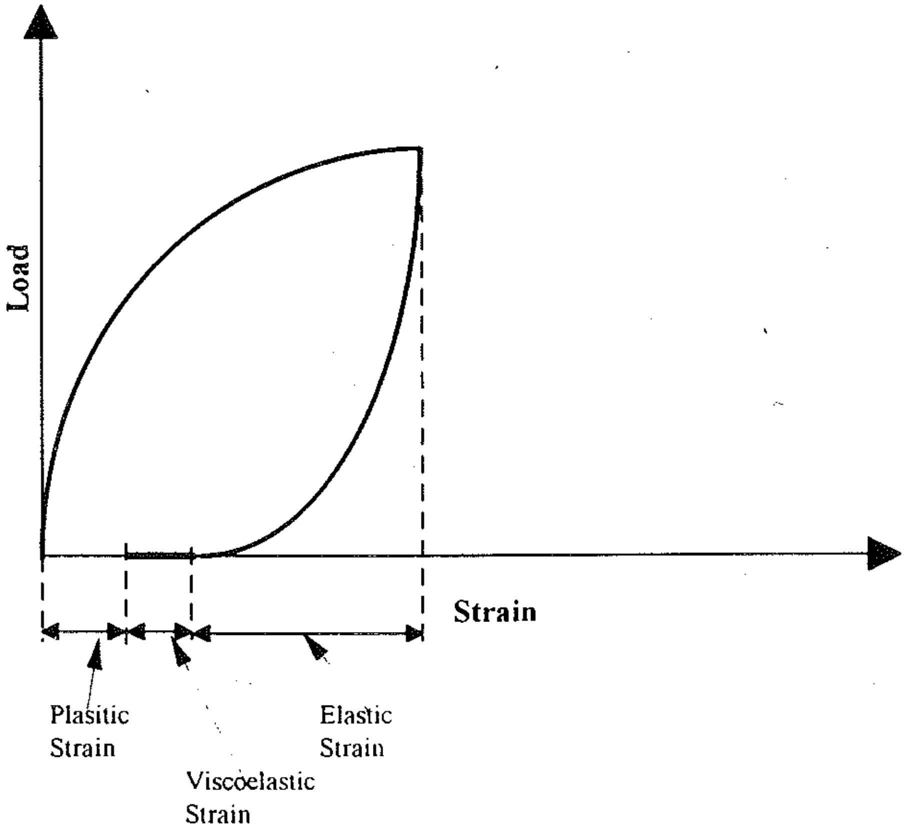
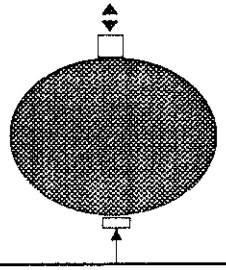


Figure III.4 Stress-strain behavior of conventional asphalt mixtures.

Indirect Tensile Cyclic Load Test

Samples are cylindrical 4 inch in diameter and 2.5 inch in height
Load Controlled test
Haversine load cycles are applied to the sample until failure



Test Temperature		23 °F (-5 °C)												77 °F (25 °C)													140 °F (60 °C)											
Asphalt Grade		AC-5				AC-10				AC-20				AC-5				AC-10					AC-20				AC-5				AC-10				AC-20			
Polymer Type		SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	CRM	SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM
Polymer Conten	ST	▨				▨								▨				▨					▨								▨							
Normal Curing	0%	▨	▨			▨	▨							▨	▨	▨	▨	▨	▨	▨	▨		▨	▨														
	1%																▨				▨																	
	2%								▨							▨	▨		▨	▨	▨					▨								▨				
	3%	▨	▨			▨	▨	▨						▨	▨	▨	▨	▨	▨	▨	▨			▨	▨							▨	▨					
	4%	▨				▨	▨							▨	▨	▨		▨	▨	▨																		
	5%	▨	▨			▨	▨							▨	▨	▨		▨	▨	▨		▨	▨	▨							▨	▨						
	7%	▨	▨											▨				▨																				
	10%																					▨																
	15%																					▨																
Aged 7 days 140° F	ST					▨												▨													▨							
	0%																																					
	1%																																					
	2%								▨												▨													▨				
	3%						▨	▨											▨	▨												▨	▨					
	4%																																					
	5%					▨	▨											▨	▨												▨	▨						
	7%																																					

Each cell represent a triplicate

▨ Shaded cells are tested

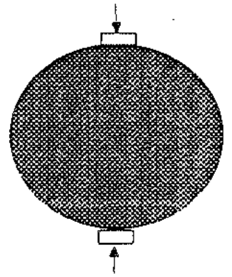
ST= Straight

0%= Processed

Figure III.5 The experimental program matrix for the indirect tensile cyclic load test.

Indirect Tensile Strength Test (ITT)

Samples are cylindrical 4 inch in diameter and 2.5 inch in height
Deformation Controlled test
Ramp load is applied to the sample until failure



Test Temperature		23 °F (-5 °C)												
Asphalt Grade		AC-5				AC-10					AC-20			
Polymer Type		SBS	SEB	SBR	EAM	SBS	SEB	SBR	EAM	CR	SBS	SEB	SBR	EAM
Polymer Content	ST	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Normal Curing	0%					▨	▨	▨	▨		▨	▨	▨	▨
	1%								▨					
	2%							▨	▨					▨
	3%					▨	▨	▨	▨			▨	▨	
	4%					▨	▨	▨						
	5%					▨	▨	▨		▨	▨	▨		
	7%					▨	▨							
	10%									▨				
	15%									▨				
Aged 7 days @140°F	ST					▨	▨	▨	▨	▨	▨	▨	▨	▨
	0%					▨	▨							
	1%													
	2%								▨	▨				▨
	3%					▨	▨	▨				▨	▨	
	4%					▨	▨							
	5%					▨	▨				▨	▨		
	7%					▨	▨							

Test Temperature		77 °F (25 °C)												
Asphalt Grade		AC-5				AC-10					AC-20			
Polymer Type		SBS	SEB	SBR	EAM	SBS	SEBS	SBR	EAM	CRM	SBS	SEBS	SBR	EAM
Polymer Content	ST	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Normal Curing	0%	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨
	1%				▨				▨					
	2%		▨	▨	▨	▨	▨		▨					▨
	3%	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨	
	4%	▨	▨	▨		▨	▨	▨						
	5%	▨	▨	▨		▨	▨	▨		▨	▨	▨		
	7%	▨	▨			▨	▨							
	10%									▨				
	15%									▨				
Aged 7 days @140°F	ST	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	0%	▨	▨	▨	▨	▨	▨	▨	▨					
	1%				▨				▨					
	2%			▨	▨			▨	▨					▨
	3%	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨	
	4%	▨	▨	▨		▨	▨	▨						
	5%	▨	▨	▨		▨	▨	▨			▨	▨		
	7%	▨	▨			▨	▨							

Test Temperature		140 °F (60 °C)												
Asphalt Grade		AC-5				AC-10					AC-20			
Polymer Type		SBS	SEBS	SBR	EAM	SBS	SEBS	SBR	EAM	CRM	SBS	SEB	SBR	EAM
Polymer Content	ST	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Normal Curing	0%	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨
	1%				▨				▨					
	2%		▨	▨	▨		▨	▨	▨					▨
	3%	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨	
	4%	▨	▨	▨		▨	▨	▨						
	5%	▨	▨	▨		▨	▨	▨		▨	▨	▨		
	7%	▨	▨			▨	▨							
	10%									▨				
	15%									▨				
Aged 7 days @140°F	ST					▨	▨	▨	▨	▨	▨	▨	▨	▨
	0%													
	1%													
	2%								▨					▨
	3%						▨	▨				▨	▨	
	4%													
	5%					▨	▨				▨	▨		
	7%													

Figure III.6 The experimental program matrix for the indirect tensile strength test.

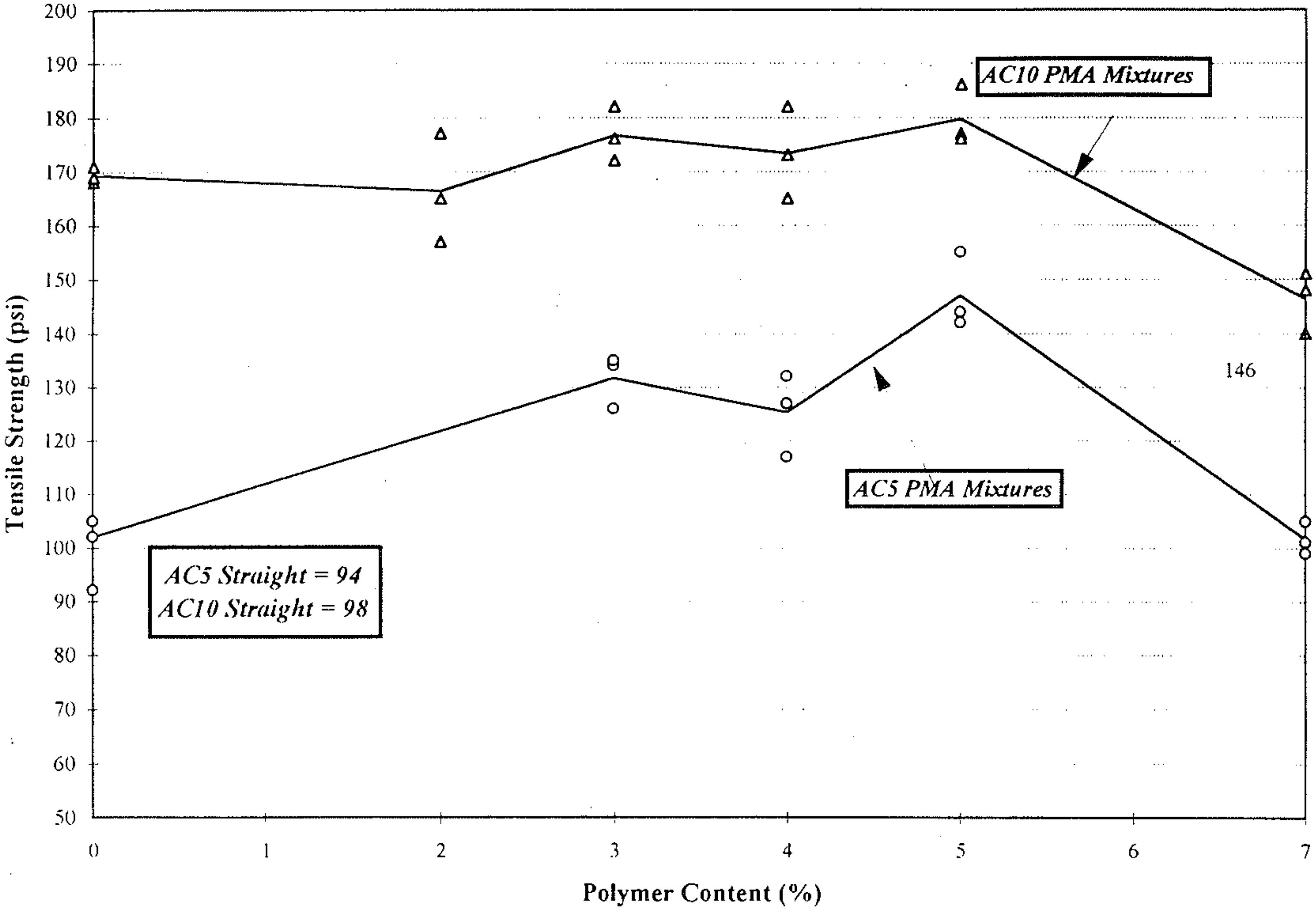


Figure III.7 Effect of SBS polymer content on the indirect tensile strength of AC5 and AC10 PMA mixtures at test temperature of 77° F.

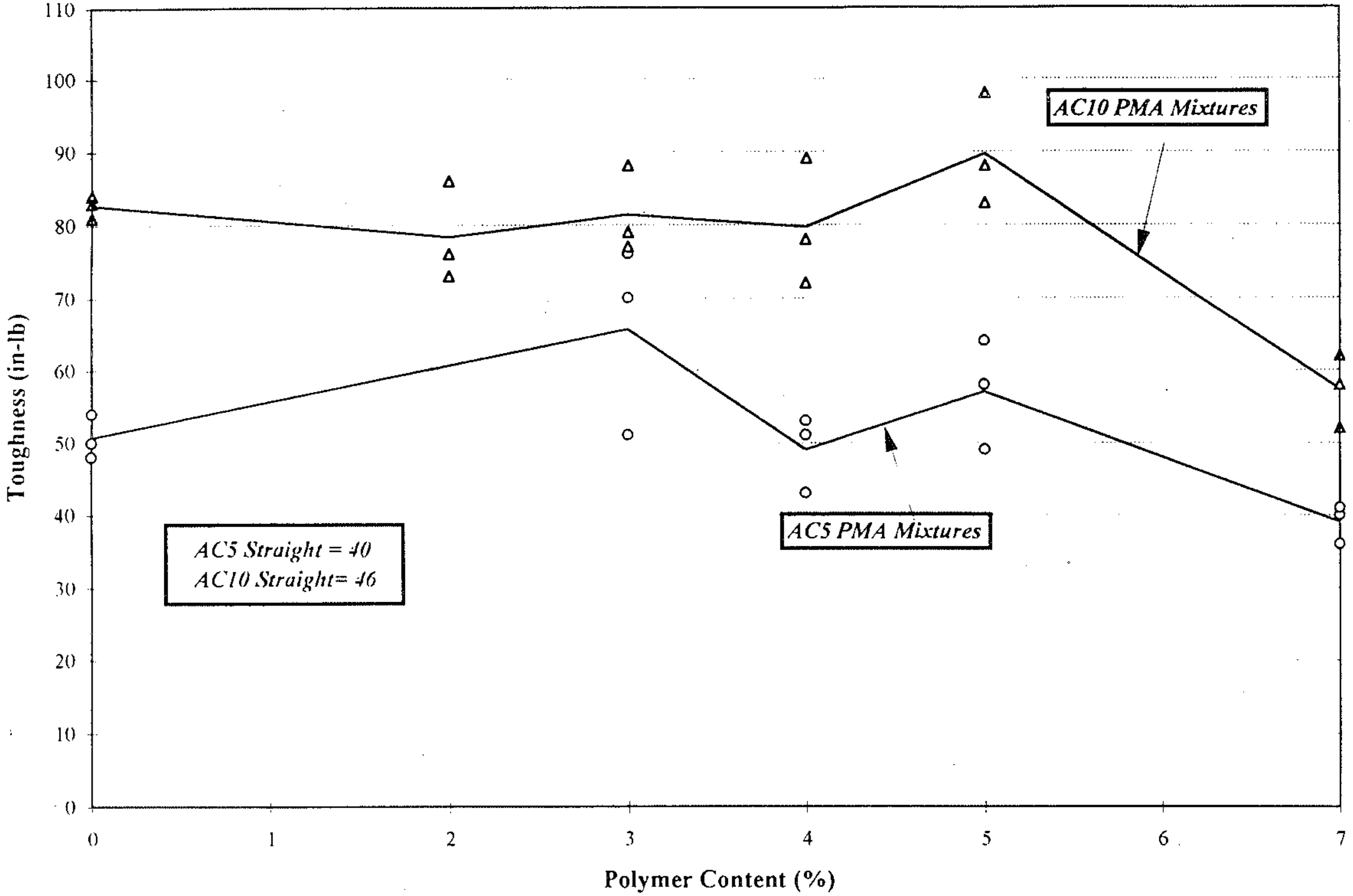


Figure III.8 Effect of SBS polymer content on the fracture toughness of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

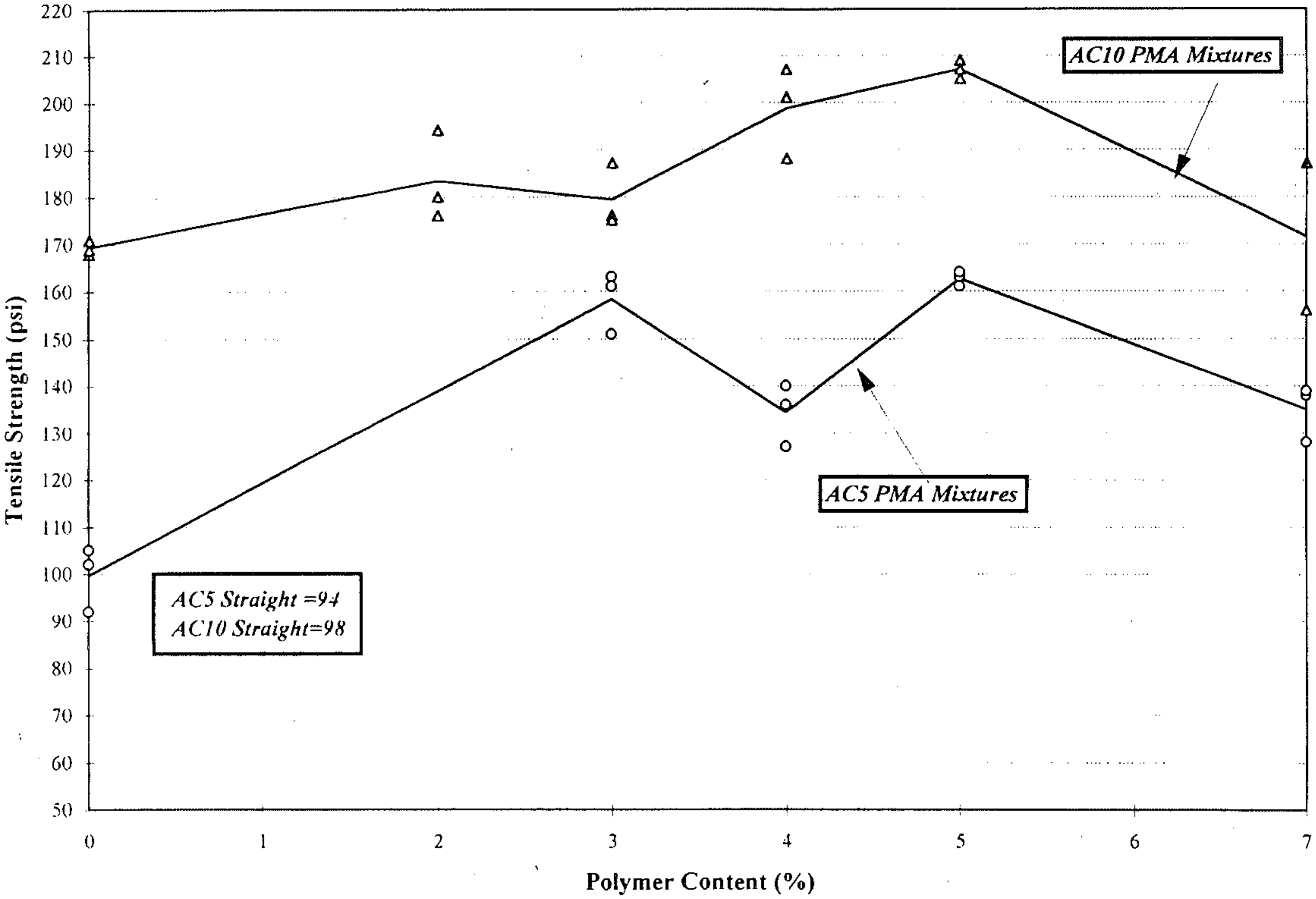


Figure III.9 Effect of SEBS polymer content on the indirect tensile strength of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

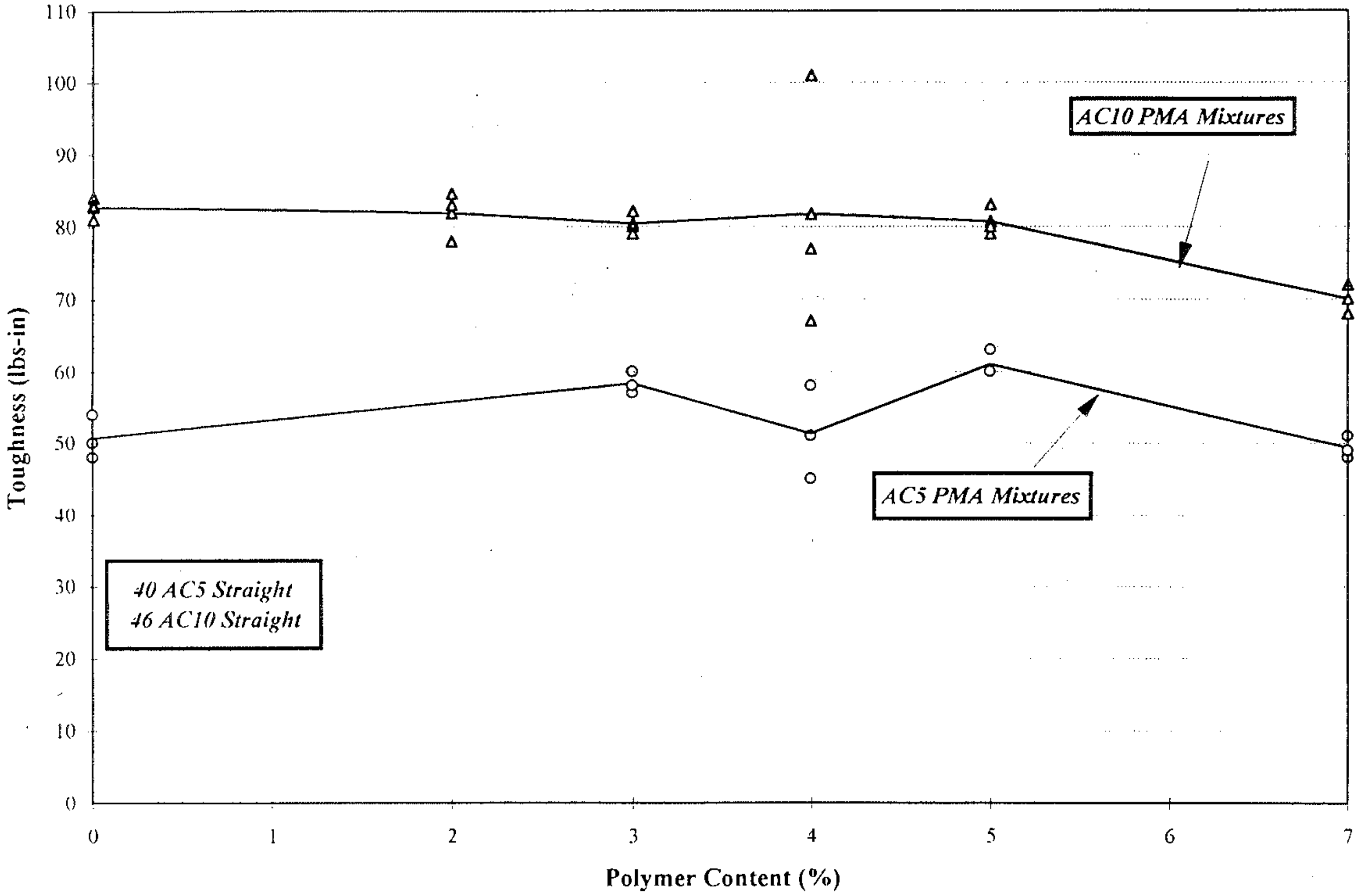


Figure III.10 Effect of SEBS polymer content on the fracture toughness of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

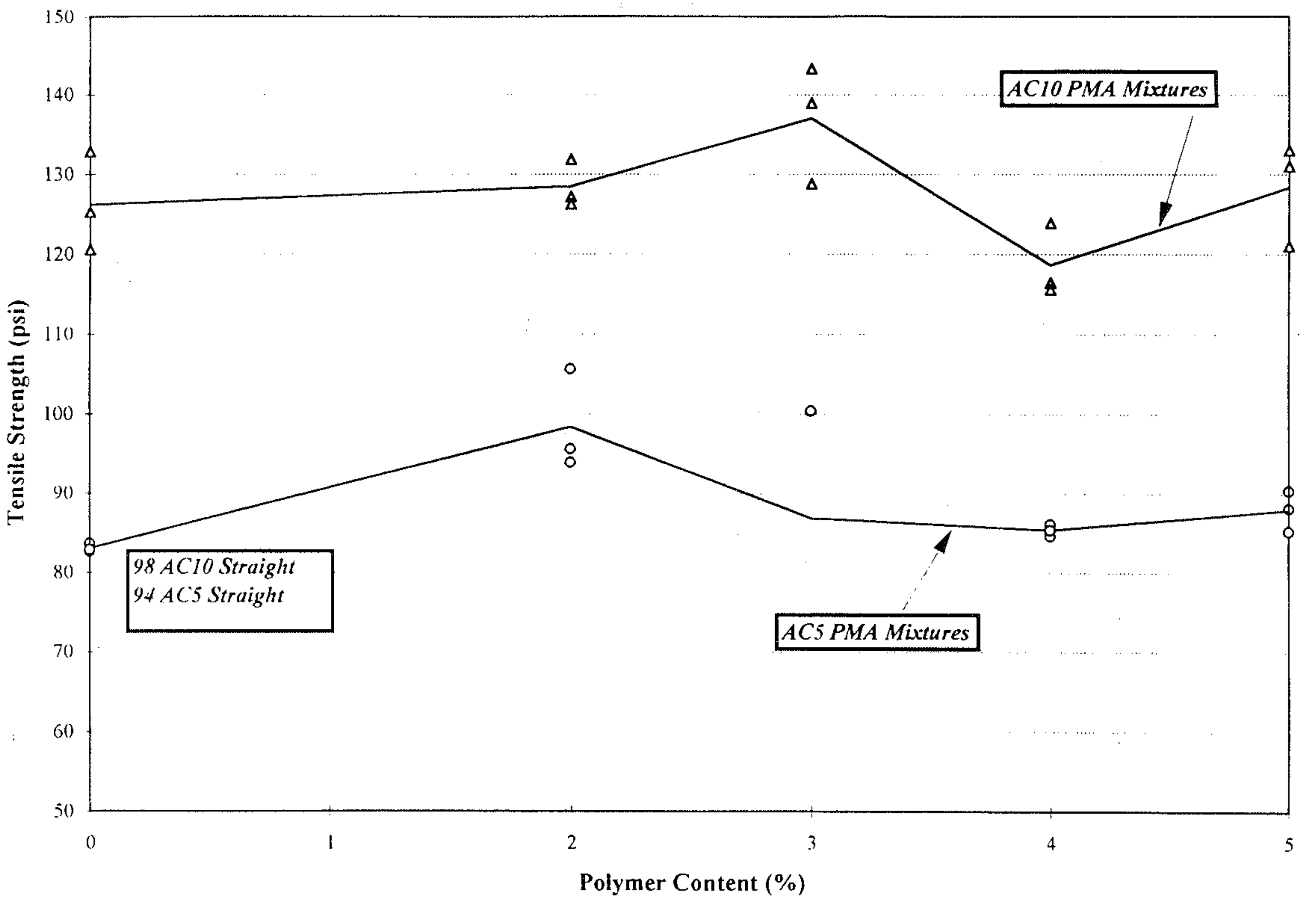


Figure III.11 Effect of SBR polymer content on the indirect tensile strength of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

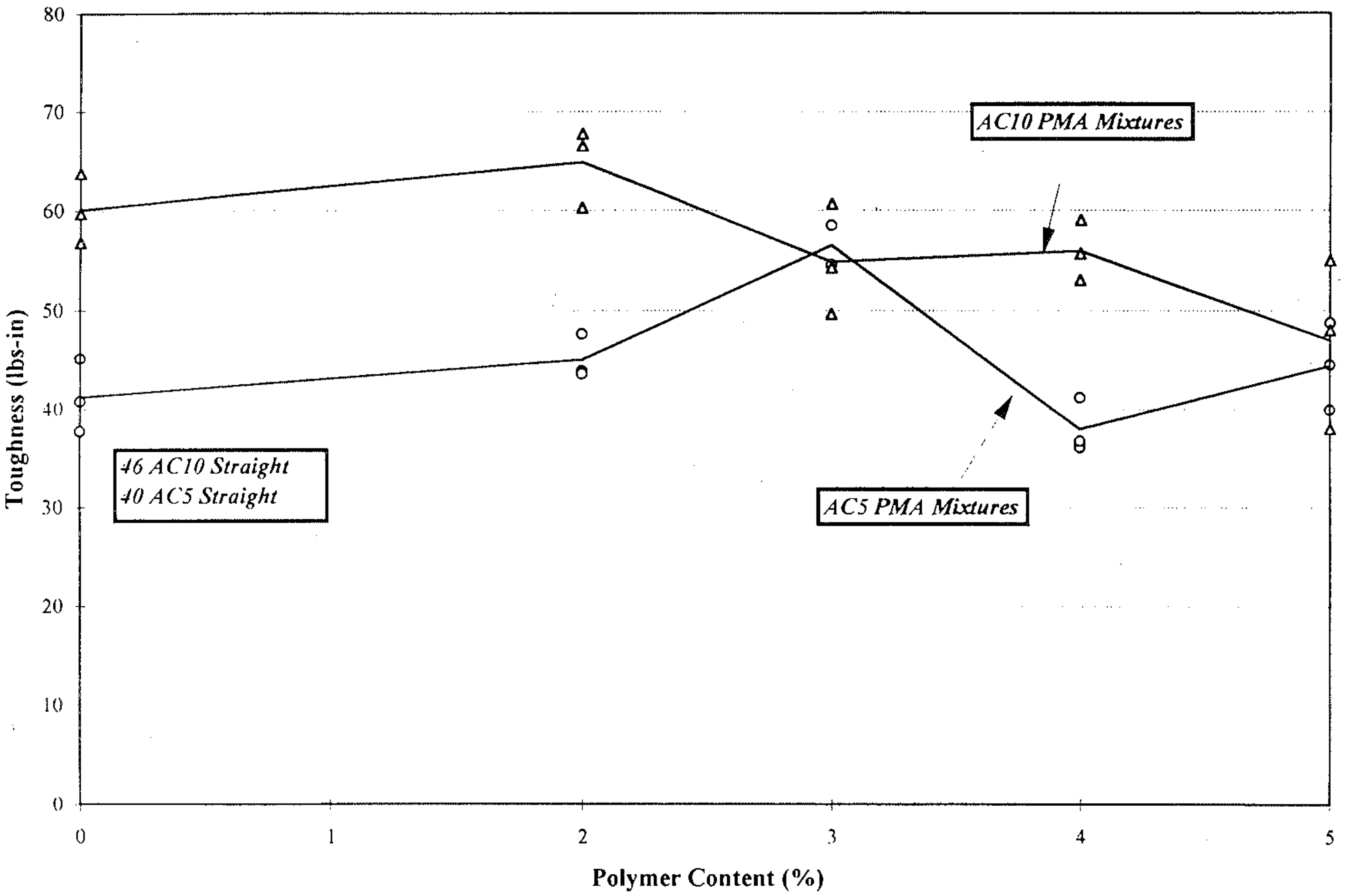


Figure III 12 Effect of SBR polymer content on the fracture toughness of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

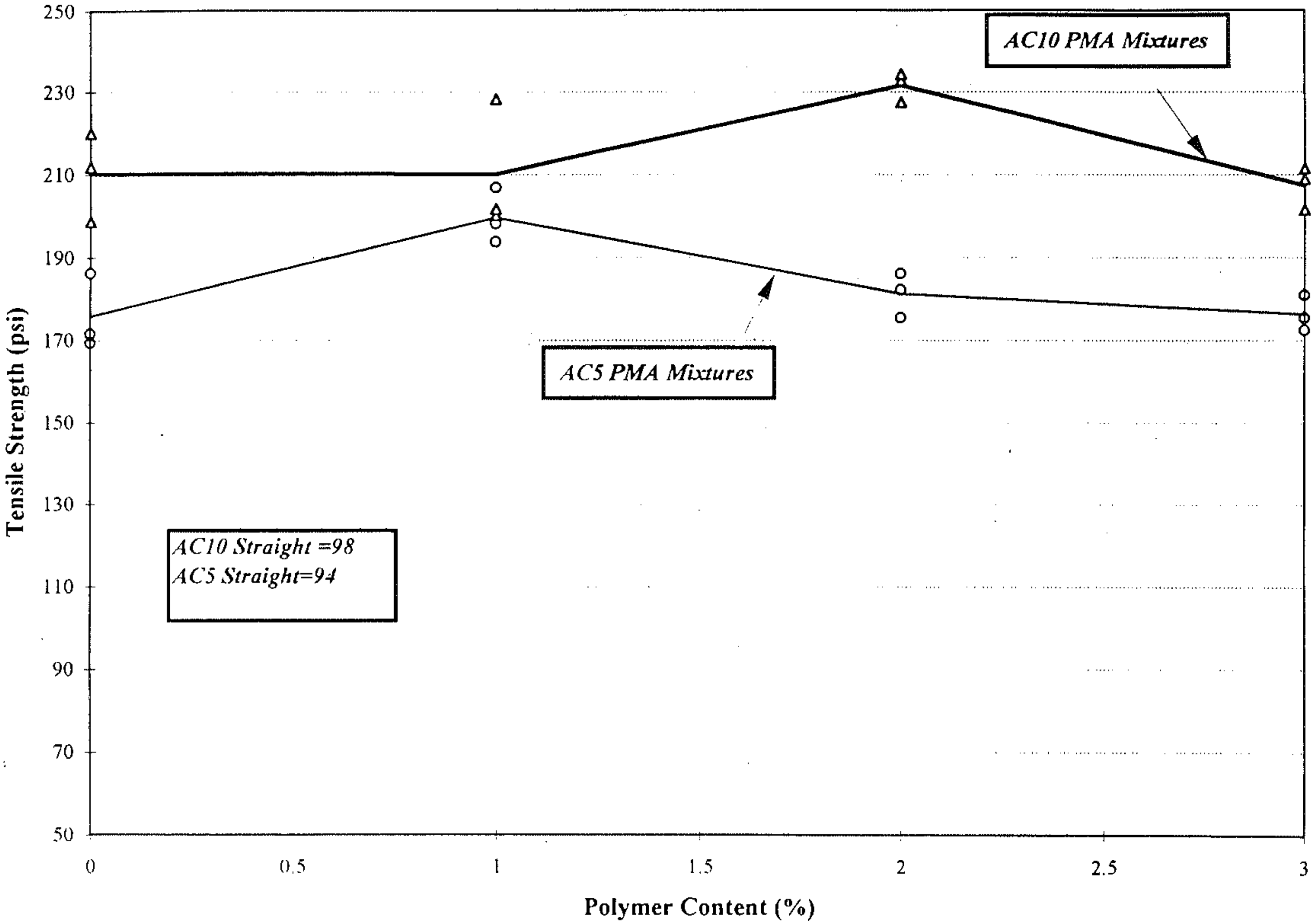


Figure III.13 Effect of ELVALOY polymer content on the indirect tensile strength of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

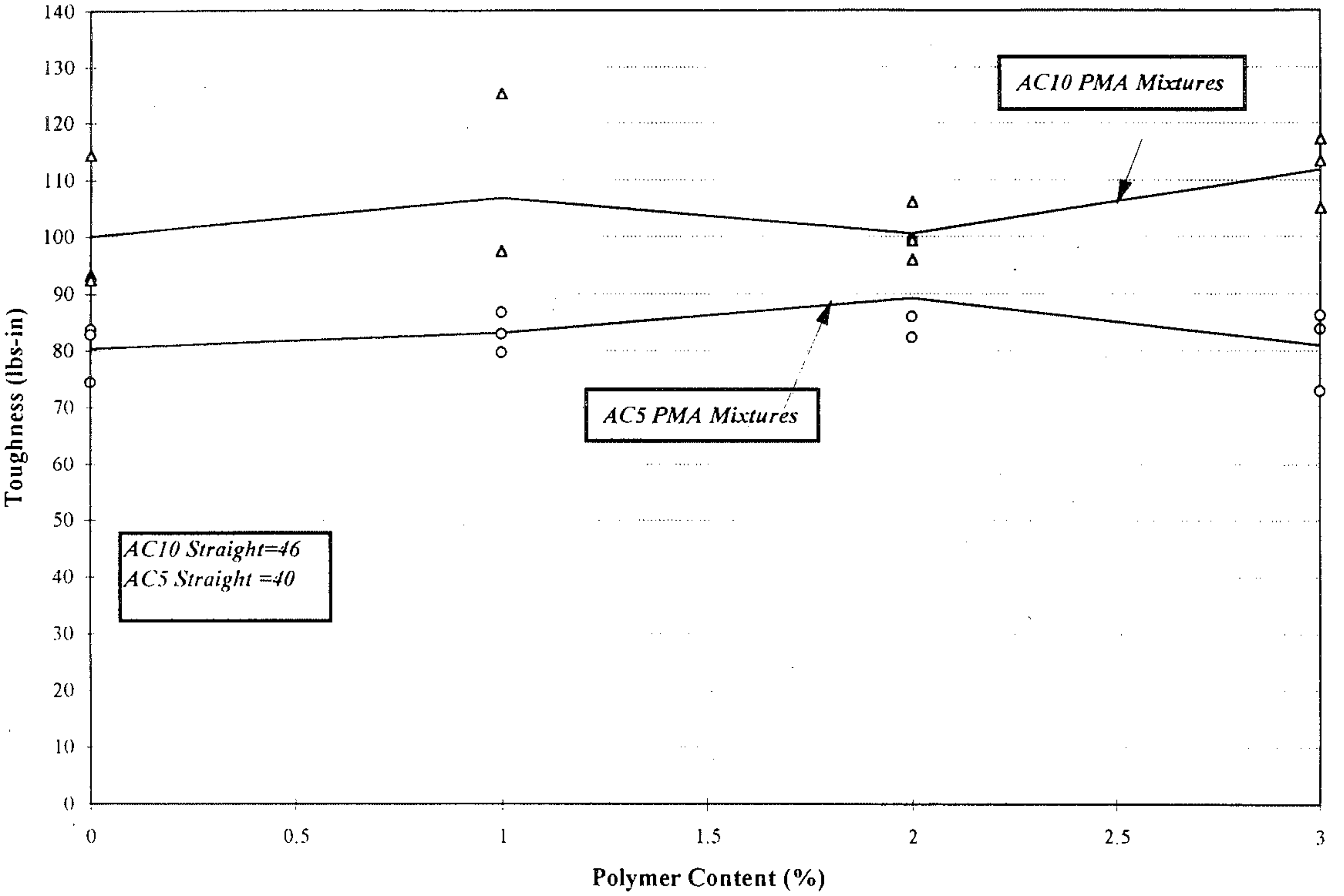


Figure III.14 Effect of ELVALOY polymer content on the fracture toughness of AC5 and AC10 PMA mixtures at the test temperature of 77° F.

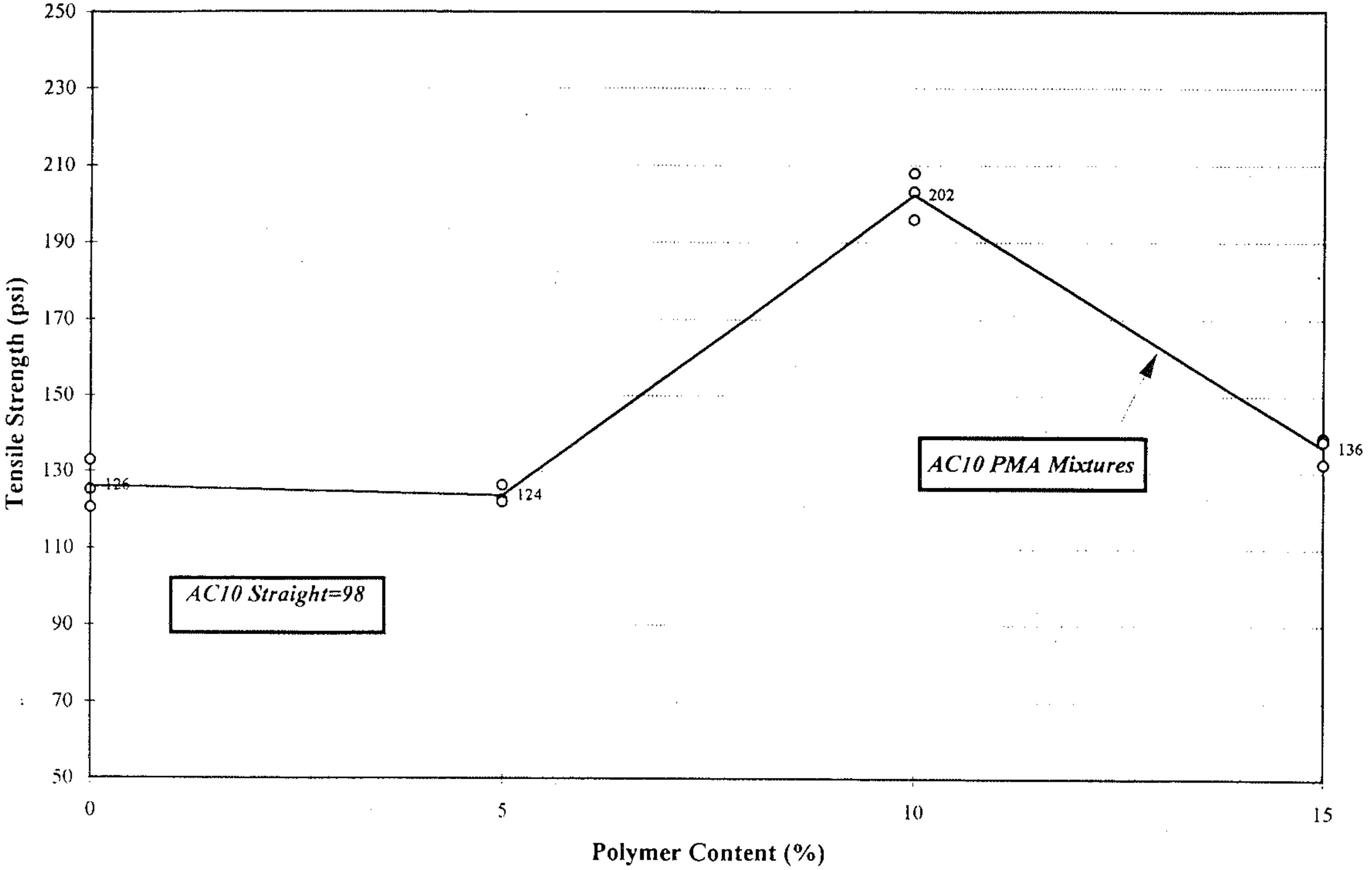


Figure III.15 Effect of CRM content on the indirect tensile strength of AC10 PMA mixtures at the test temperature of 77° F.

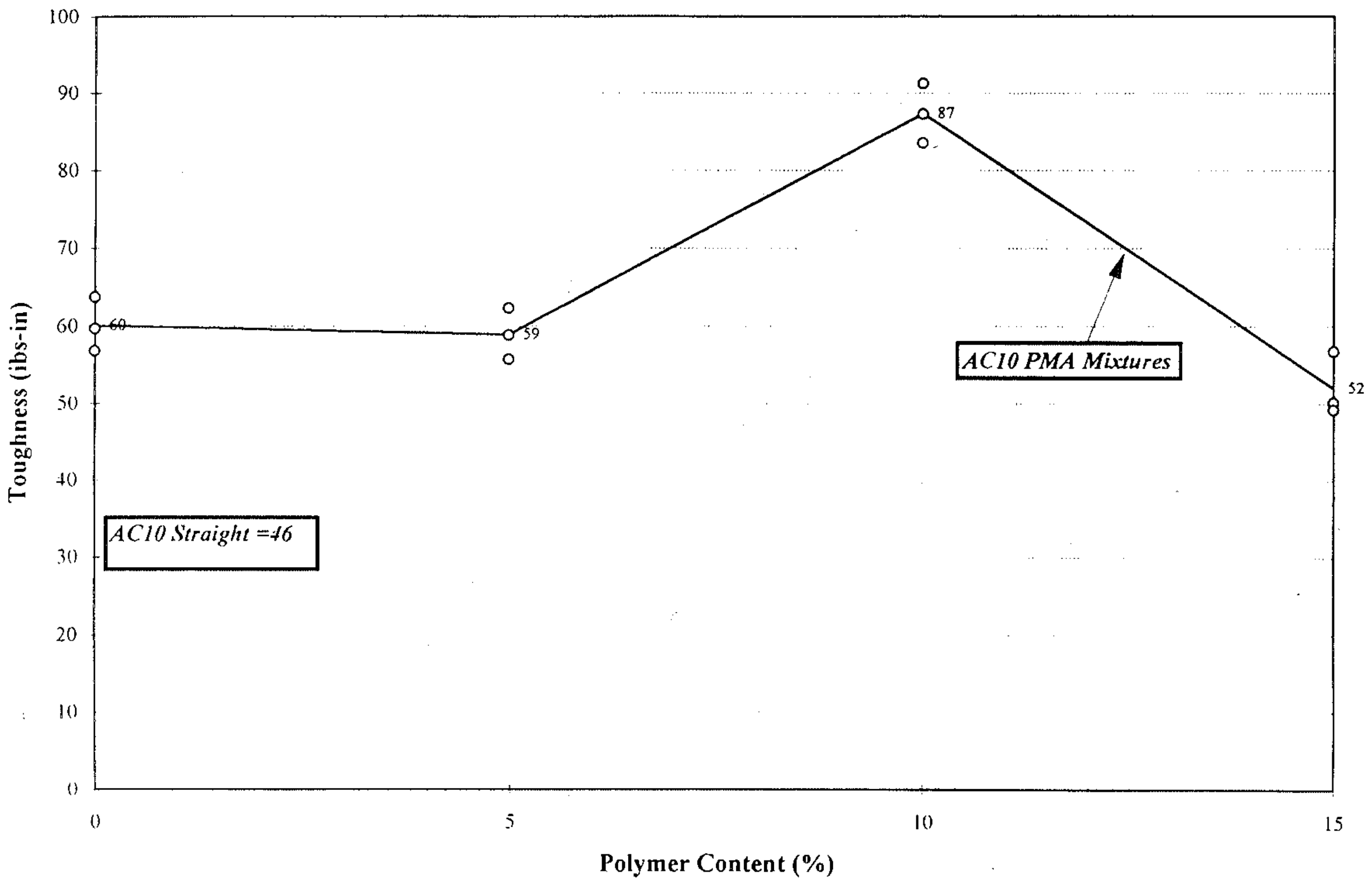
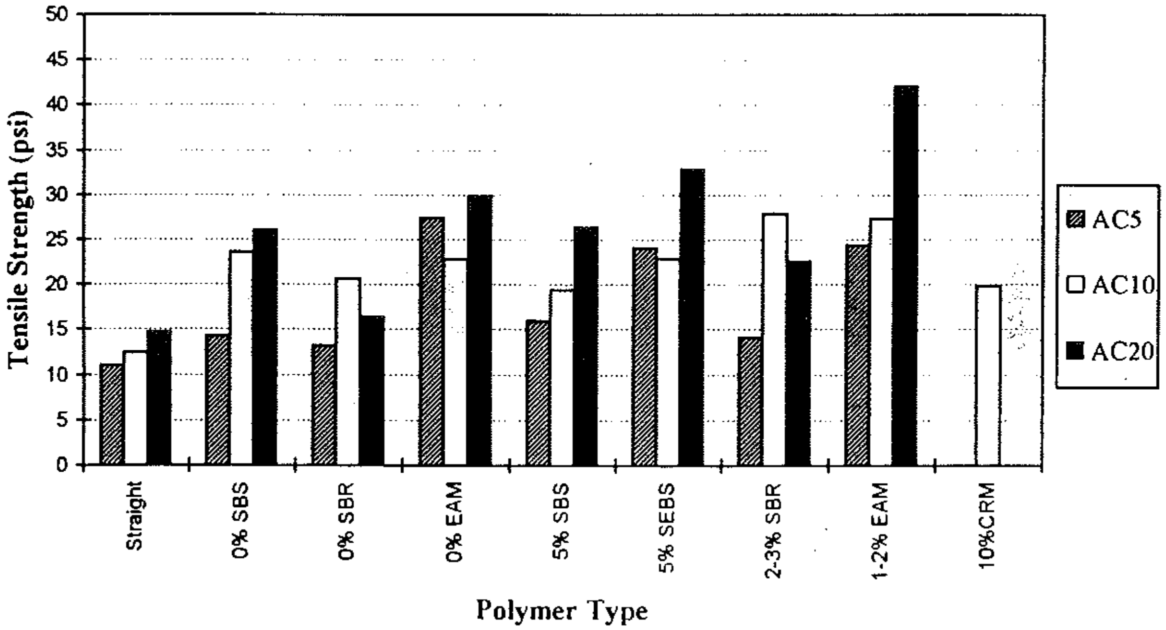


Figure III.16 Effect of CRM content on the fracture toughness of AC10 PMA mixtures at the test temperature of 77° F.

a) Indirect Tensile Strength



b) Fracture Toughness

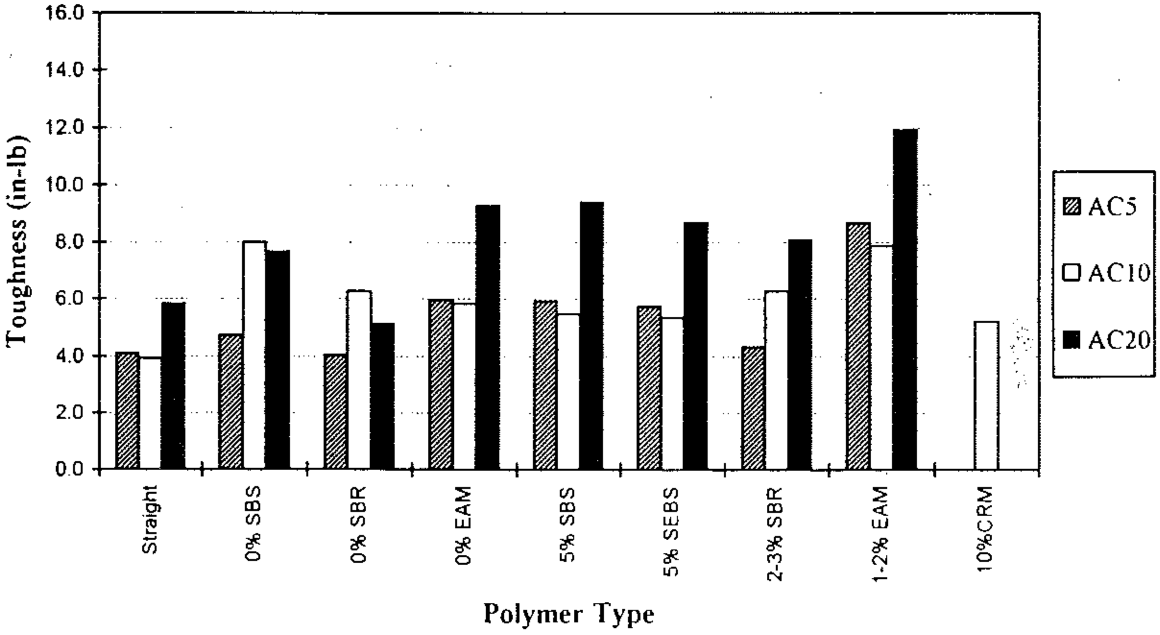
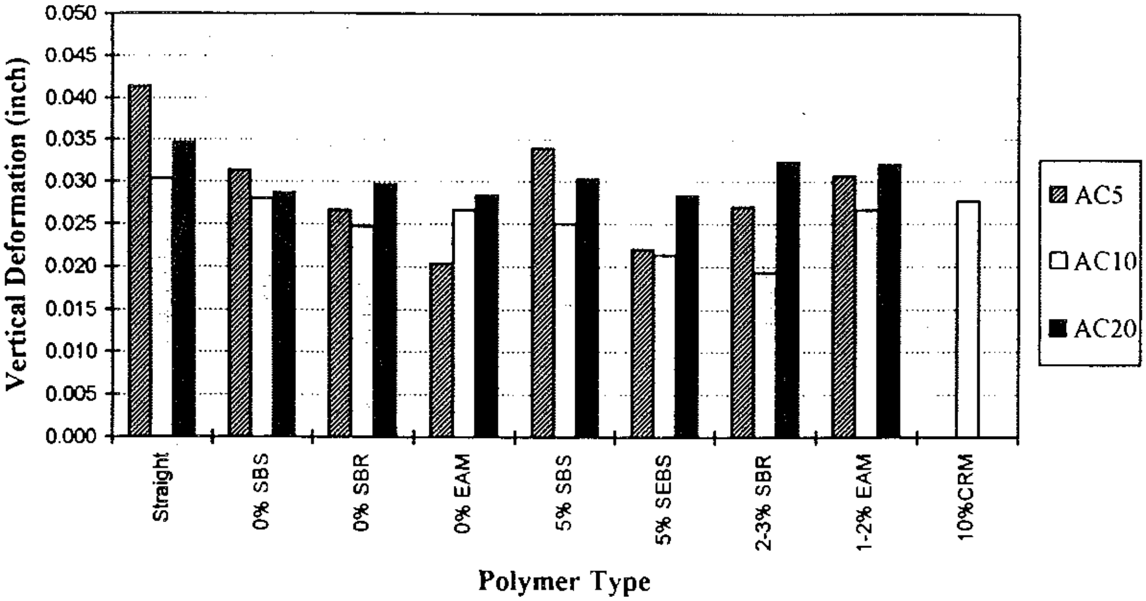


Figure III.17 Effect of polymer type on the indirect tensile strength and fracture toughness of PMA mixtures at 140° F.

a) Vertical Deformation at Failure



b) Total Modulus

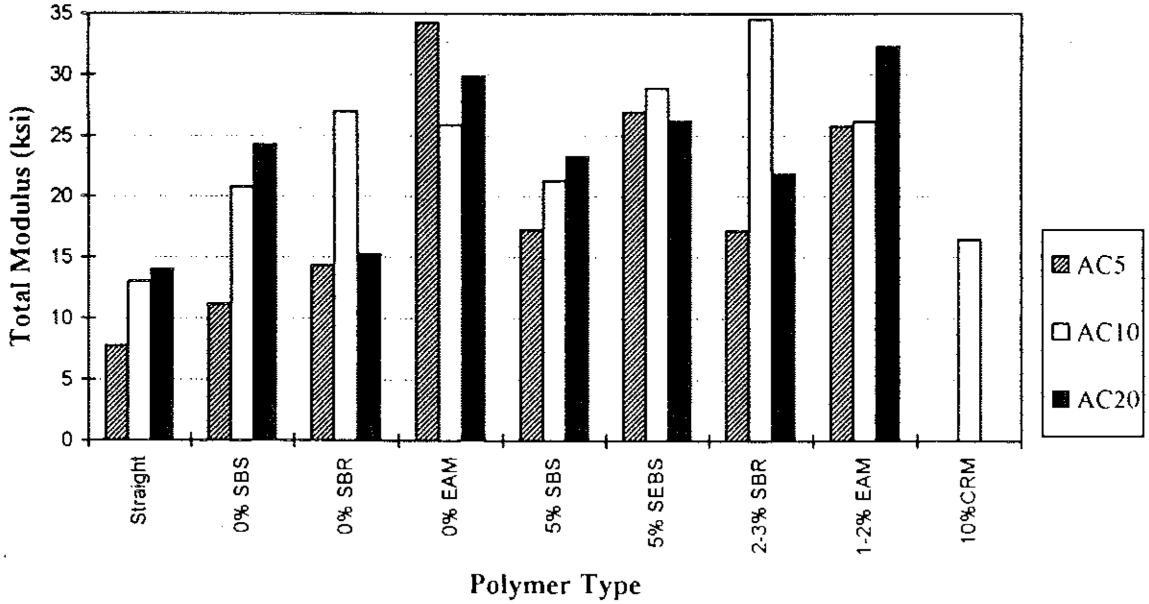
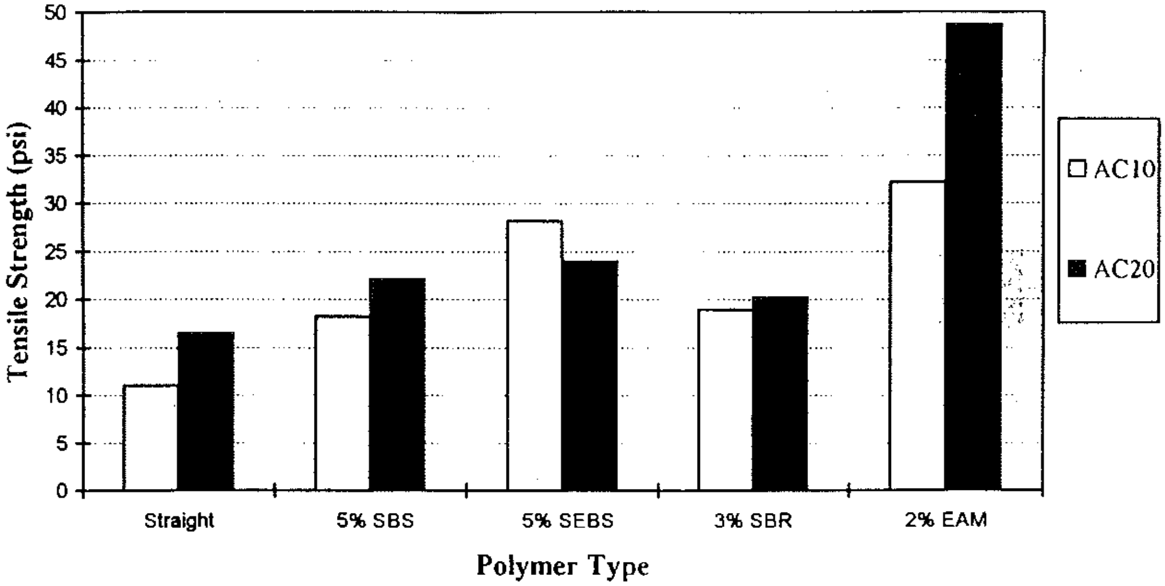


Figure III.18 Effect of polymer type on the vertical deformation and total modulus of PMA mixtures at 140° F.

a) Indirect Tensile Strength
Oven Aged



b) Fracture Toughness
Oven Aged

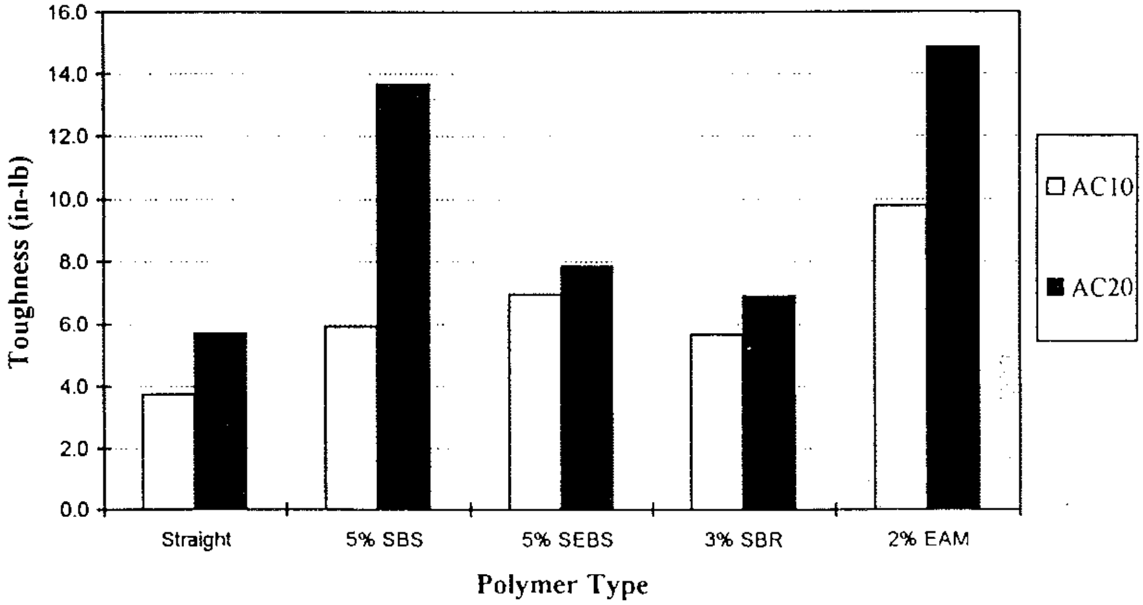
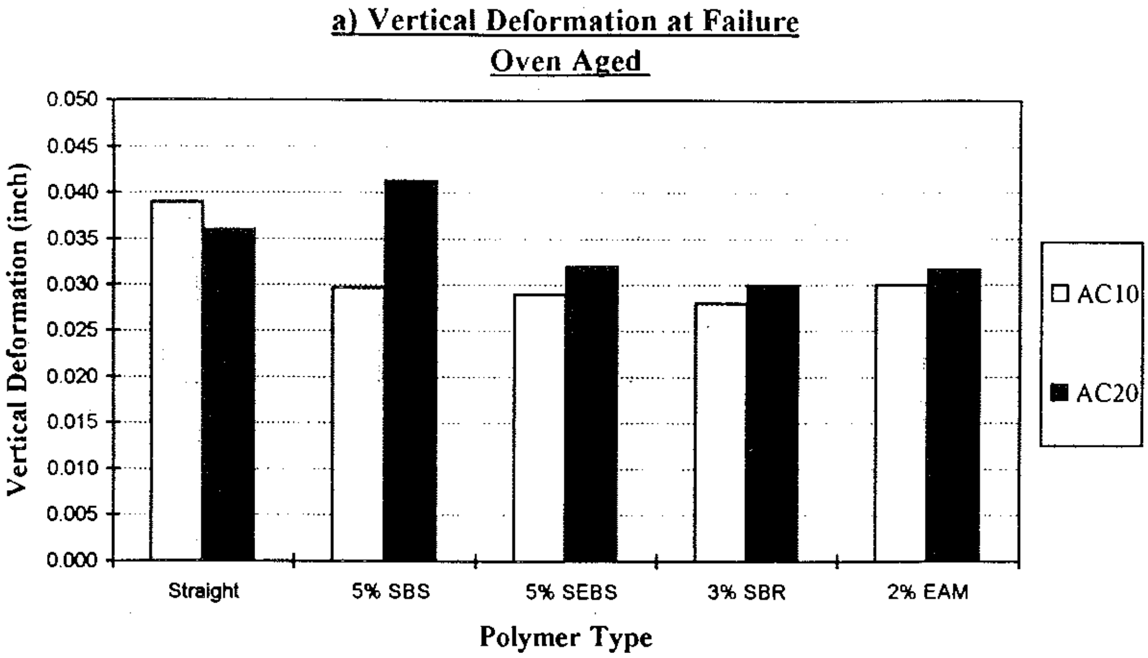


Figure III.19 Effect of polymer type on the indirect tensile strength and toughness of oven aged PMA mixtures at 140° F.



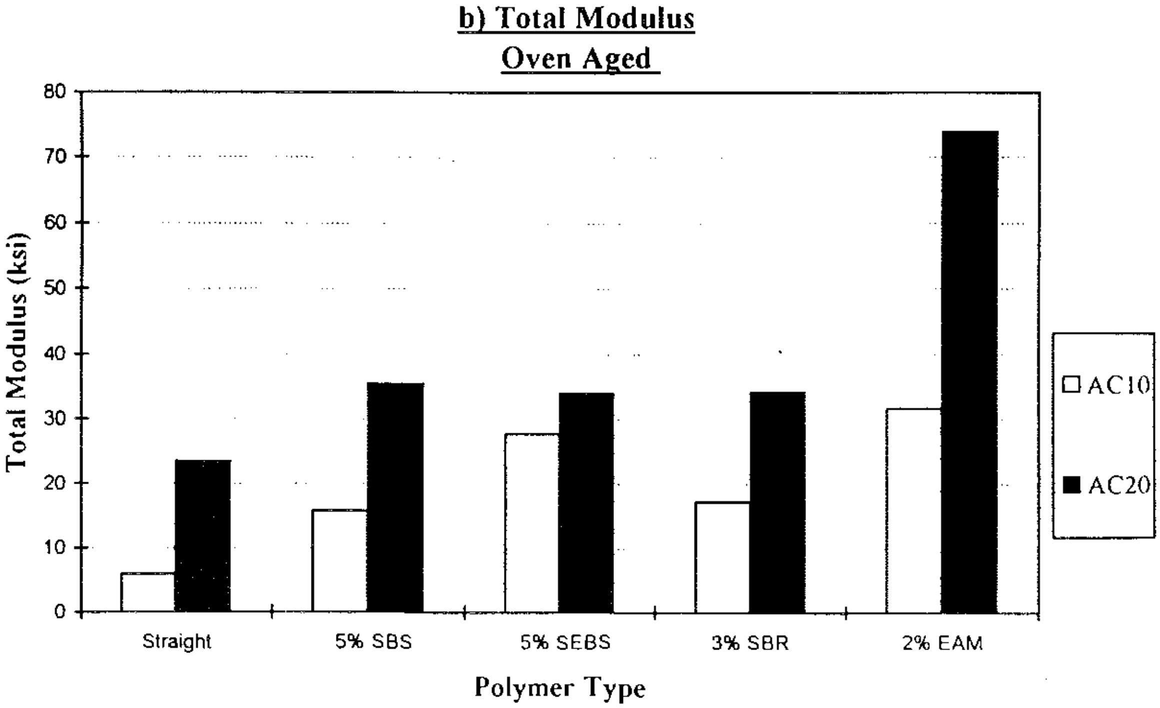
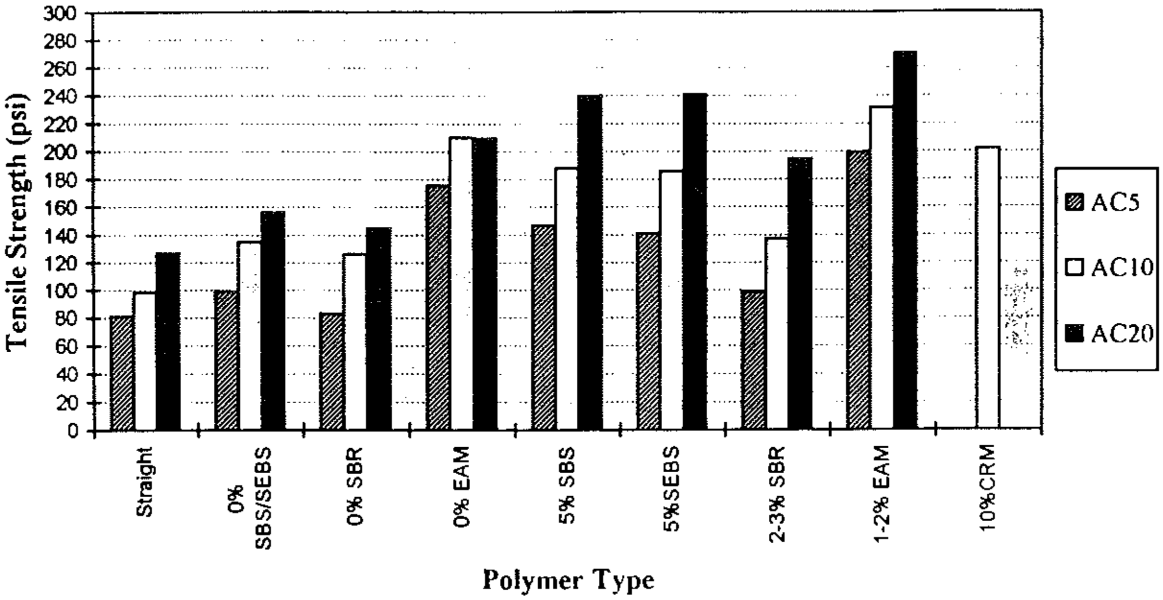
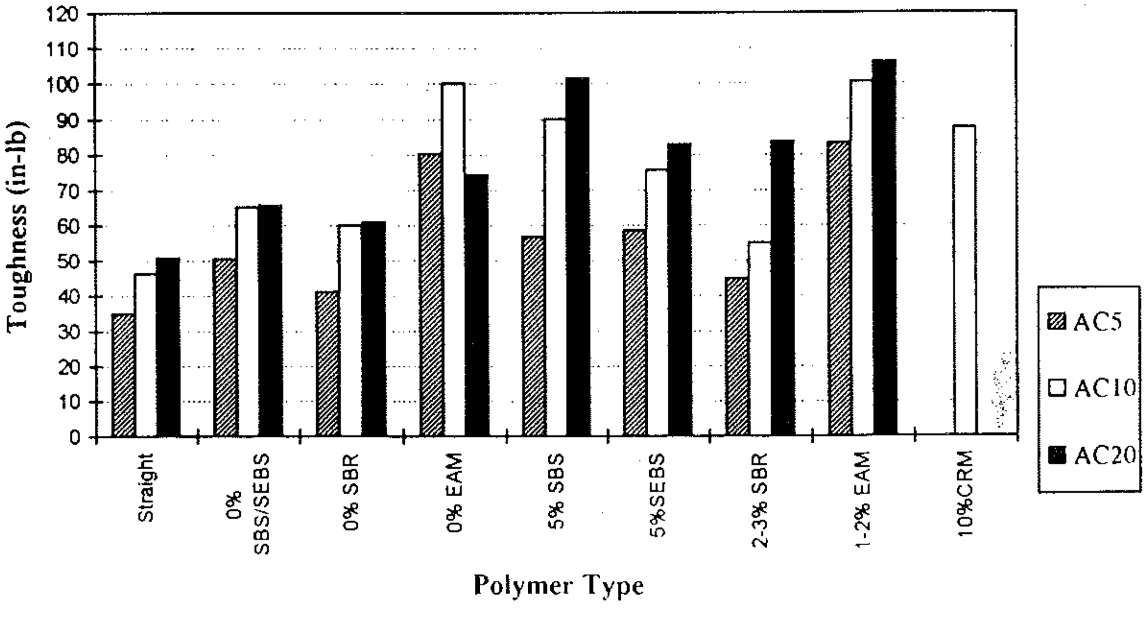


Figure III.20 Effect of polymer type on the vertical deformation and total modulus of oven aged PMA mixtures at 140° F.



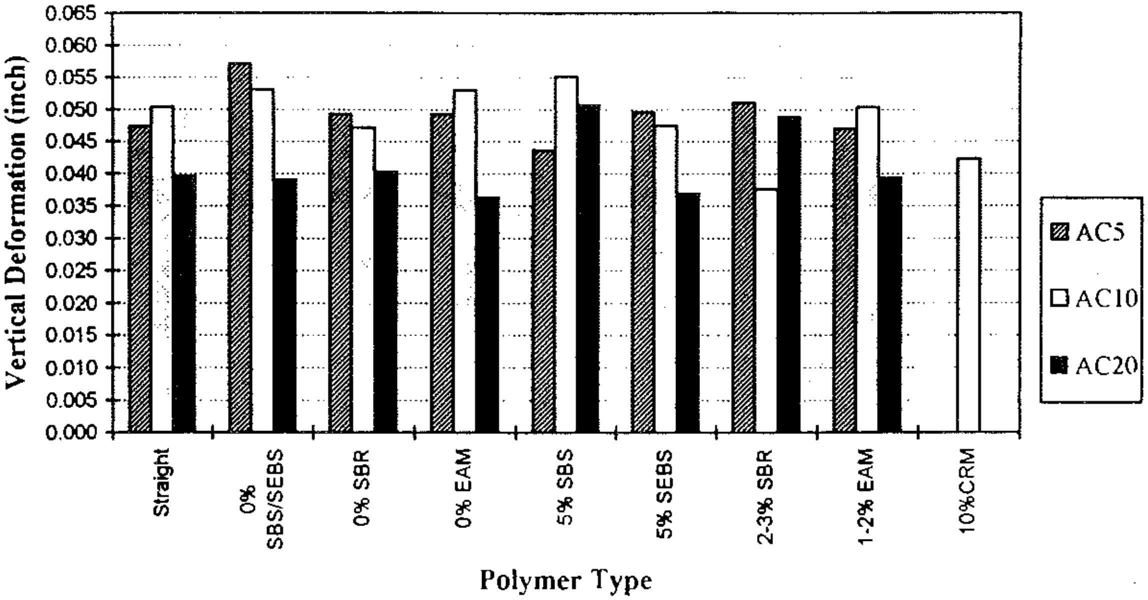
a) Indirect Tensile Strength



b) Fracture Toughness

Figure III.21 Effect of polymer type on the indirect tensile strength and toughness of PMA mixtures at 77° F.

a) Vertical Deformation at Failure



b)Total Modulus

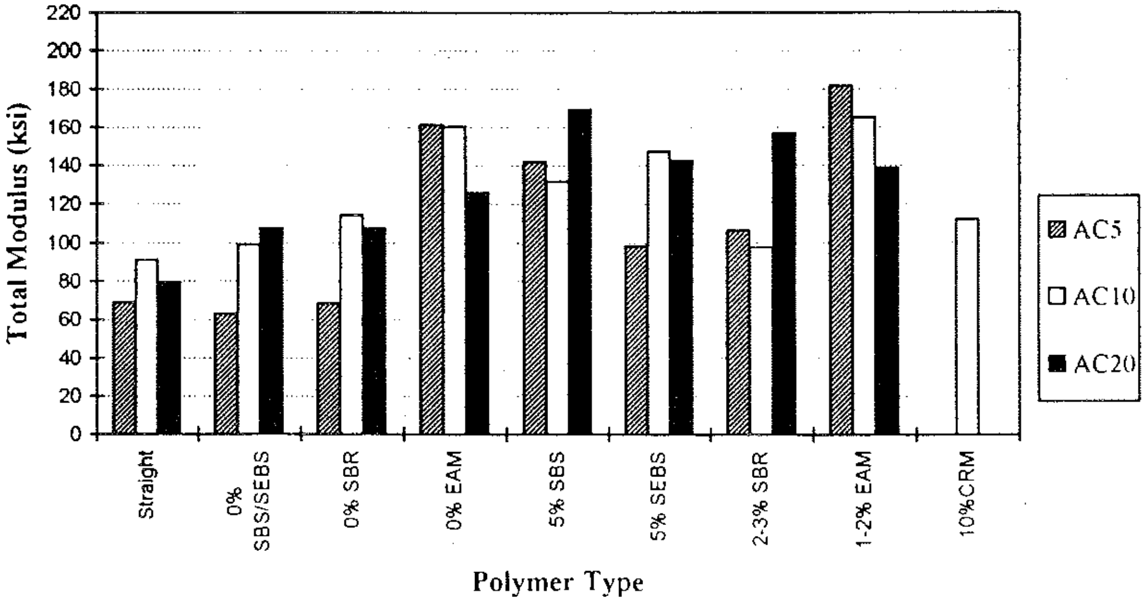
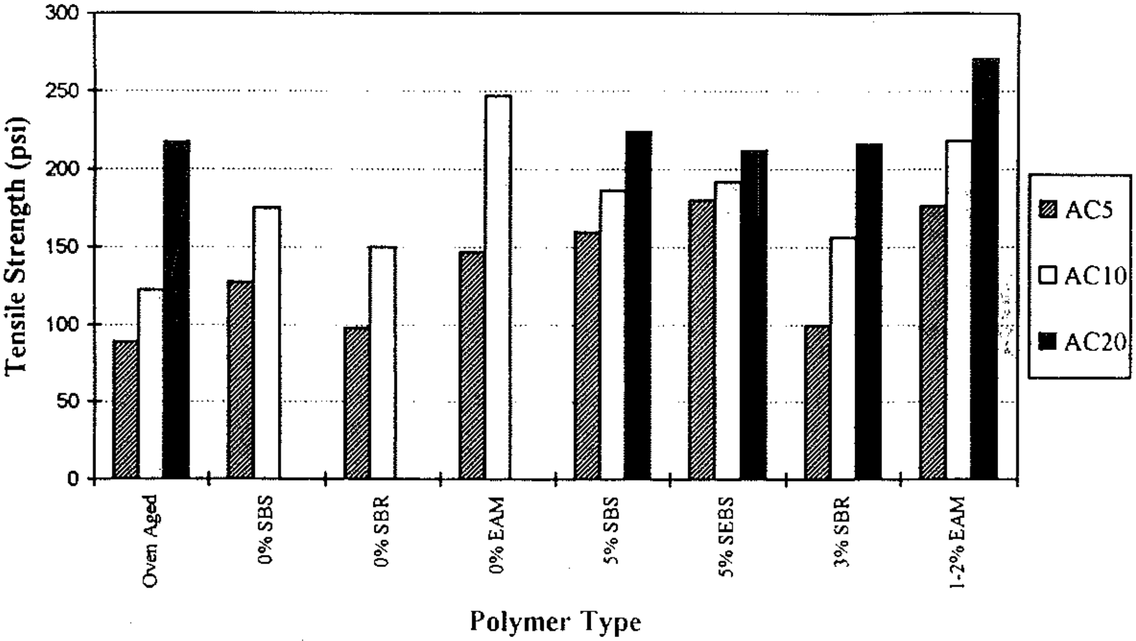


Figure III.22 Effect of polymer type on the vertical deformation and total modulus of PMA mixtures at 77° F.

a) Indirect Tensile Strength
Oven Aged



b) Fracture Toughness
Oven Aged

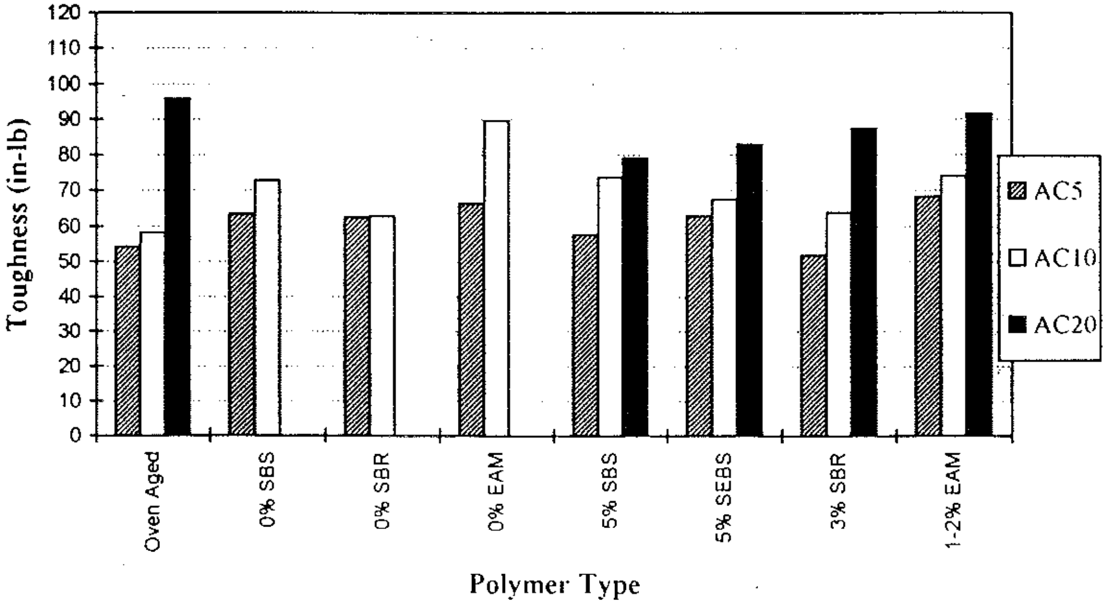
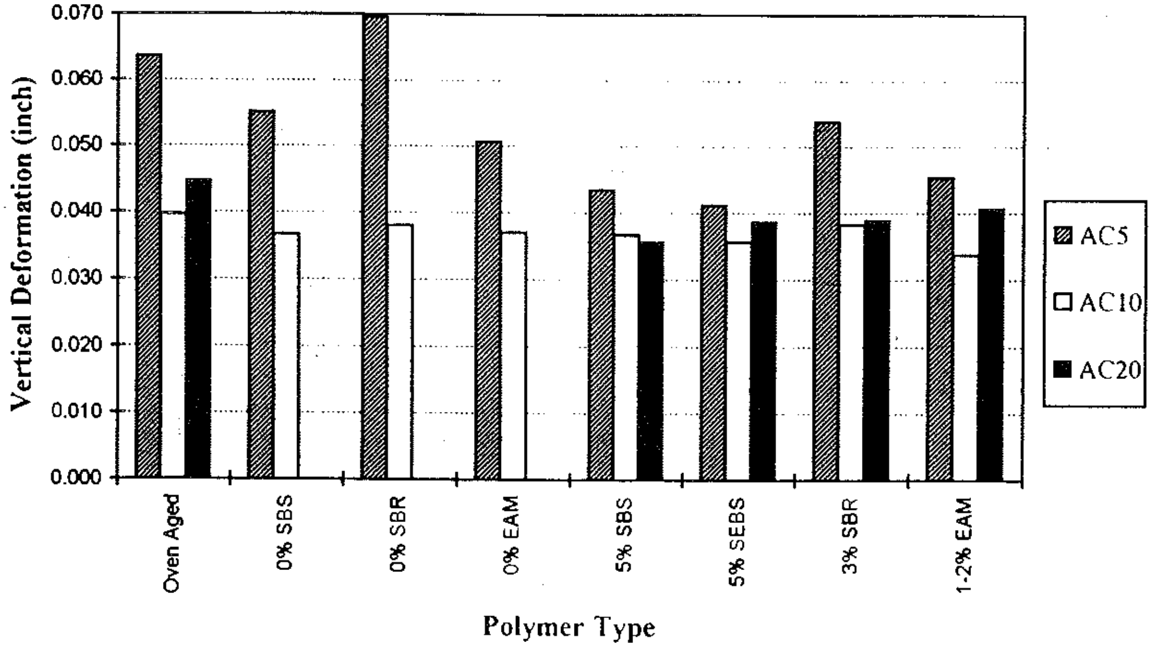


Figure III.23 Effect of polymer type on the indirect tensile strength and toughness of oven aged PMA mixtures at 77° F.

a) Vertical Deformation at Failure Oven Aged



b) Total Modulus Oven Aged

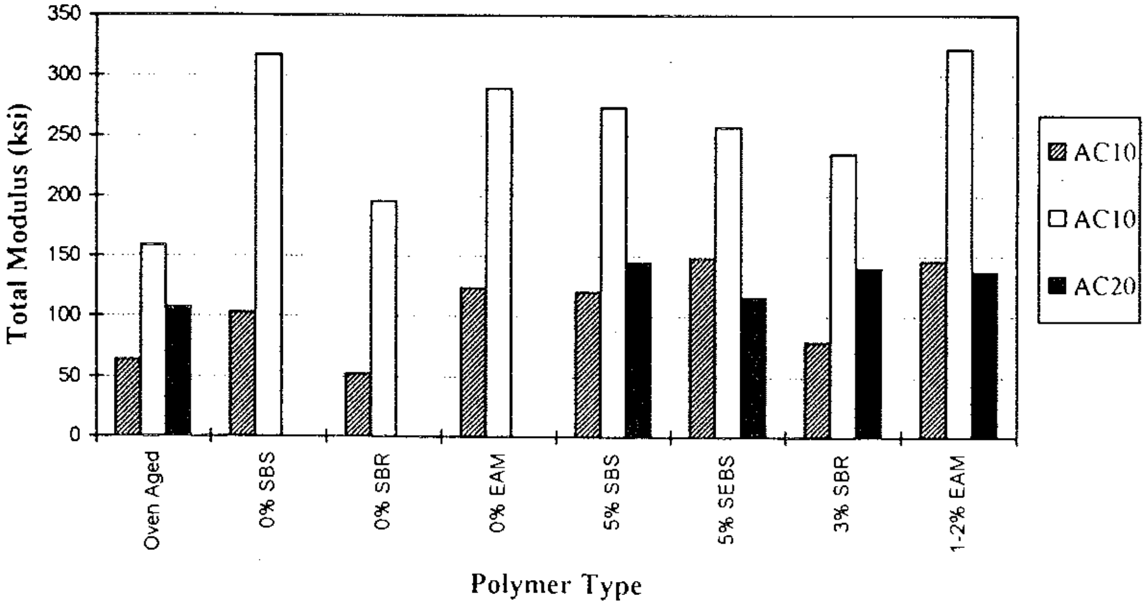
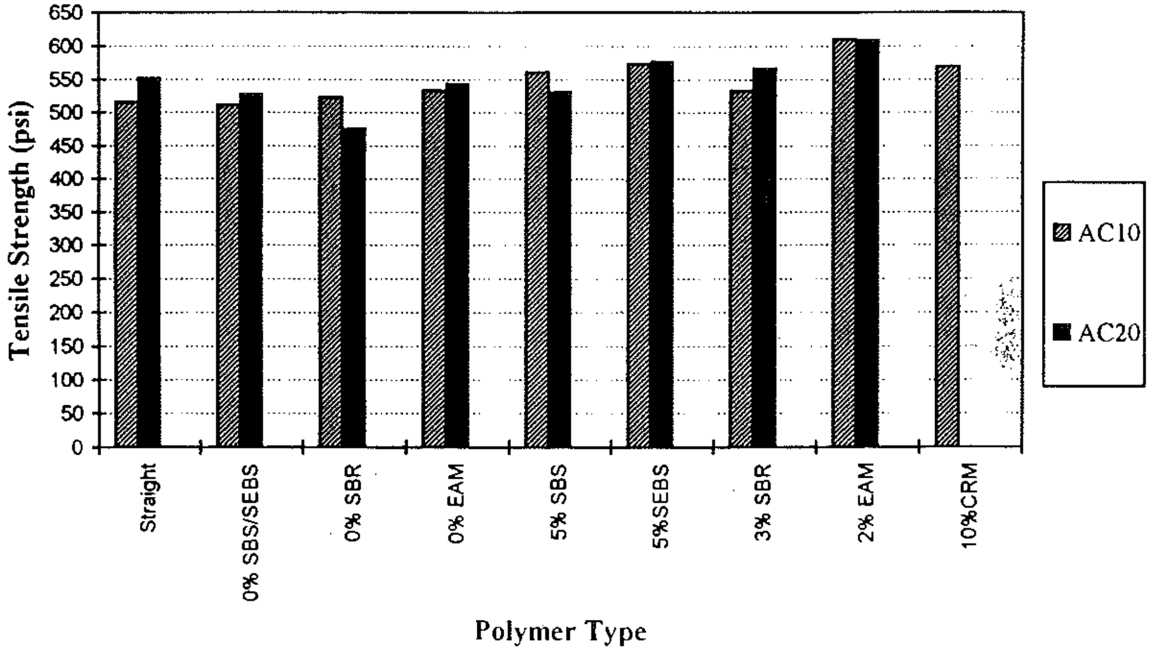
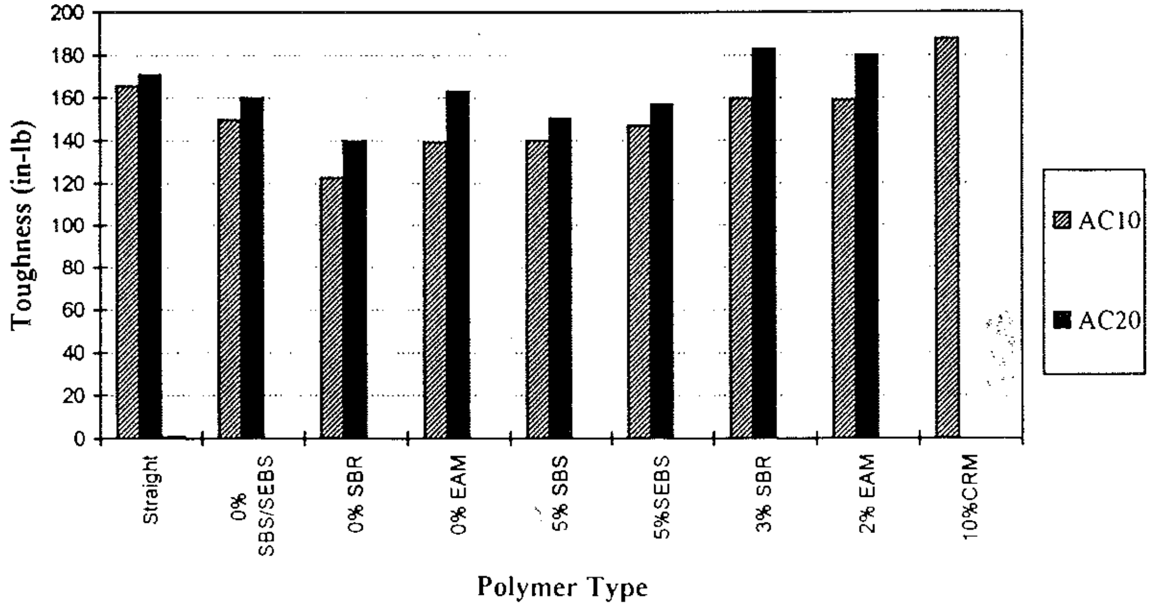


Figure III.24 Effect of polymer type on the vertical deformation and total modulus of oven aged PMA mixtures at 77° F.

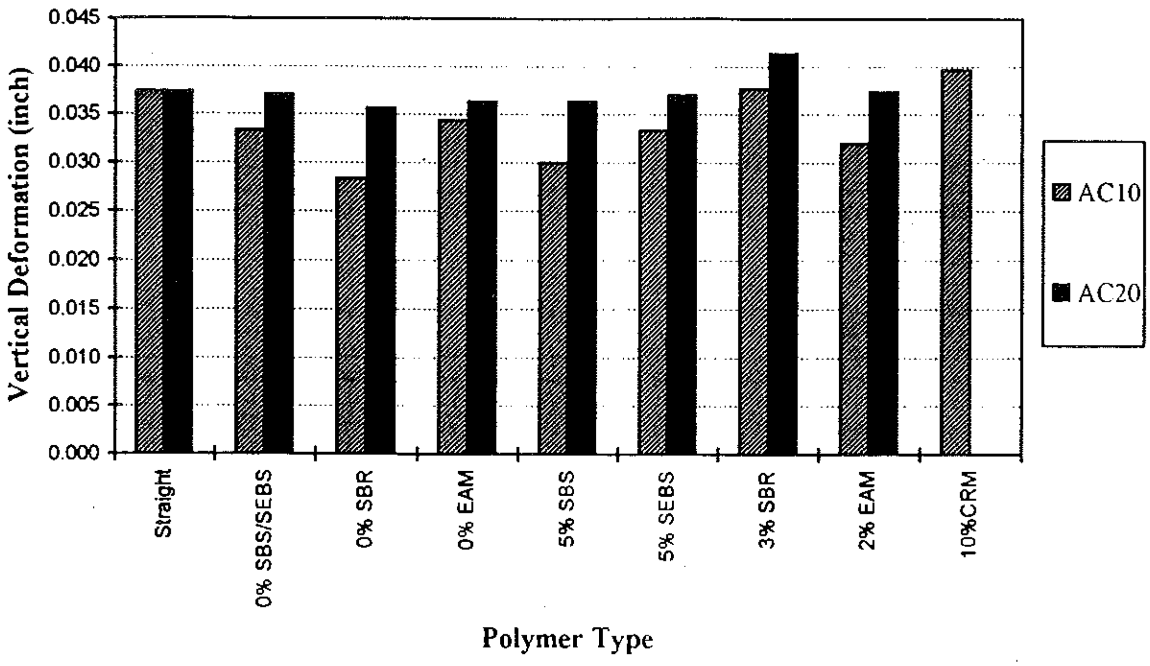


a) Indirect Tensile Strength

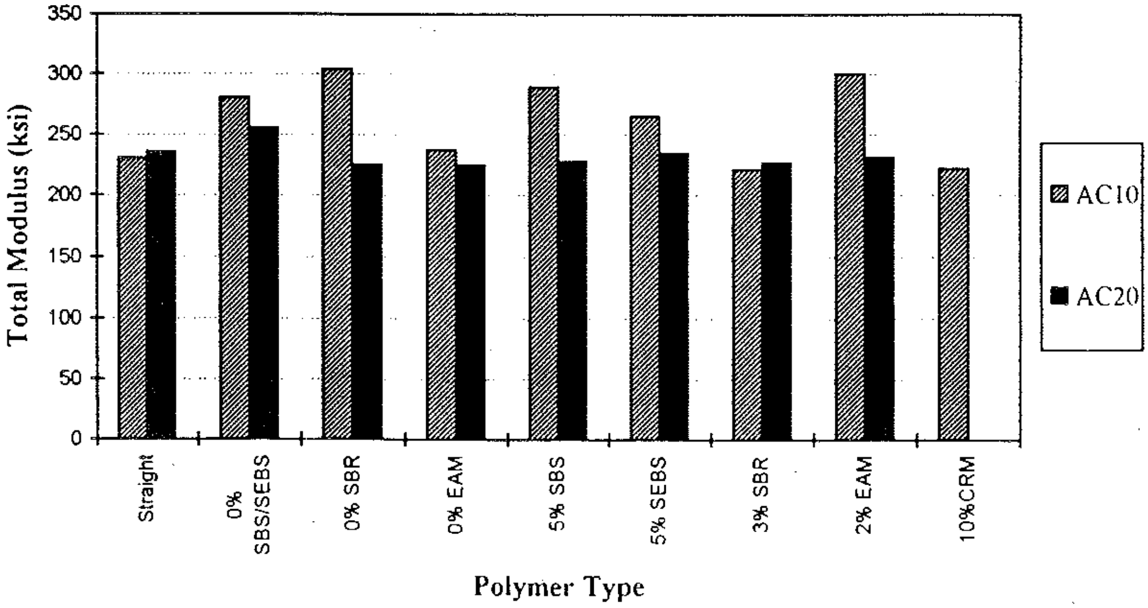


b) Fracture Toughness

Figure III.25 Effect of polymer type on the indirect tensile strength and toughness of PMA mixtures at 23° F.

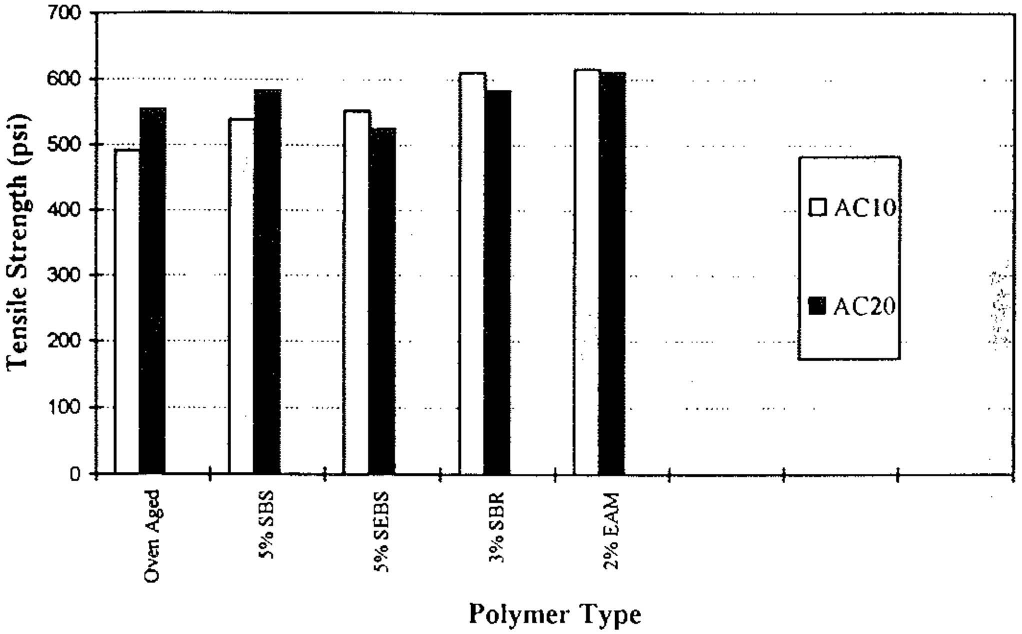


a) Vertical Deformation at Failure

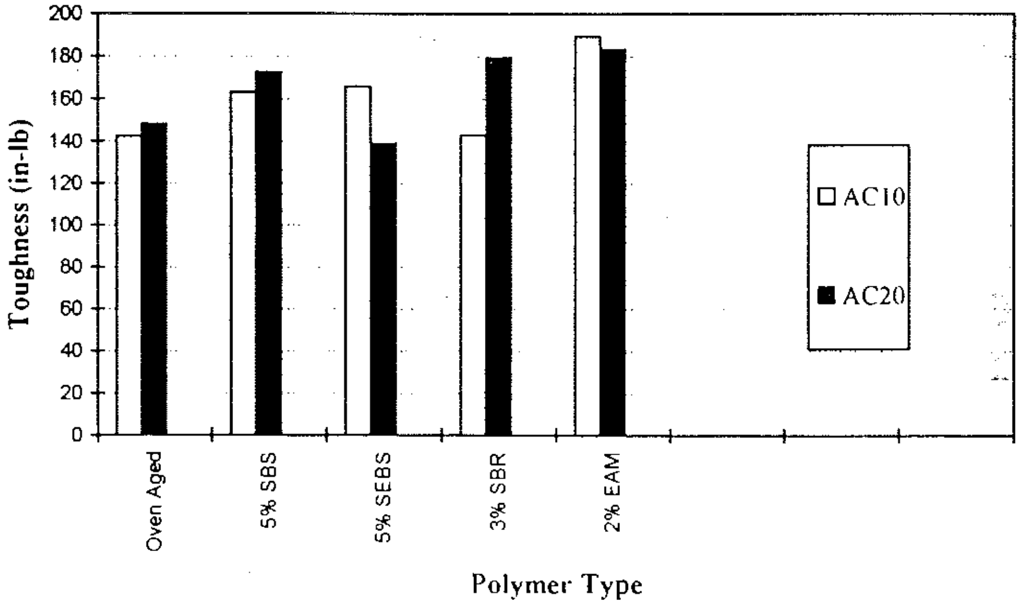


b) Total Modulus

Figure III.26 Effect of polymer type on the vertical deformation and total modulus of PMA mixtures at 23° F.

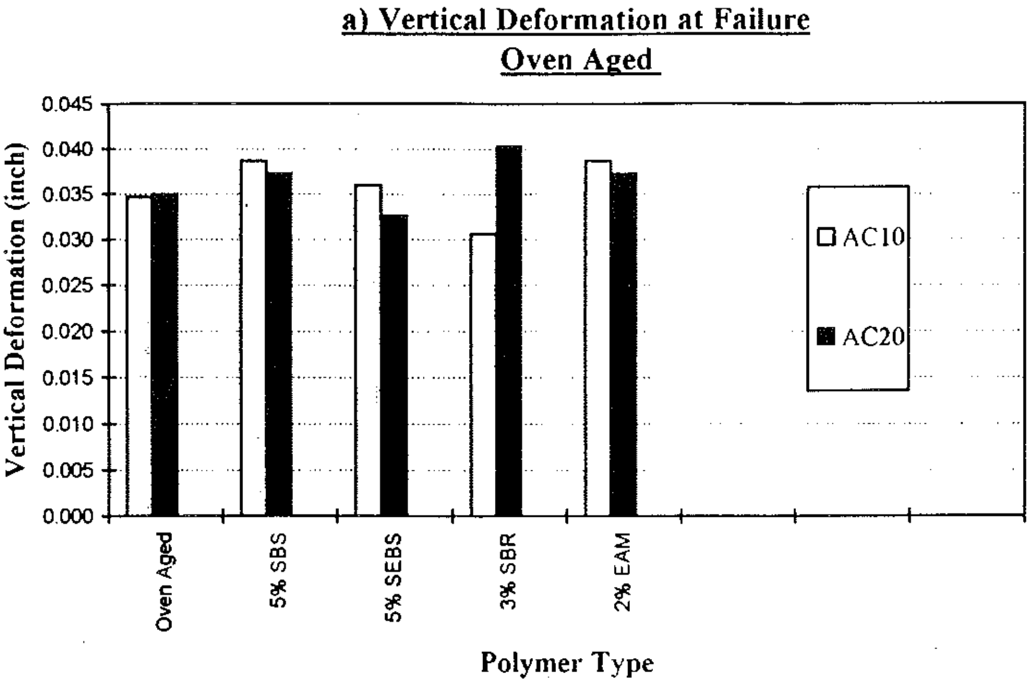


a) Indirect Tensile Strength
Oven Aged

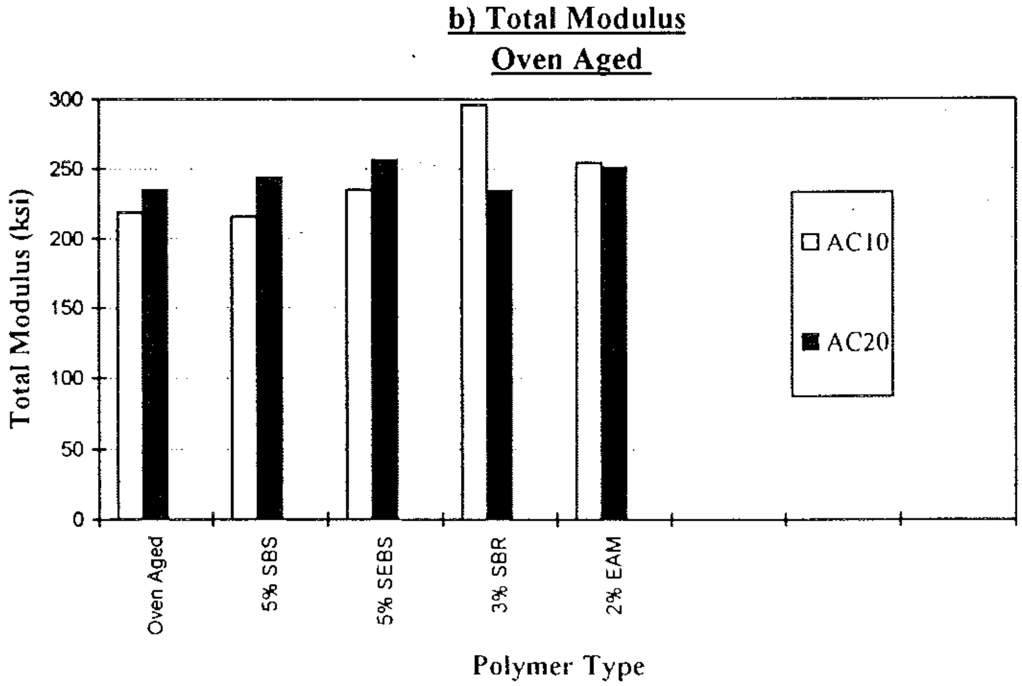


b) Fracture Toughness
Oven Aged

Figure III.27 Effect of polymer type on the indirect tensile strength and toughness of oven aged PMA mixtures at 23° F.



a) Vertical Deformation at Failure
Oven Aged



b) Total Modulus
Oven Aged

Figure III.28 Effect of polymer type on the vertical deformation and total modulus of oven aged PMA mixtures at 23° F.

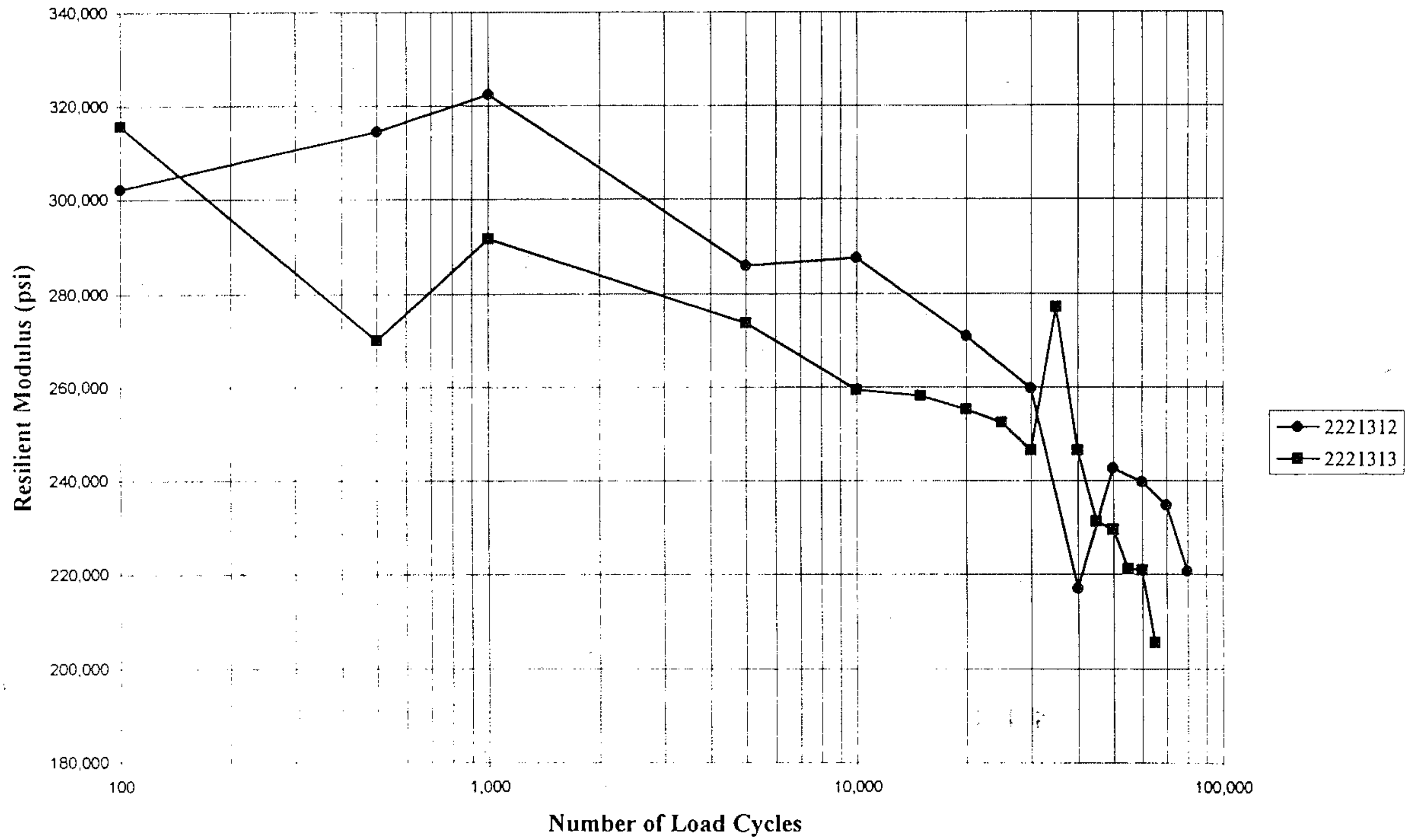


Figure III.29 Drop of resilient modulus with respect to number of load repetitions.

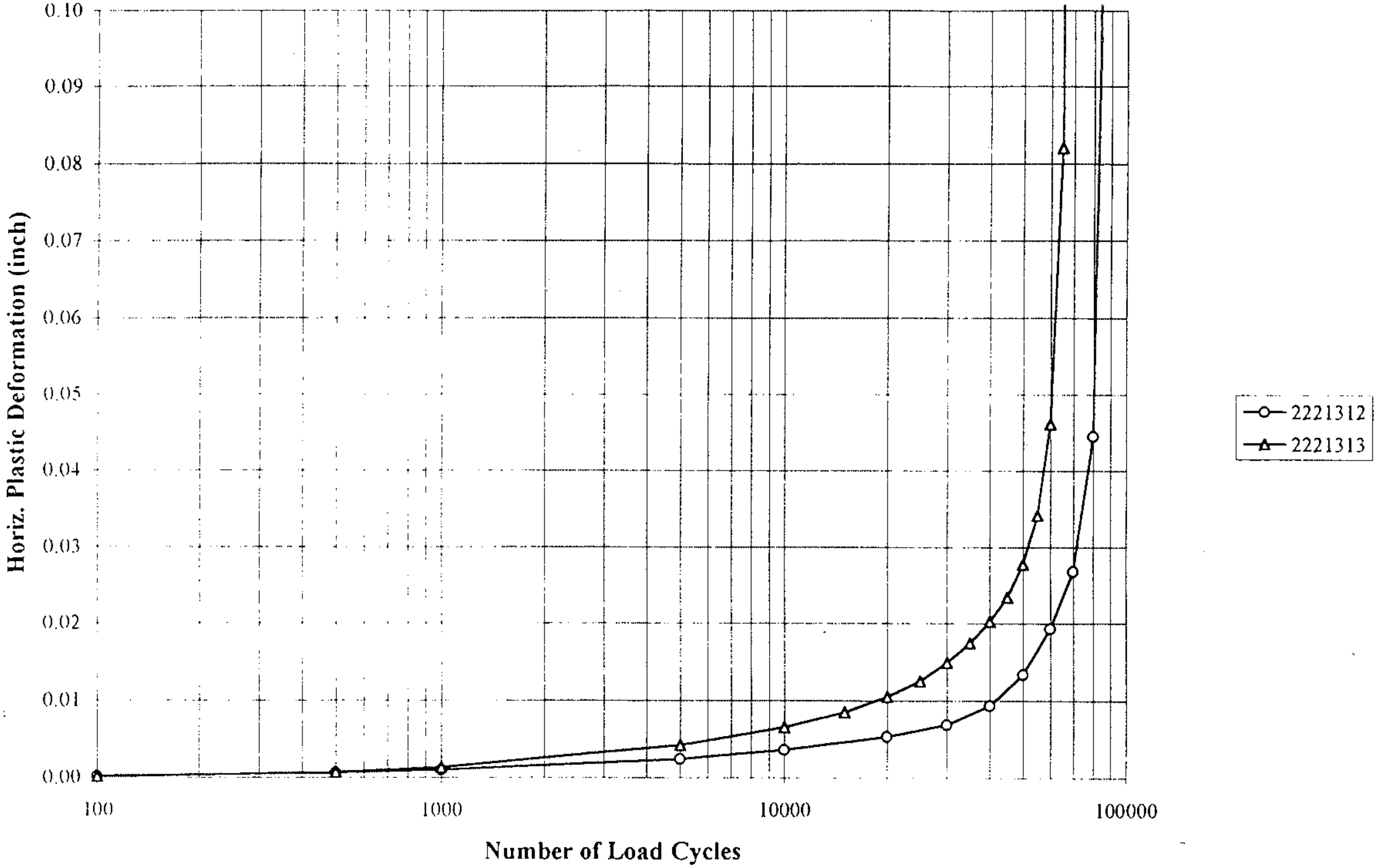


Figure III.30 Horizontal plastic deformation as a function of the number of load cycles to failure.

Figure III.29-33 Chart 2

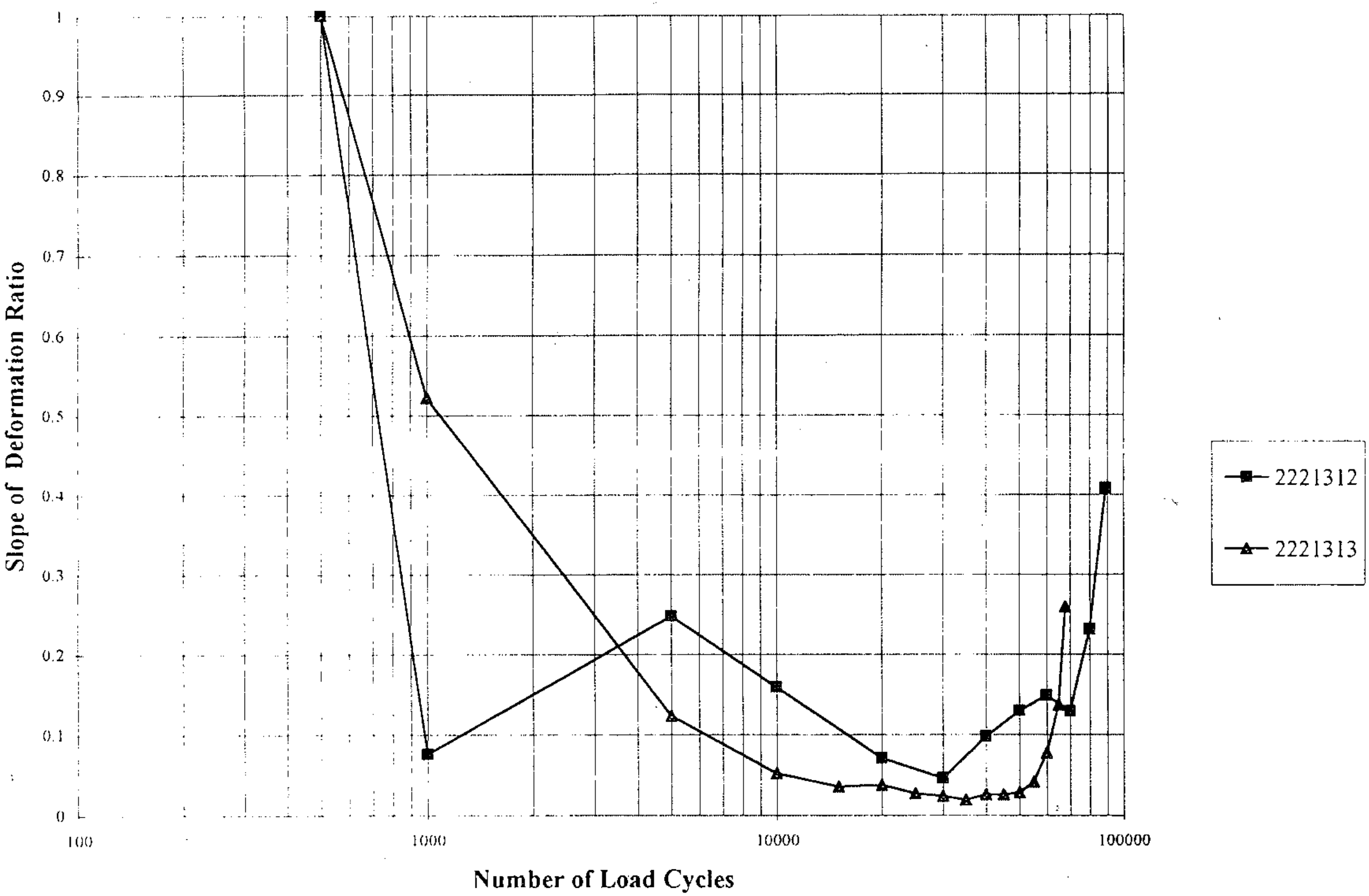


Figure III.31 The slope of the deformation ratio versus number of load cycles to failure.

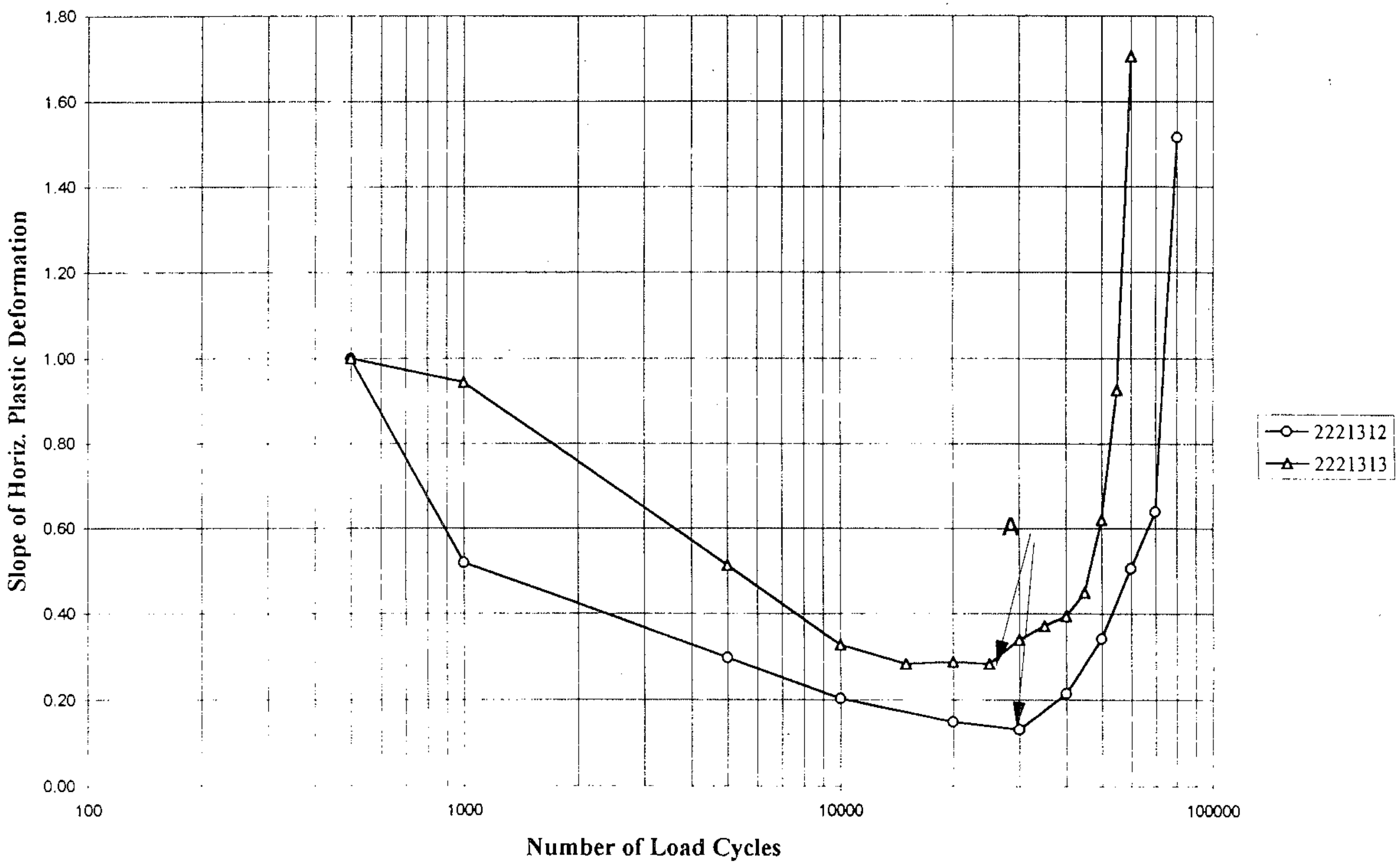


Figure III.32 Slope of horizontal plastic deformation as a function of number of load cycles to failure.

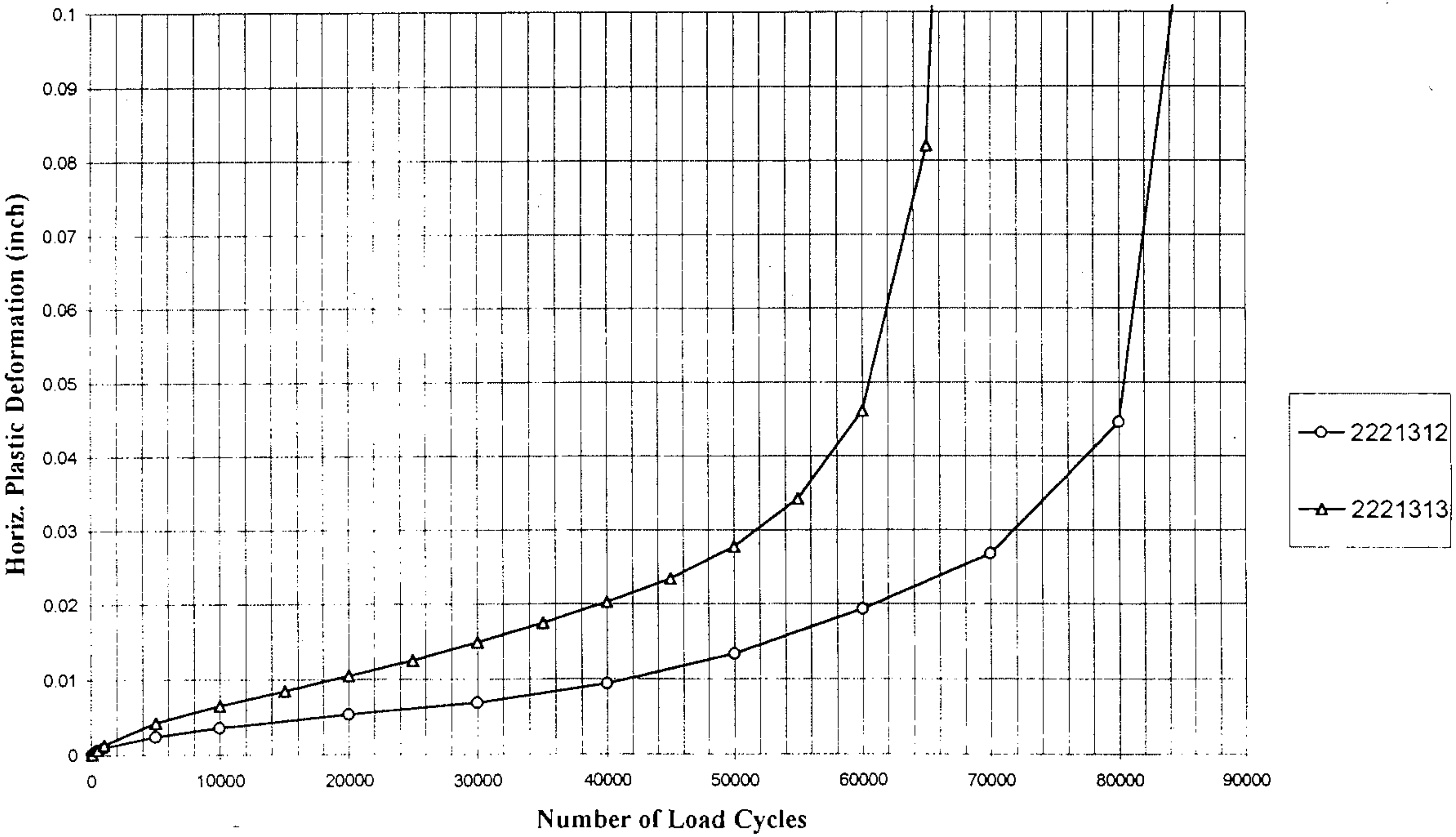


Figure III.33 Horizontal plastic deformation as a function of number of load cycles to failure.

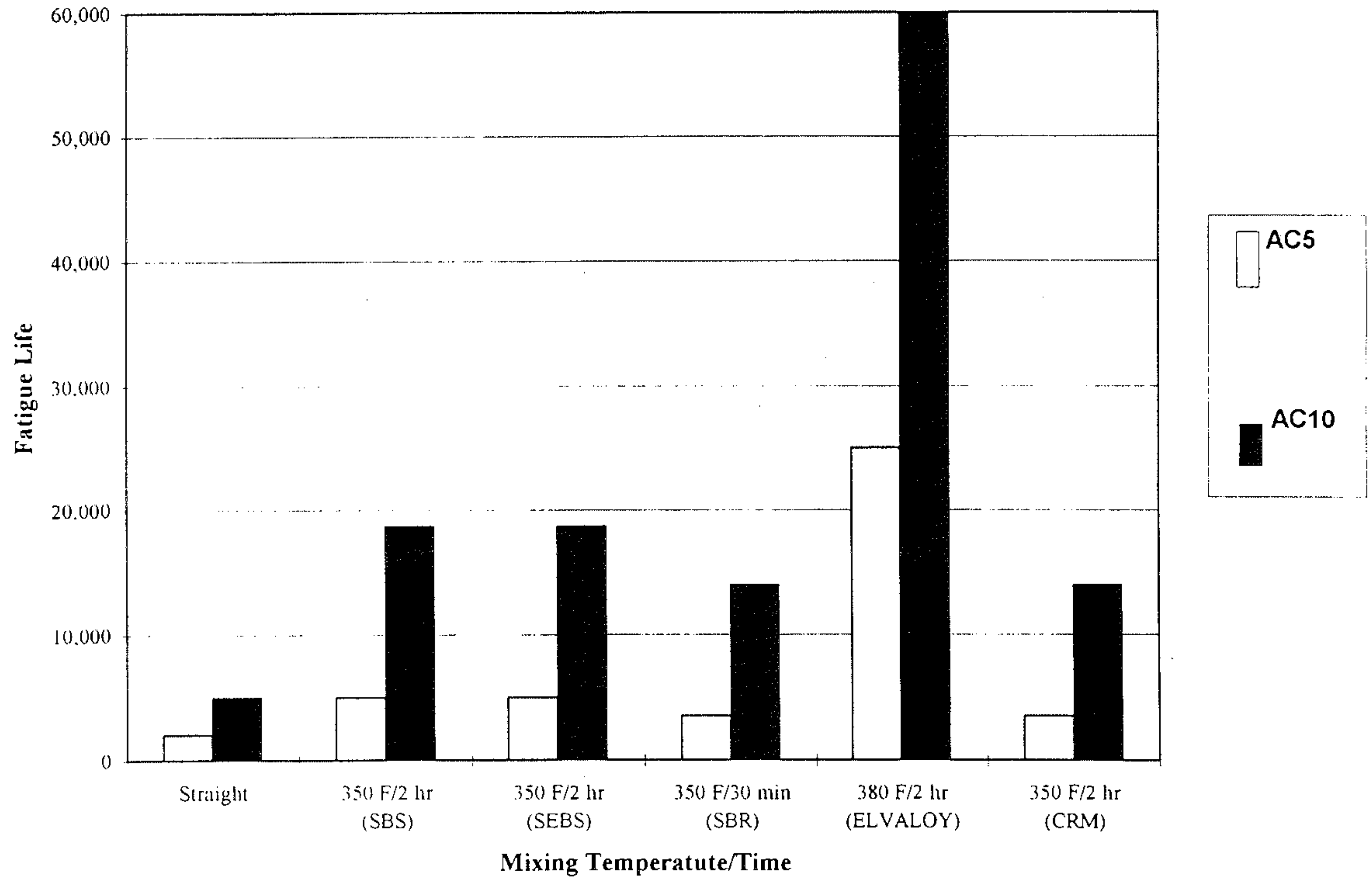


Figure III.34: Effect of mixing temperature and time on the fatigue life of AC[illegible] mixtures at test temperature of 77°F

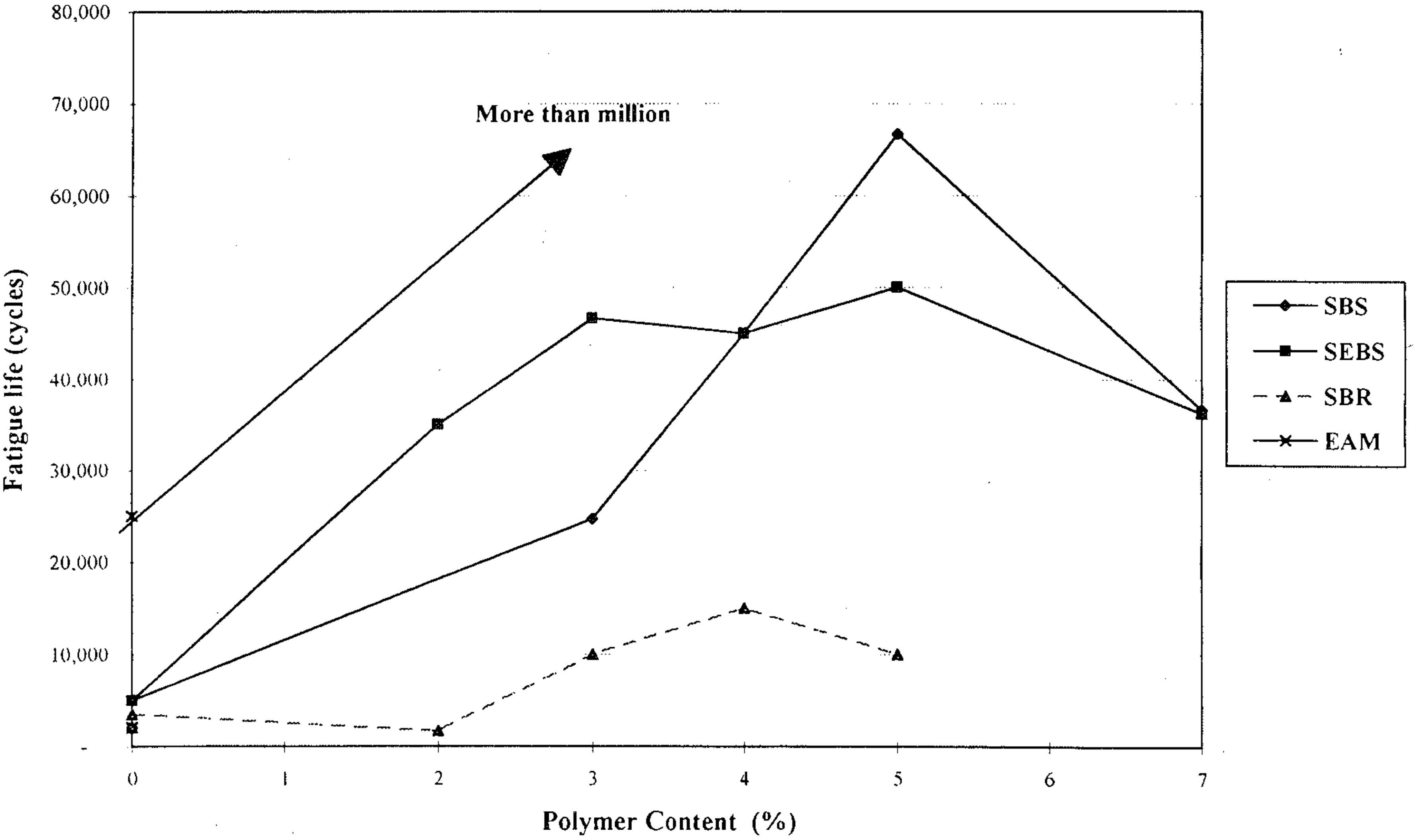


Figure III.35 Effect of polymer content on the fatigue life of AC5 PMA mixture at the test temperature of 77° F

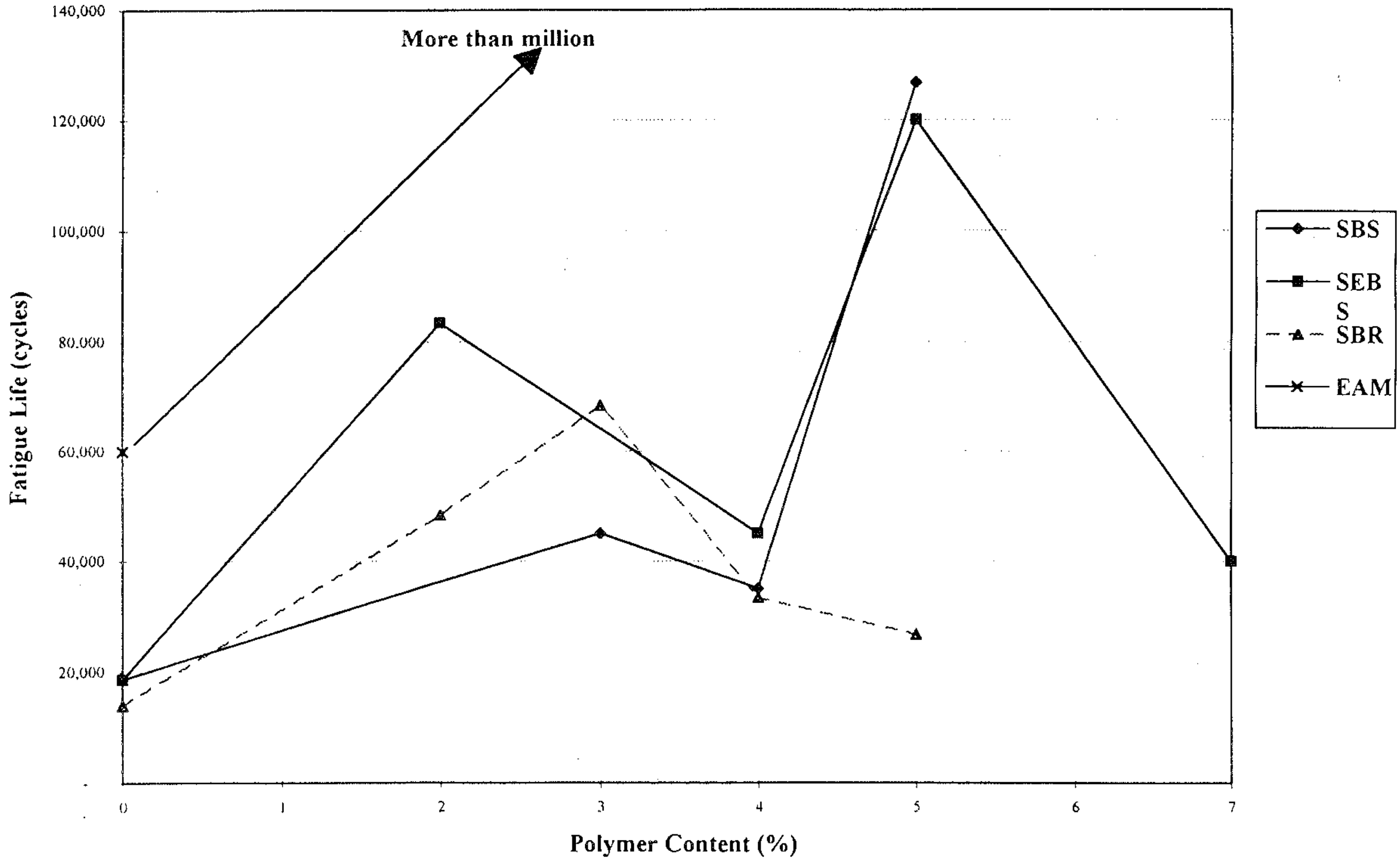


Figure III.36 Effect of polymer content on the fatigue life of AC10 PMA mixtures at test temperature of 77° F.

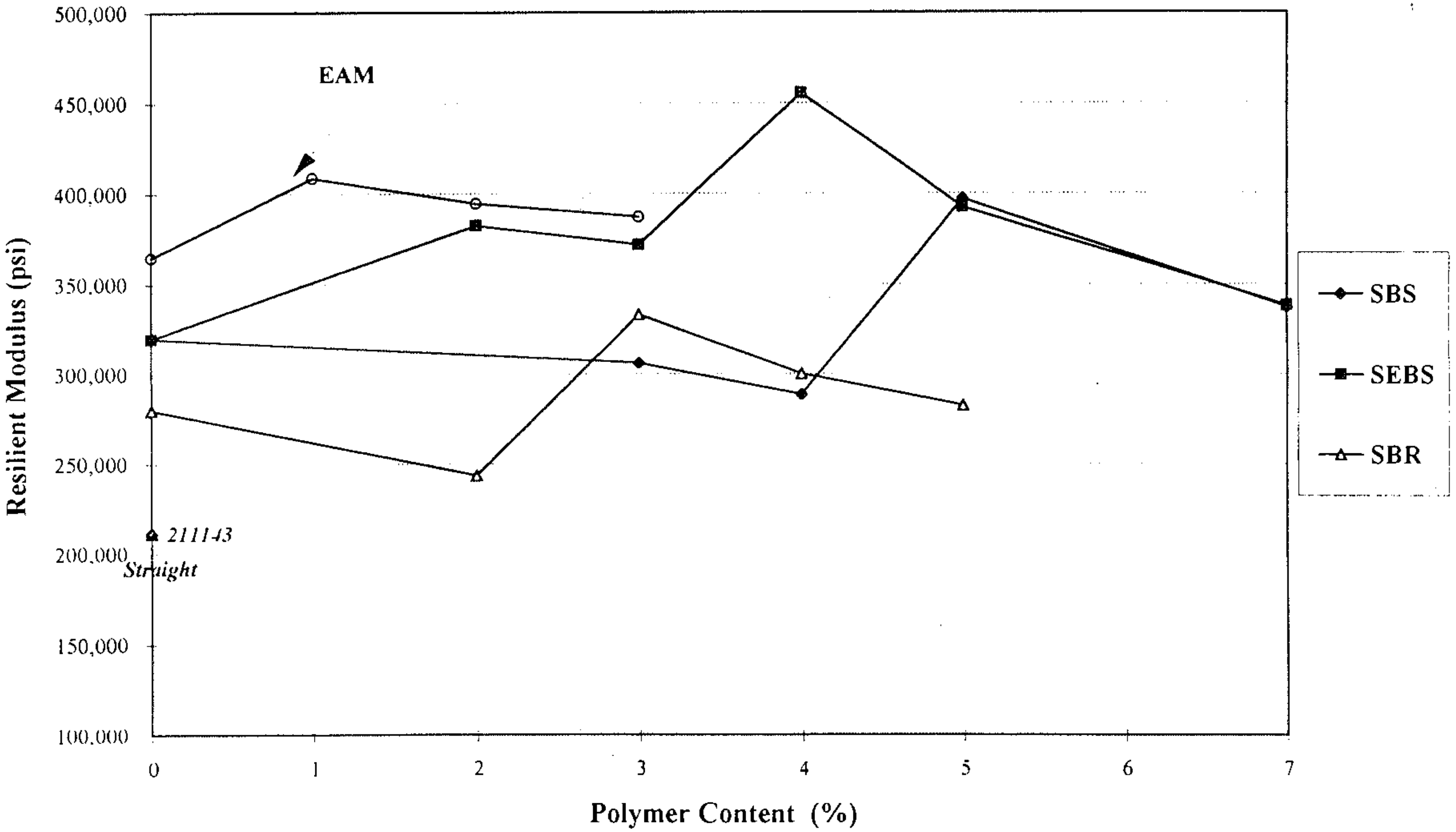


Figure III.37 Effect of polymer content on the resilient modulus of AC5 PMA mixtures at the test temperature of 77° F.

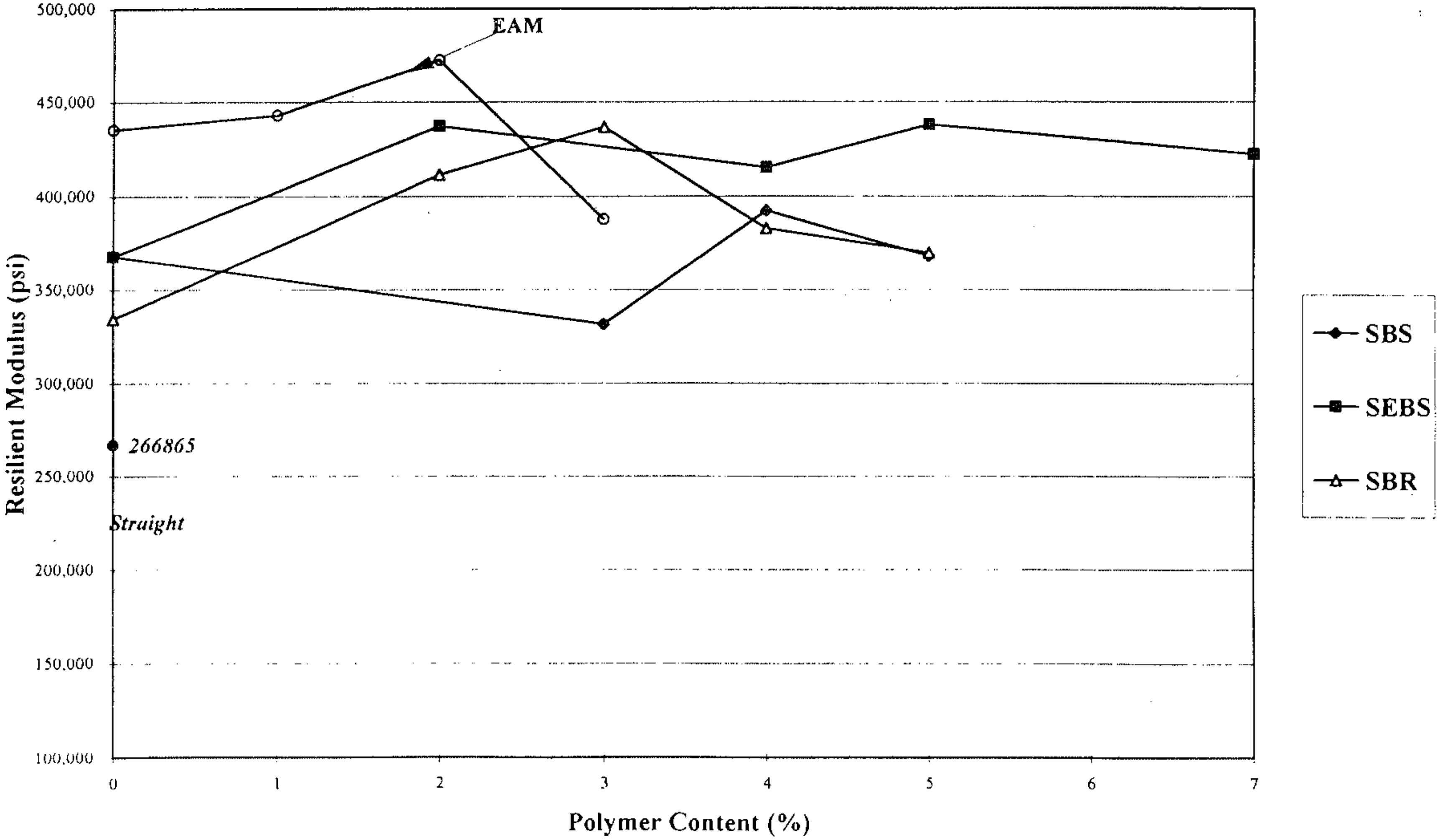
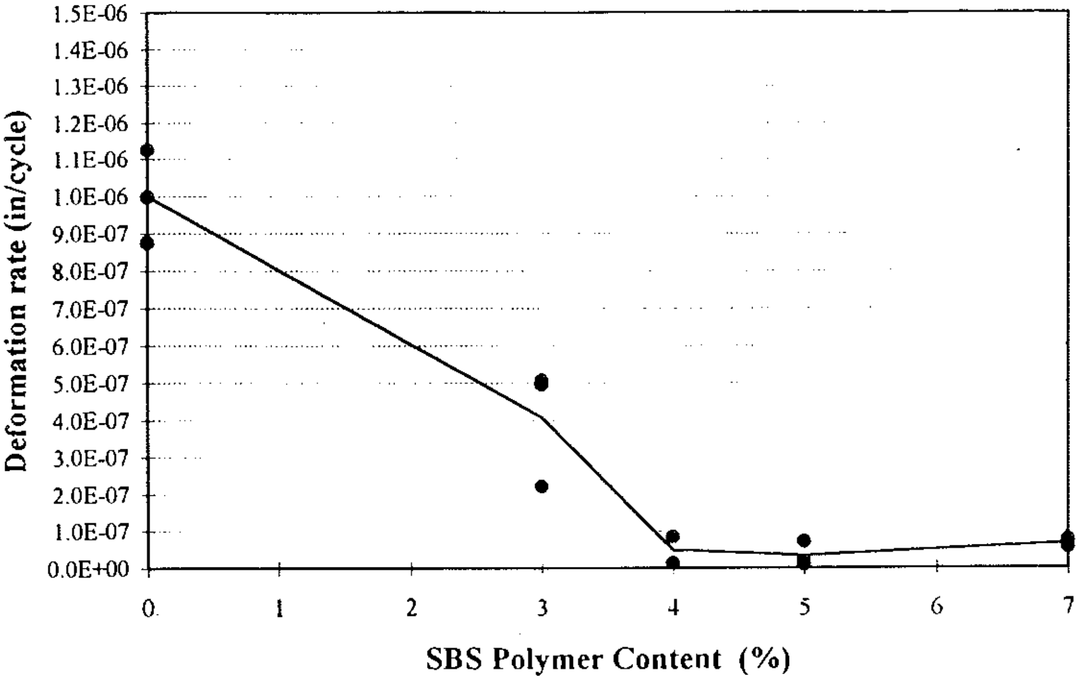


Figure III.38 Effect of polymer content on the resilient modulus of AC10 PMA mixtures at the test temperature of 77° F.



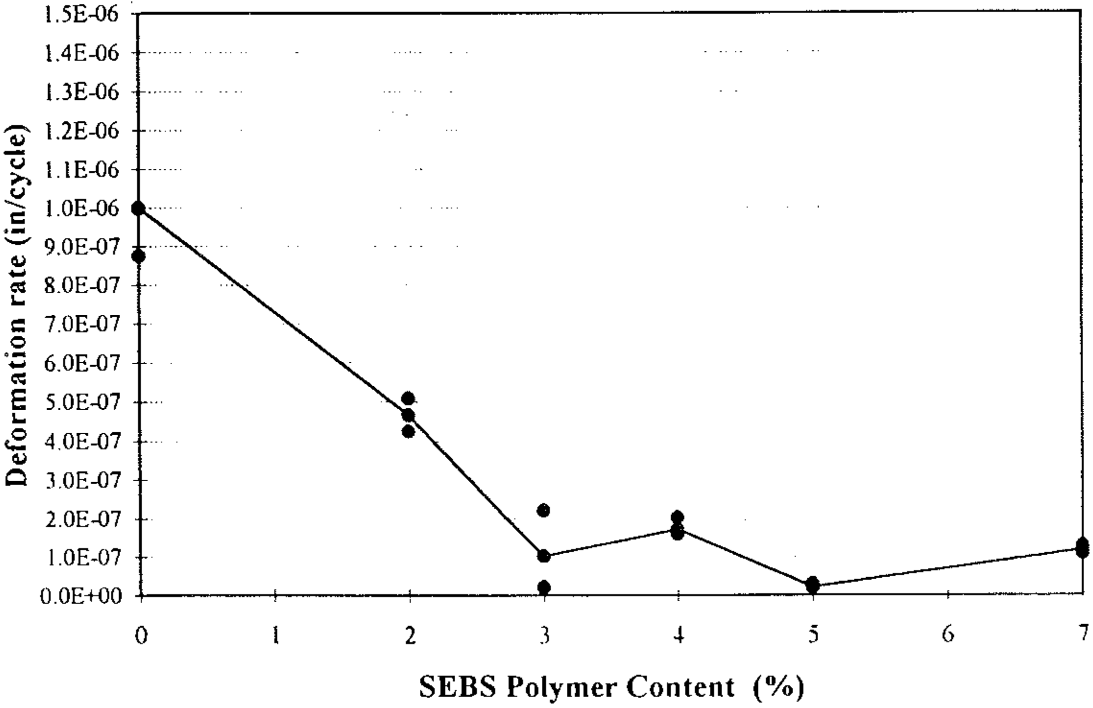
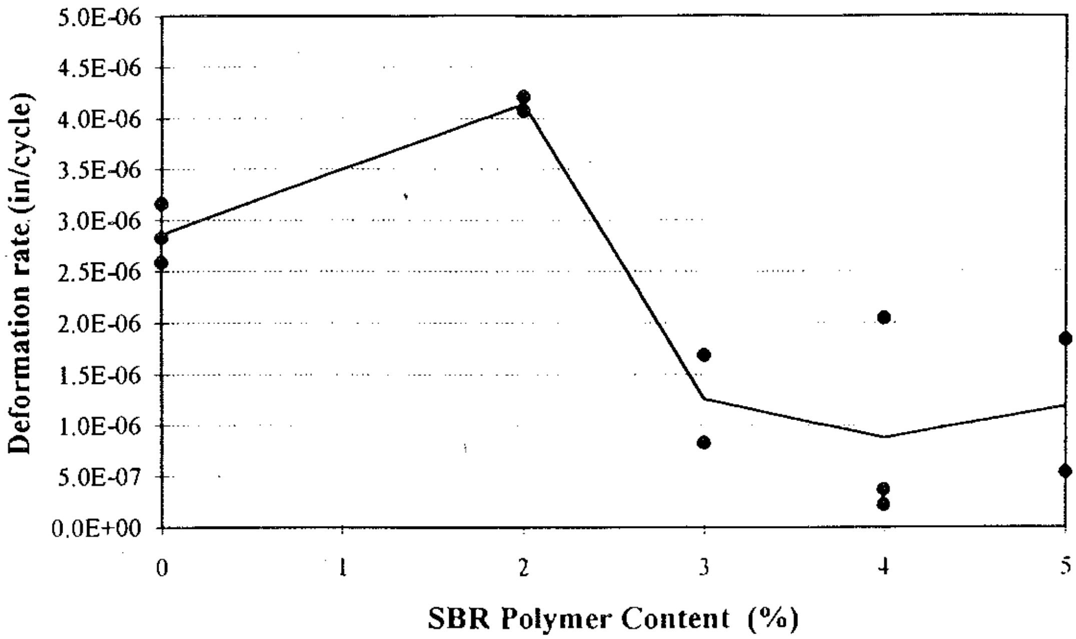


Figure III.39 Effect of polymer content on the deformation rate of AC5 mixtures modified with SBS and SEBS polymers at test temperature of 77° F.



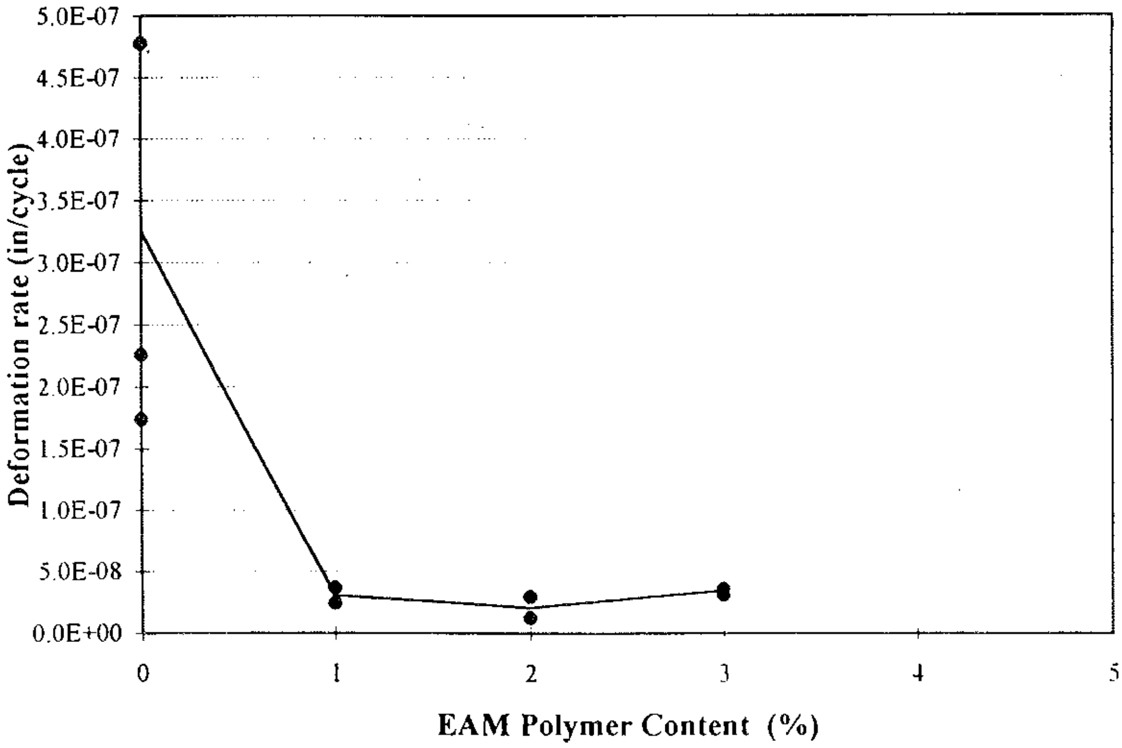
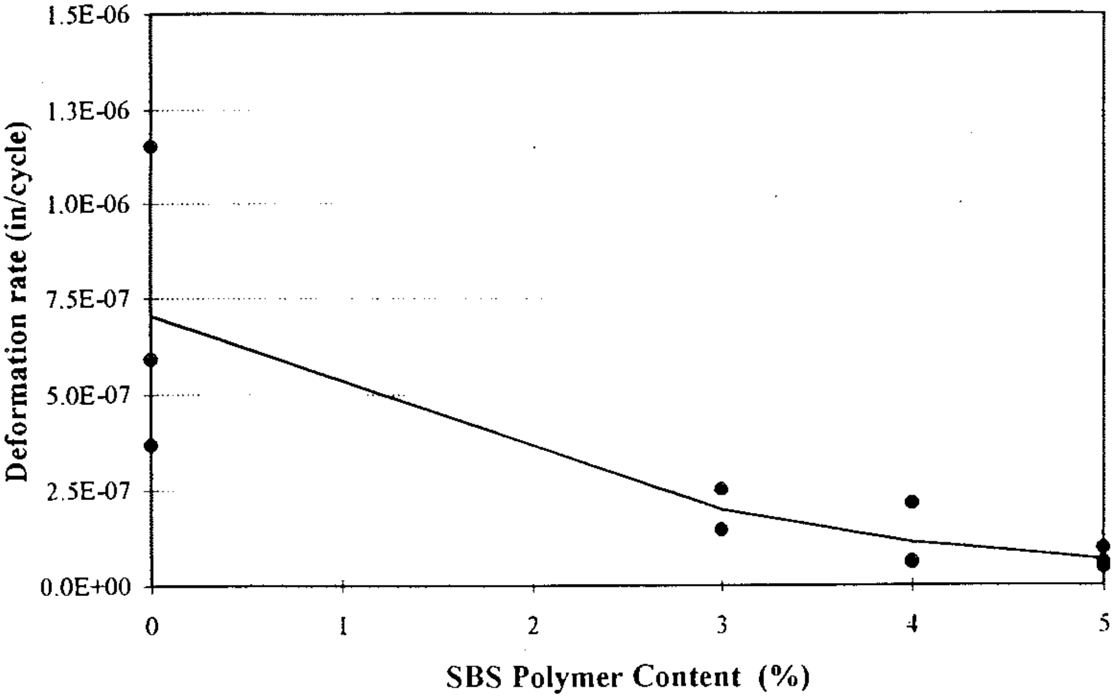


Figure III.40 Effect of polymer content on the deformation rate of AC5 mixtures modified with SBR and EAM polymers at test temperature of 77° F.



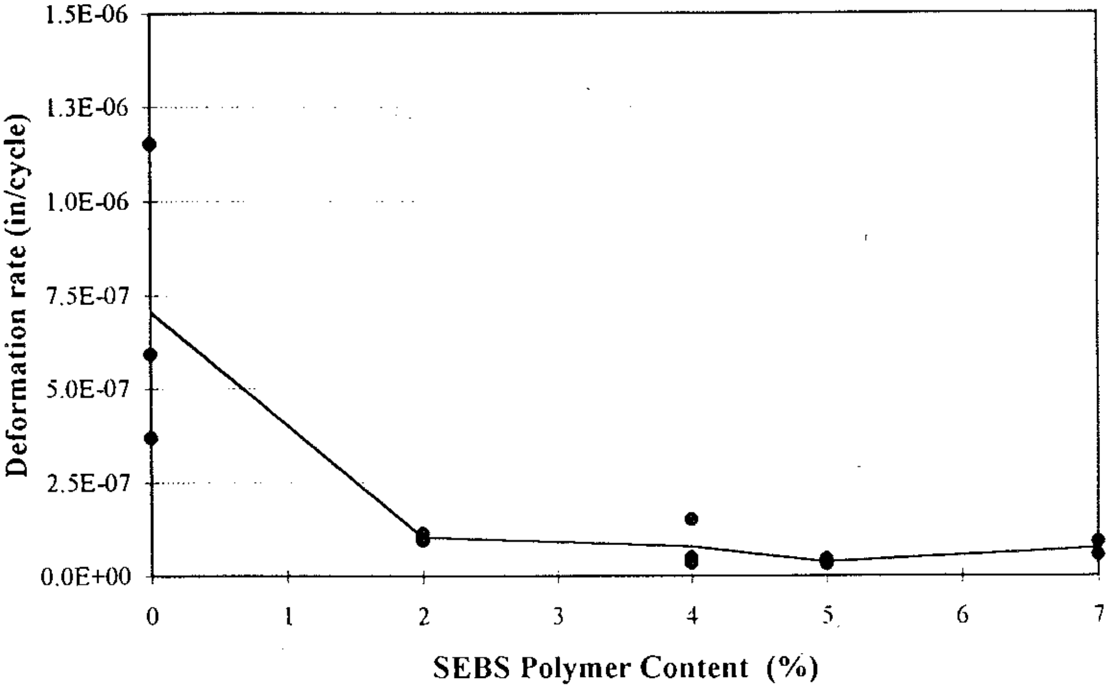
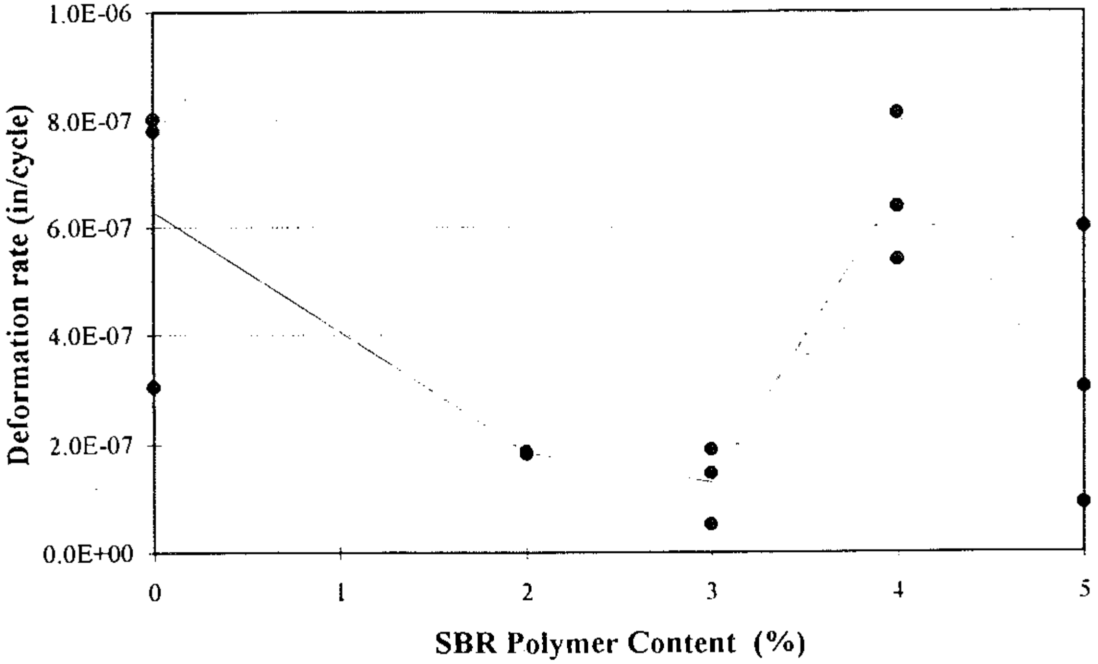


Figure III.41 Effect of polymer content on the deformation rate of AC10 mixtures modified with SBS and SEBS polymers at test temperature of 77° F.



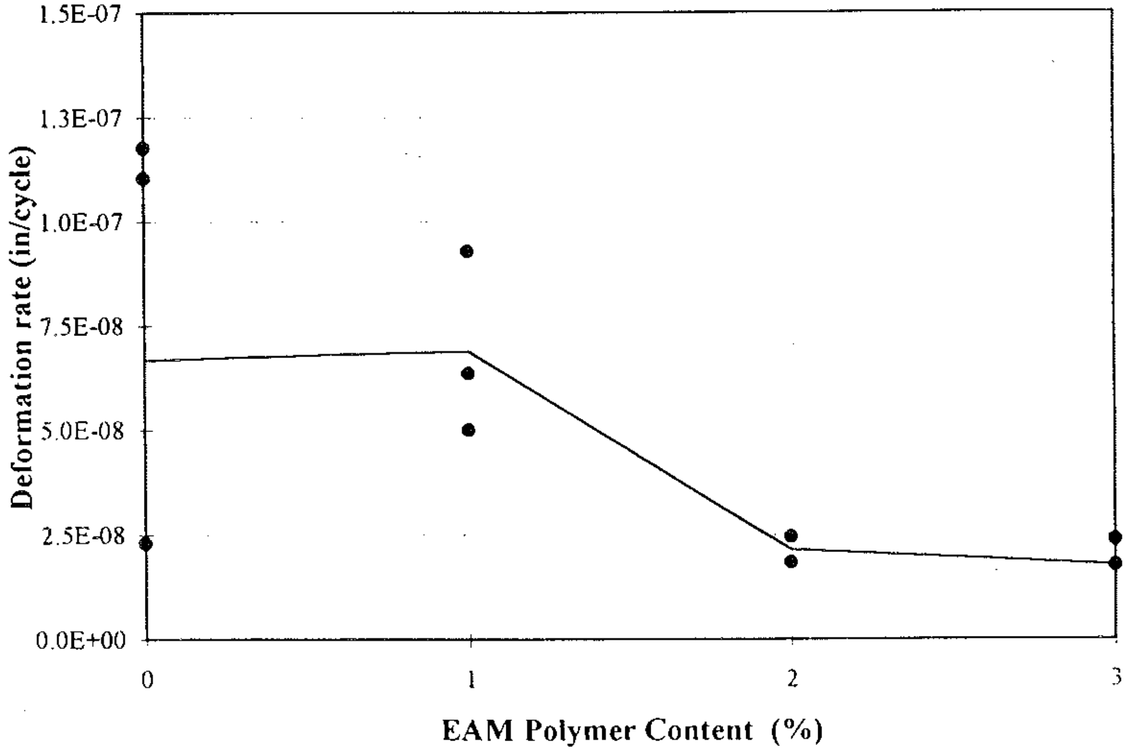
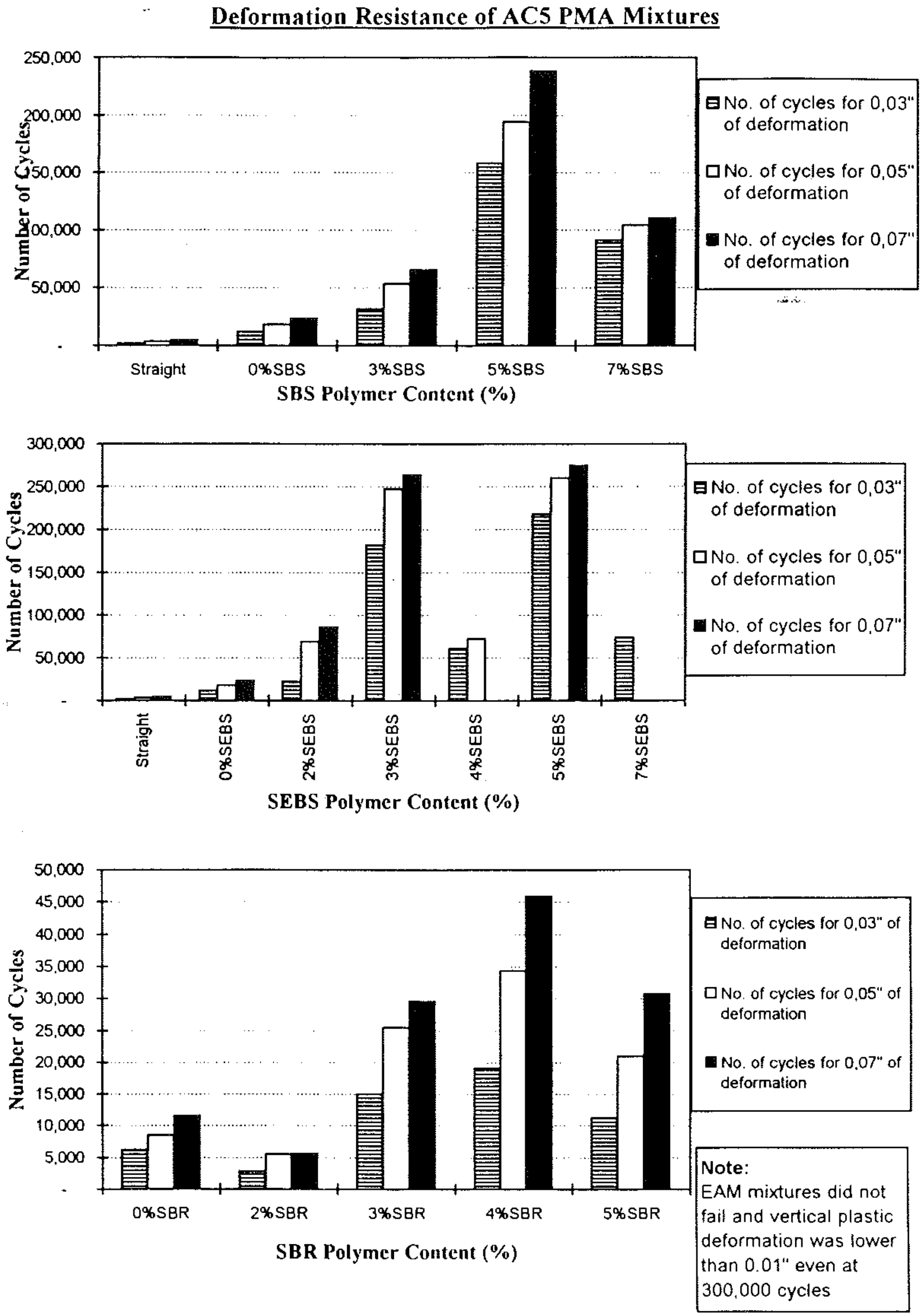
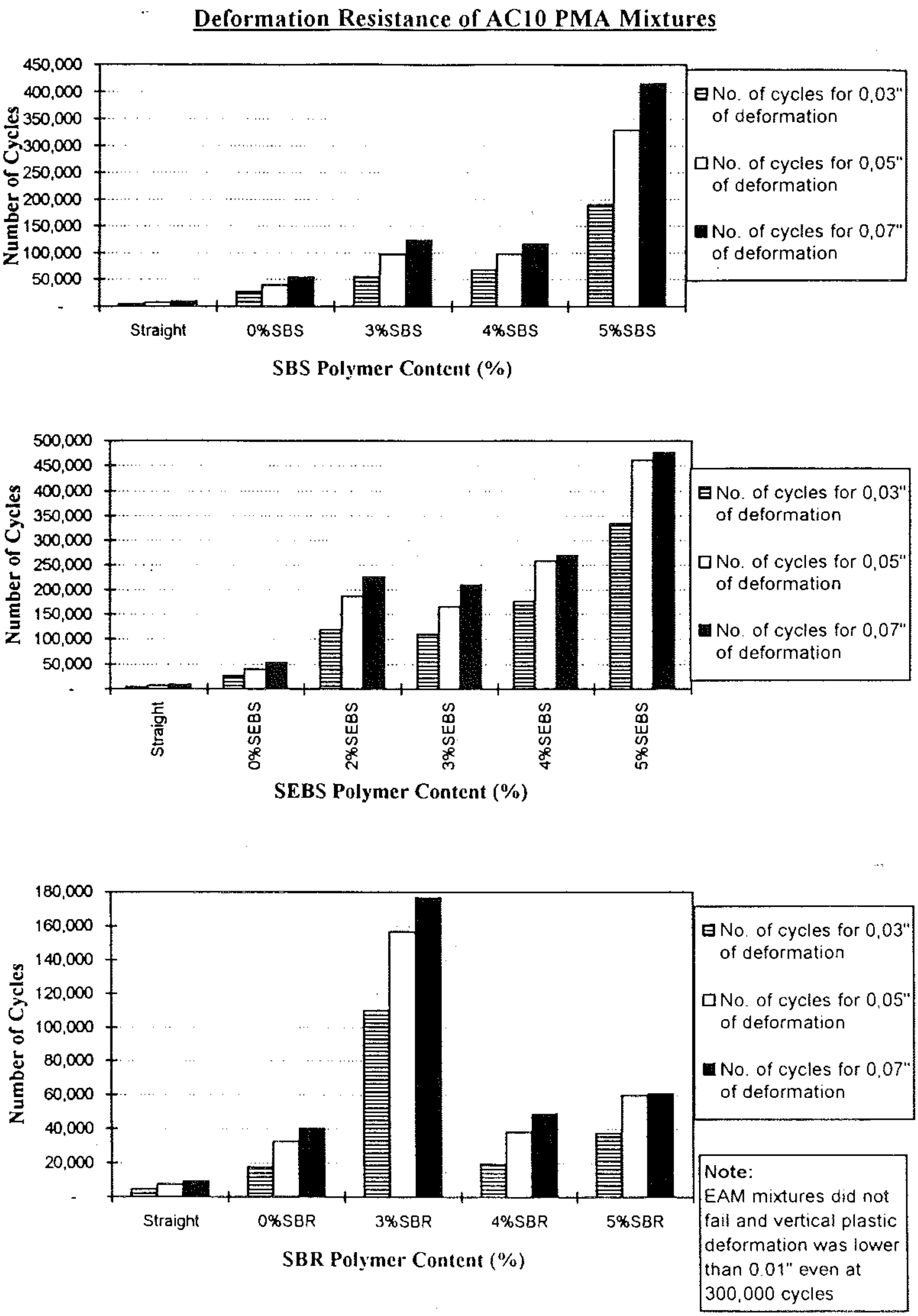


Figure III.42 Effect of polymer content on the deformation rate of AC10 mixtures modified with SBR and EAM polymers at test temperature of 77° F.



Note:
EAM mixtures did not fail and vertical plastic deformation was lower than 0.01" even at 300,000 cycles

Figure III.43 Effect of polymer content on the deformation resistance of AC5 PMA mixtures at the test temeprature of 77° F.



Note:
EAM mixtures did not fail and vertical plastic deformation was lower than 0.01" even at 300,000 cycles

Figure III.44 Effect of polymer content on the deformation resistance of AC10 PMA mixtures at the test temeprature of 77° F.

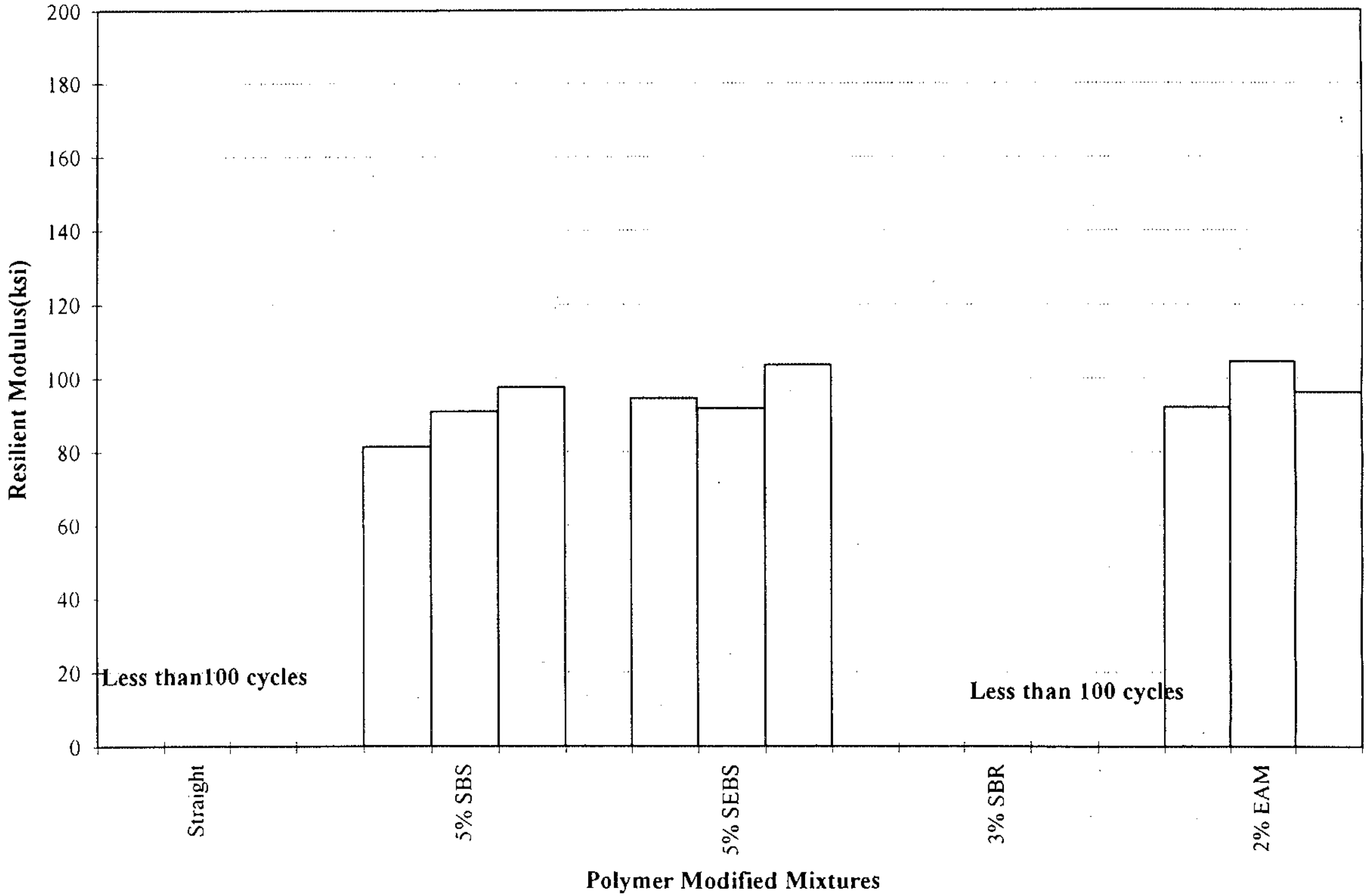


Figure III.45 Effect of polymers on the resilient modulus of AC10 polymer modified asphalt mixtures at 140°F (60°C).

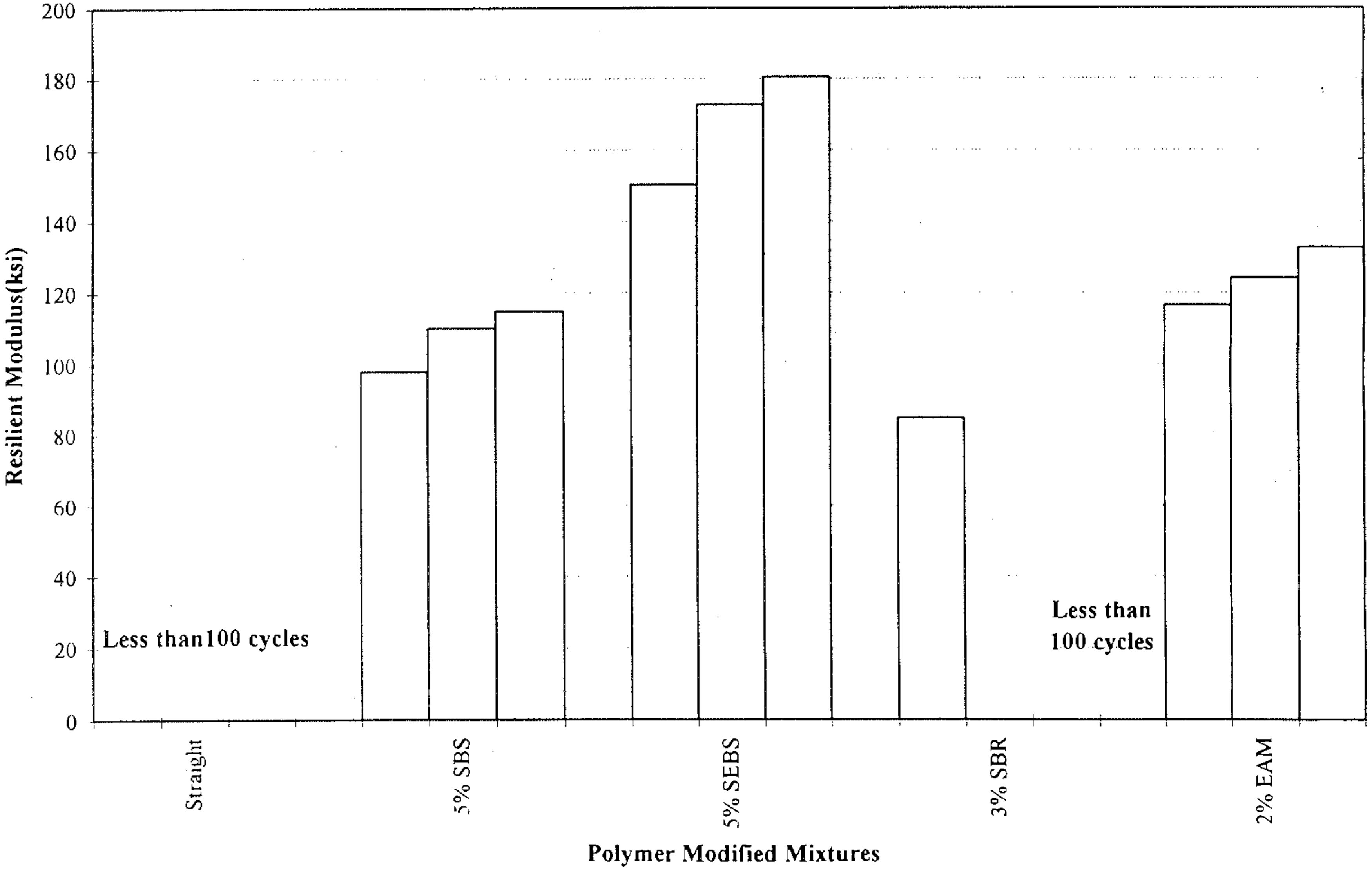


Figure III.46 Effect of oven aging on the resilint modulus of polymer modified asphalt mixtures at 140°F (60°C)

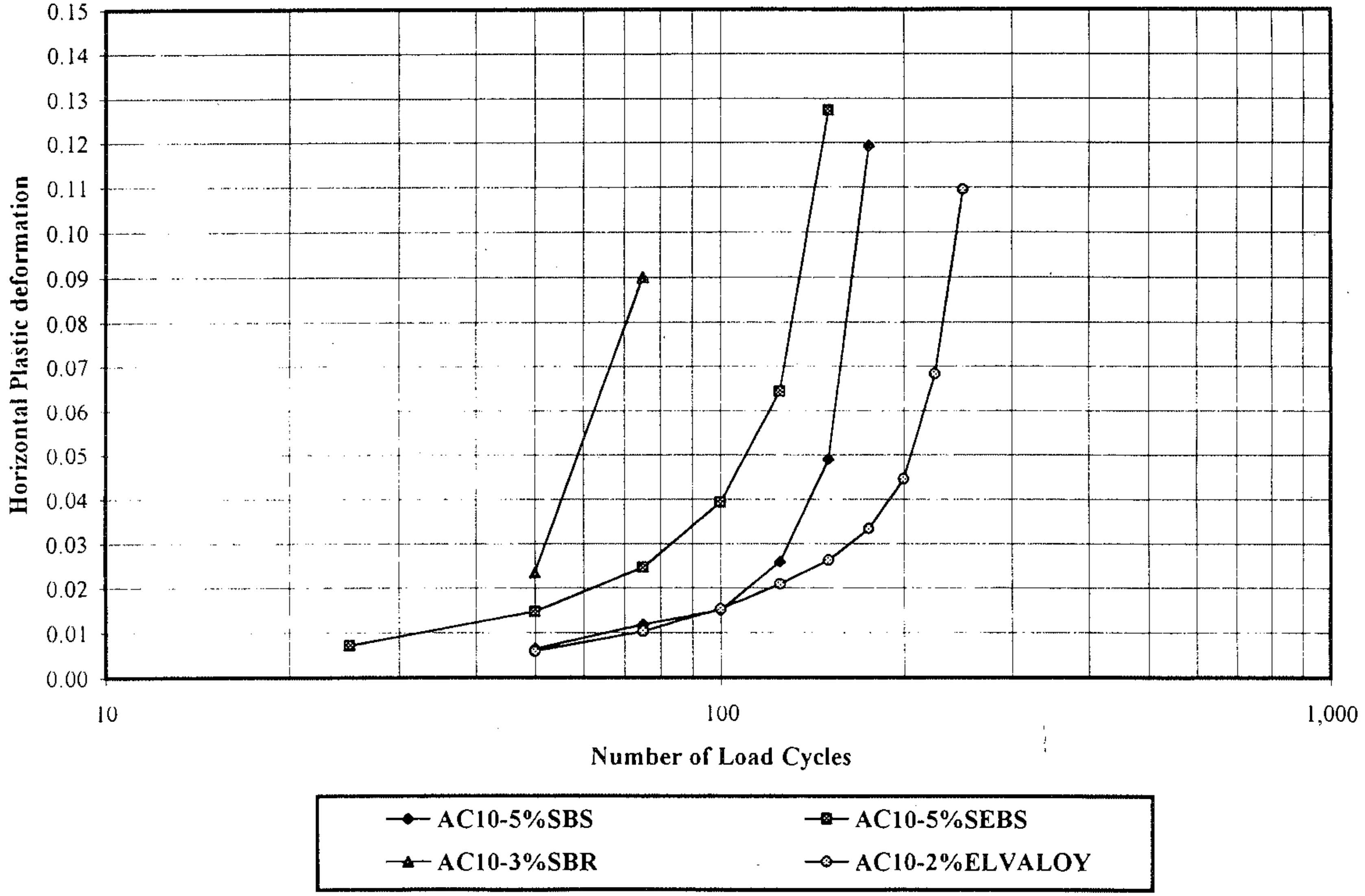


Figure III.47. Horizontal plastic deformation versus number of load repetitions for AC10-polymer modified asphalt mixtures at 140 F.

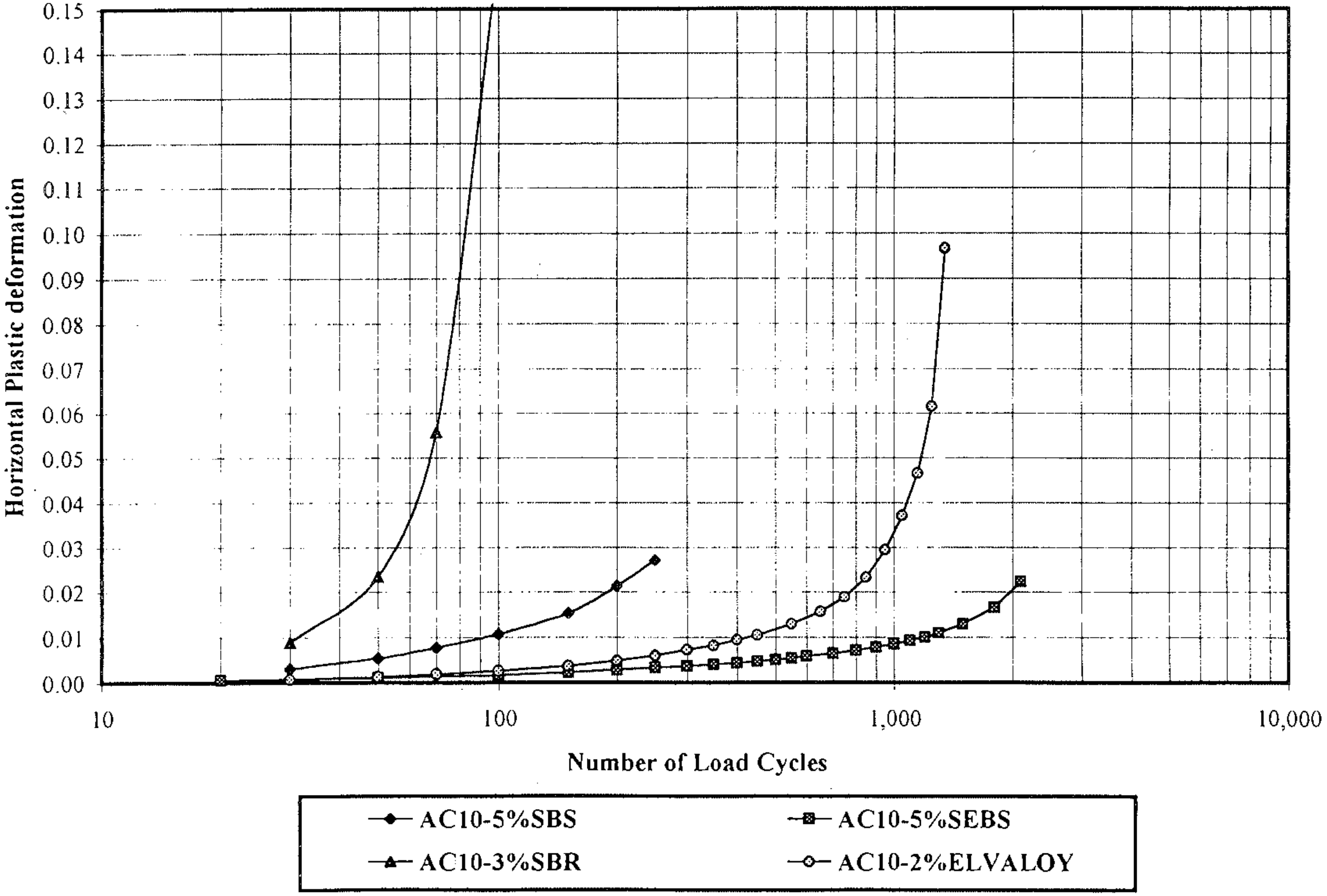


Figure III.48 Horizontal plastic deformation versus number of load repetitions of oven aged AC10 polymer modified asphalt mixtures at 140 F

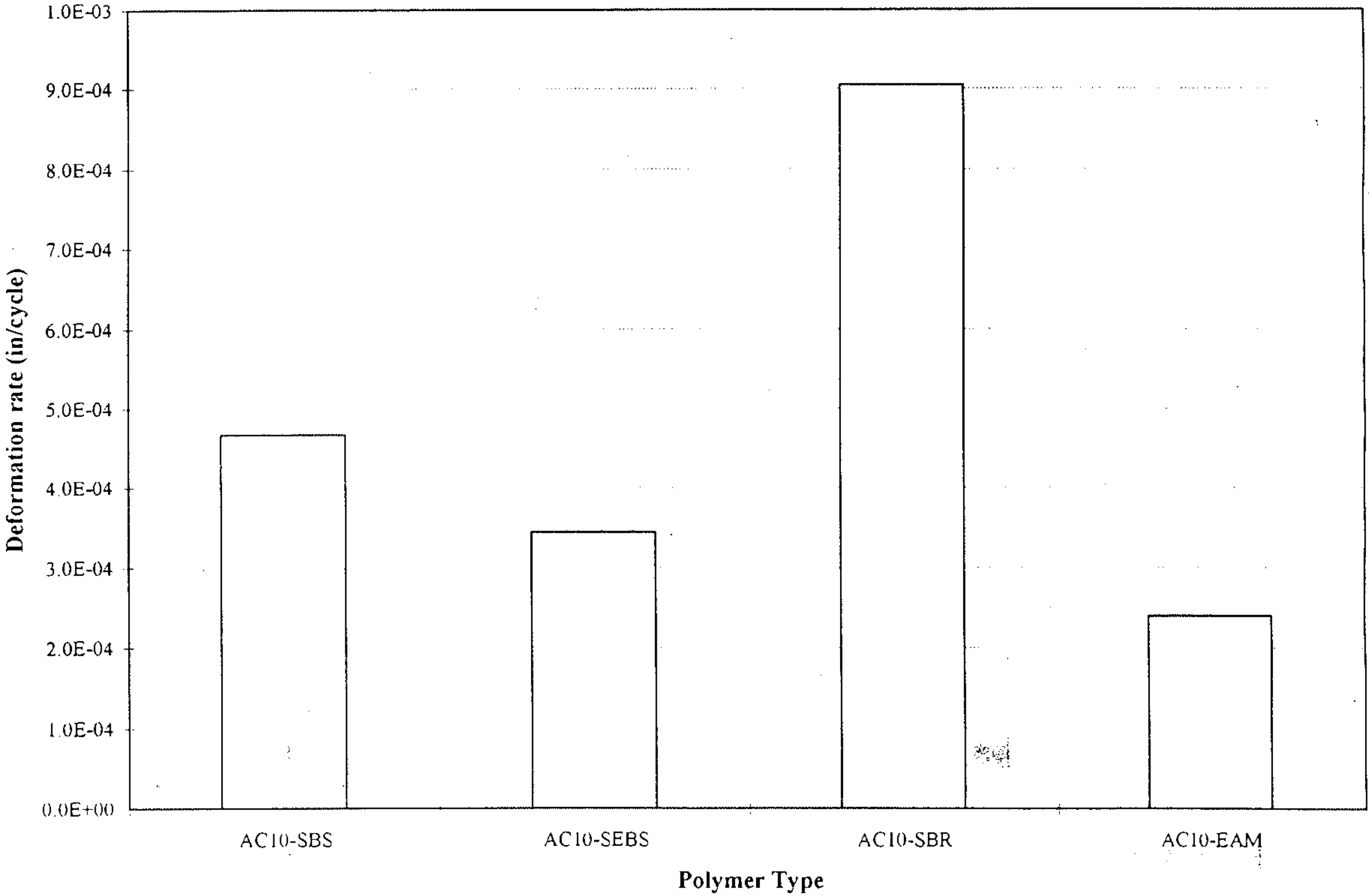


Figure III.49 Effect of polymer on the deformation rate of AC10 polymer modified asphalt mixtures at 140 °F

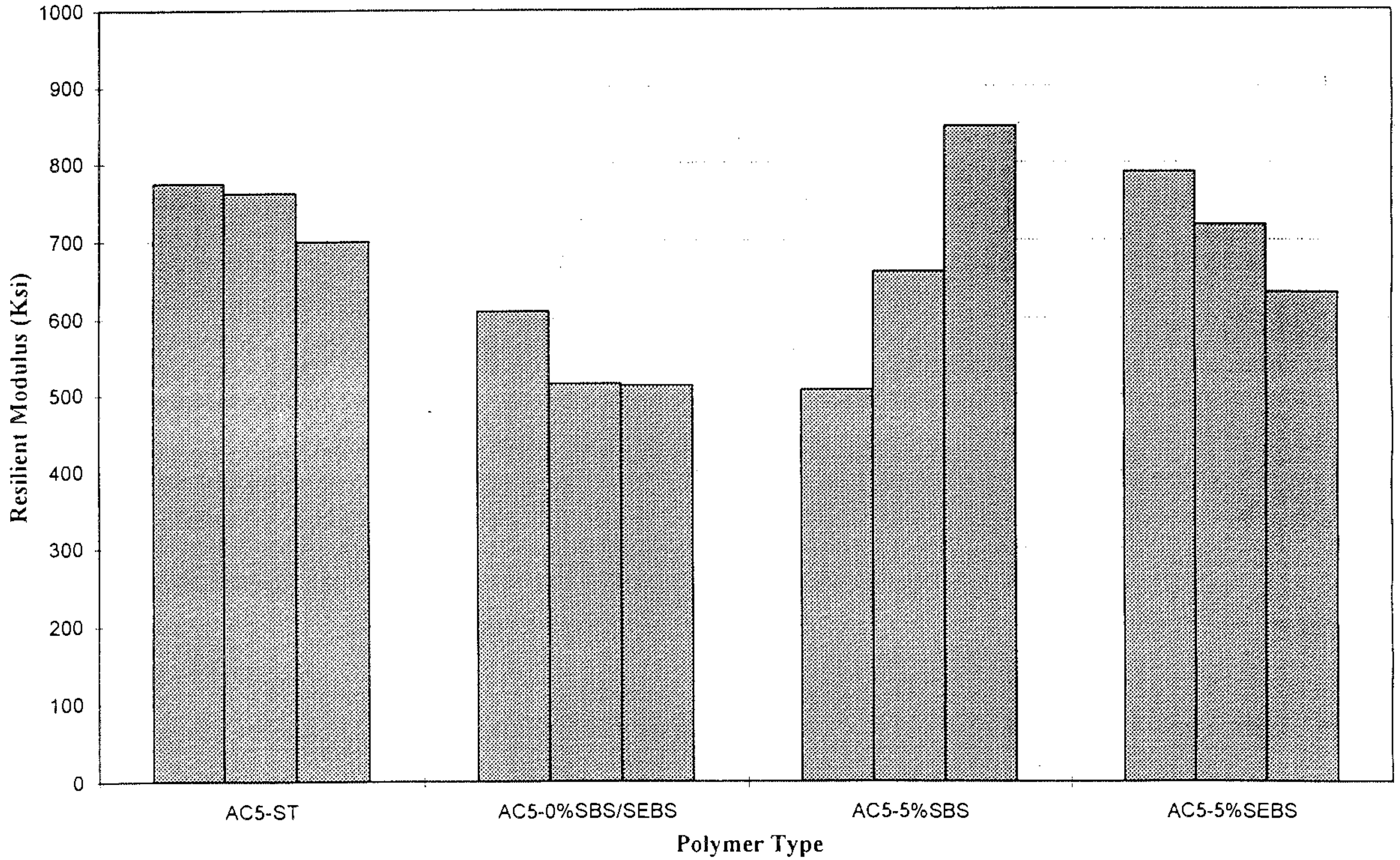
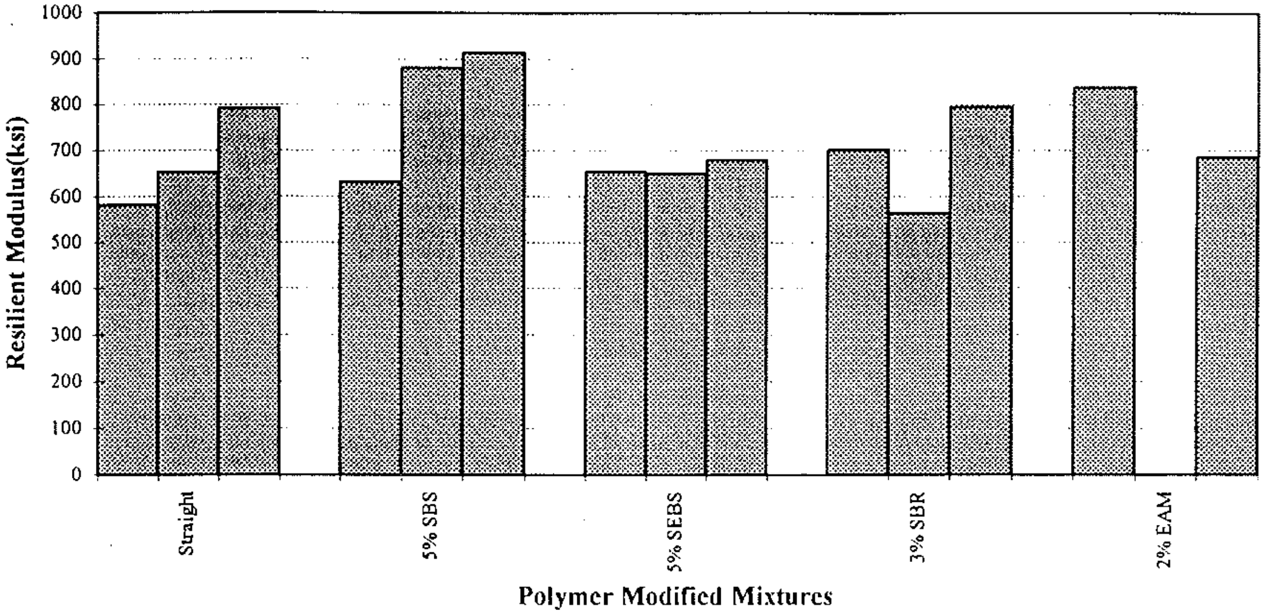


Figure III 50 Effect of polymers on the resilient modulus of AC5 polymer modified aspahlt mixtures at 23 °F

***a)* Resilient Modulus of AC10 PMA Mixtures at 23° F**



***b)* Resilient Modulus of AC10 Oven Aged PMA mixtures at 23° F**

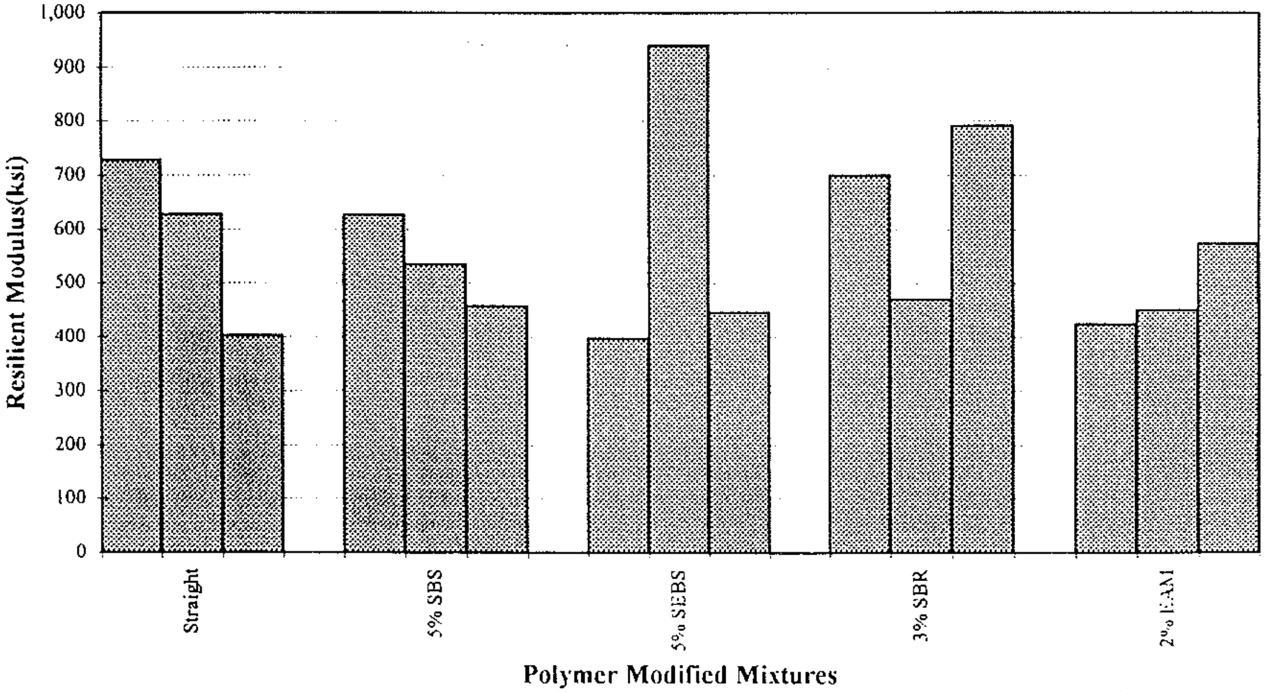
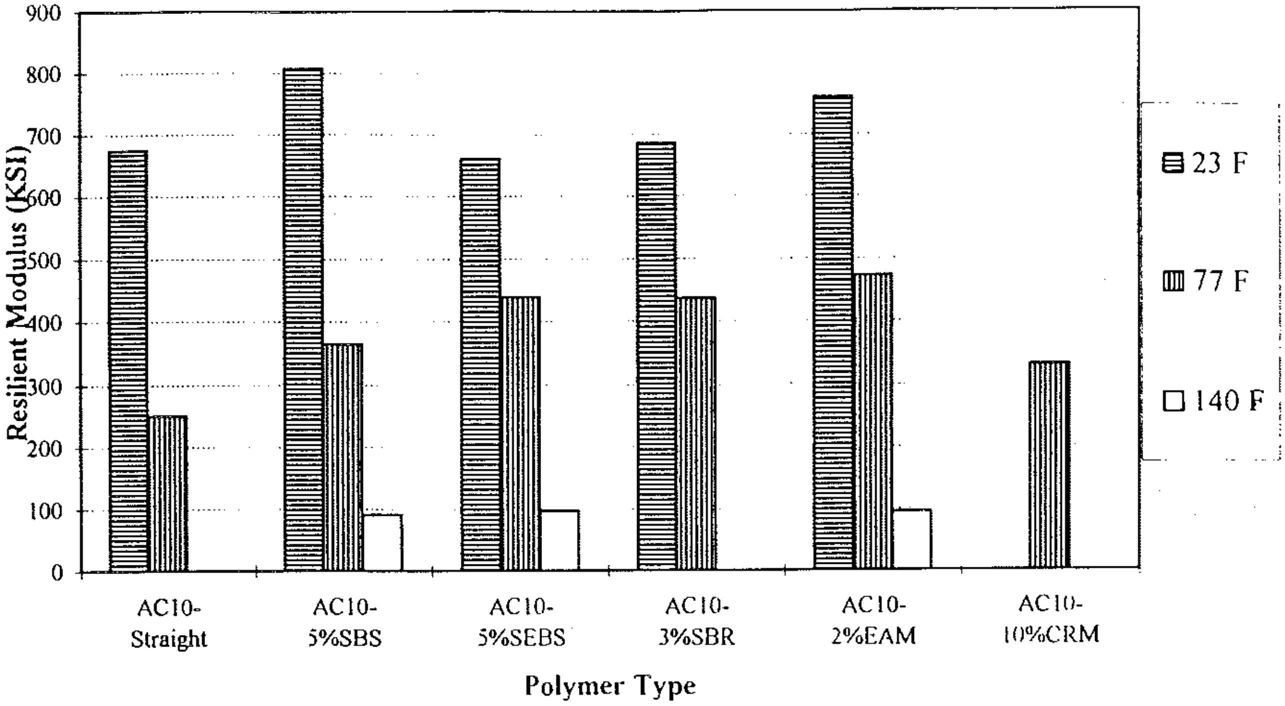


Figure III.51 Effect of polymer type on the resilient modulus of AC10 PMA mixtures at the test temperature of 23° F.

a) Resilient Modulus AC 10 PMA Mixtures



b) Resilient Modulus of Oven Aged AC 10 PMA Mixtures

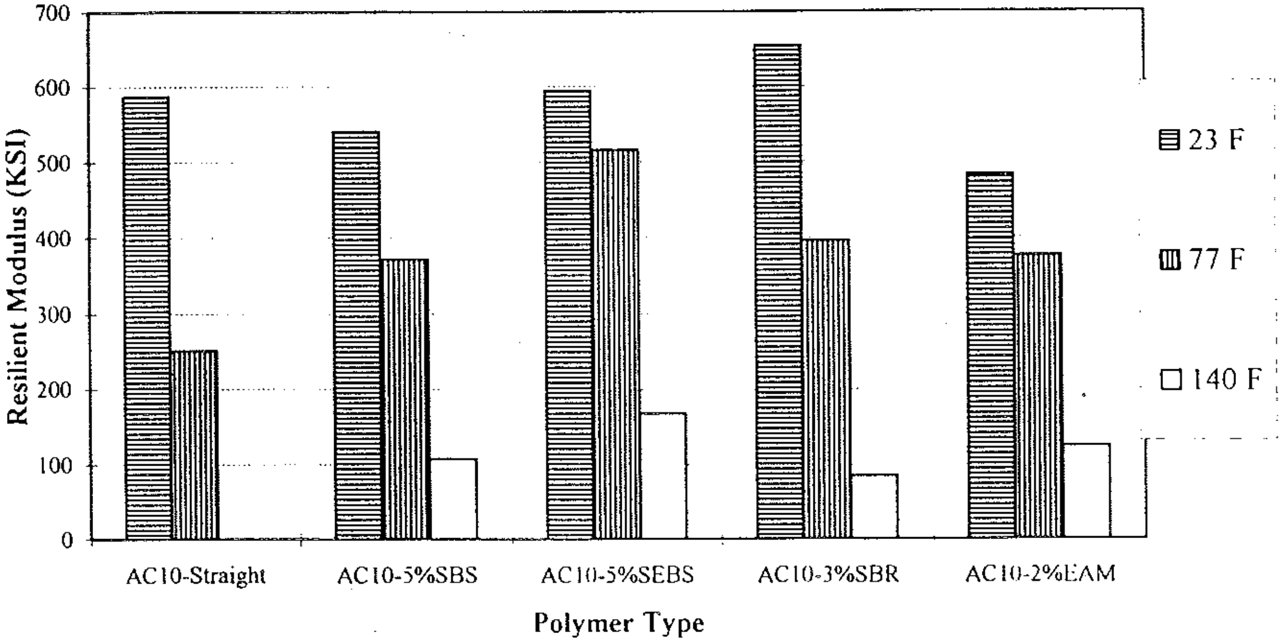


Figure III.52 Effect of temperature on the resilient modulus AC10 mixtures.

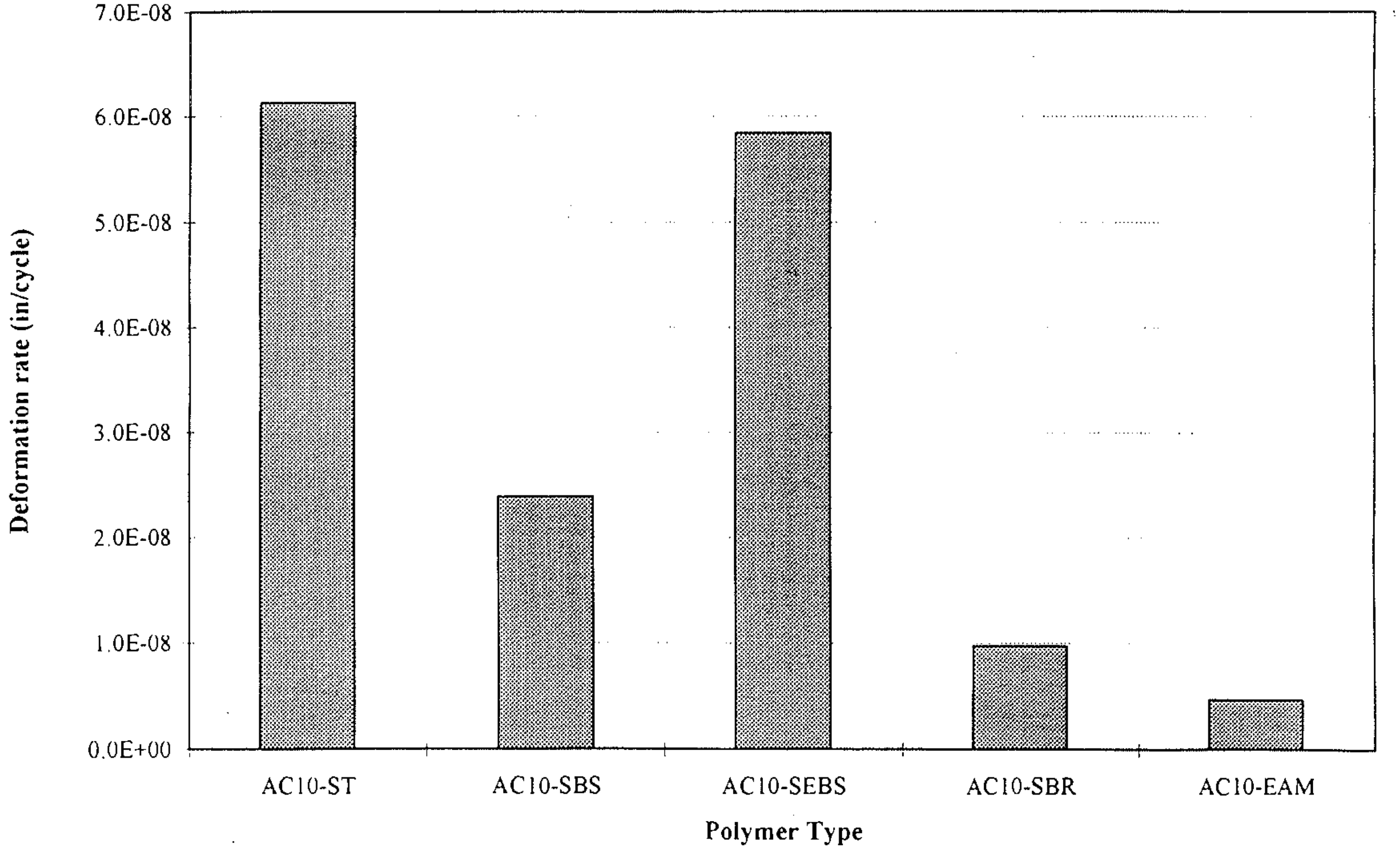
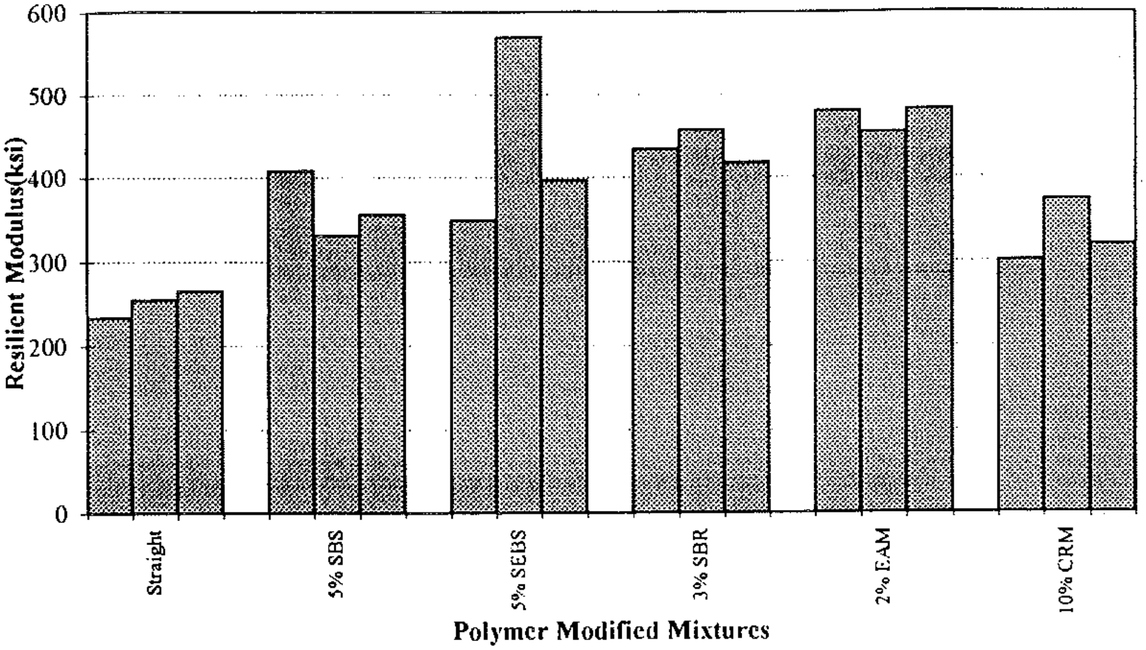


Figure III.53 Effect of polymer on the deformation rate of AC10 Polymer modified asphalt mixtures at 23 °F.

a) Resilient Modulus of AC10 PMA at 77°F



b) Resilient Modulus of AC10 Oven Aged PMA at 77°F

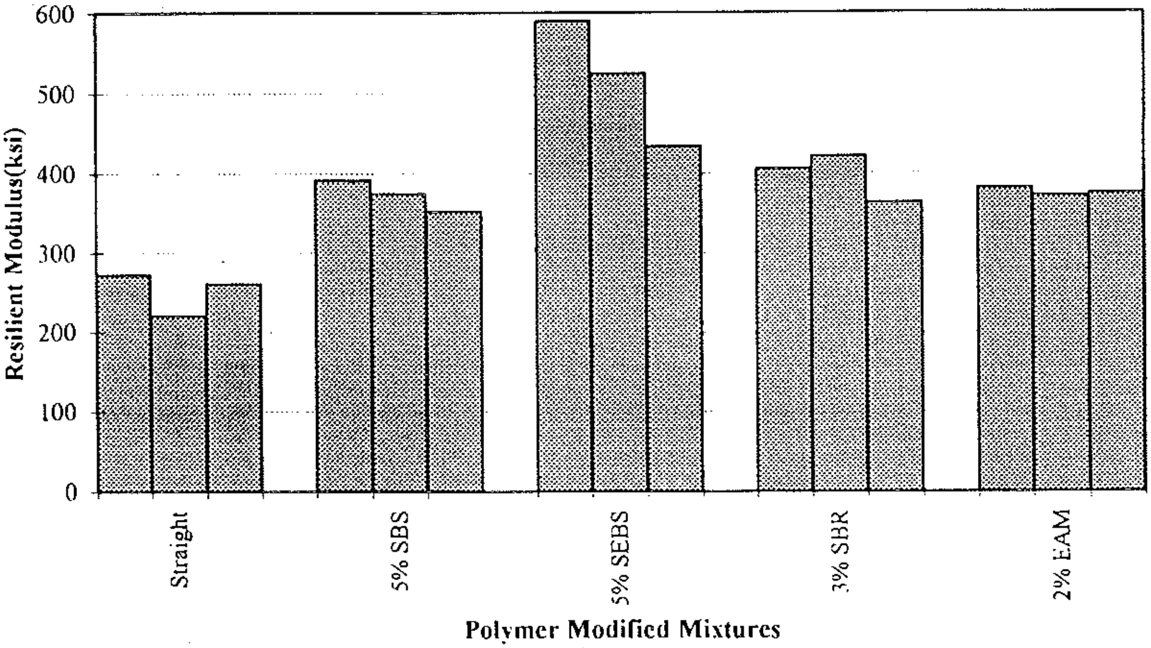


Figure III.54 Effect of polymers on the resilient modulus on the AC10 PMA mixtures at 77° F.

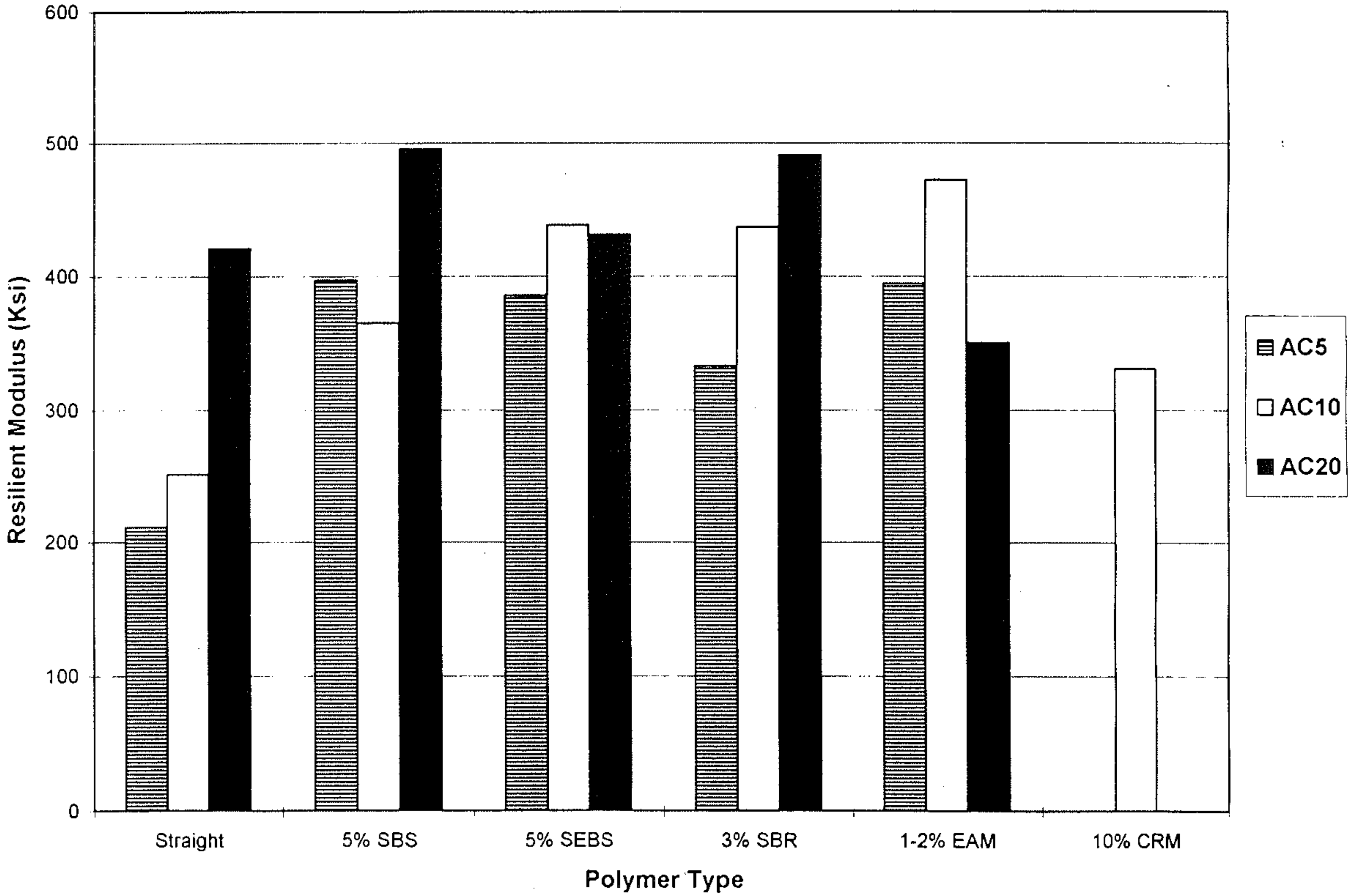


Figure III.55 Effect of polymer type on the resilient modulus of PMA mixtures at 77° F.

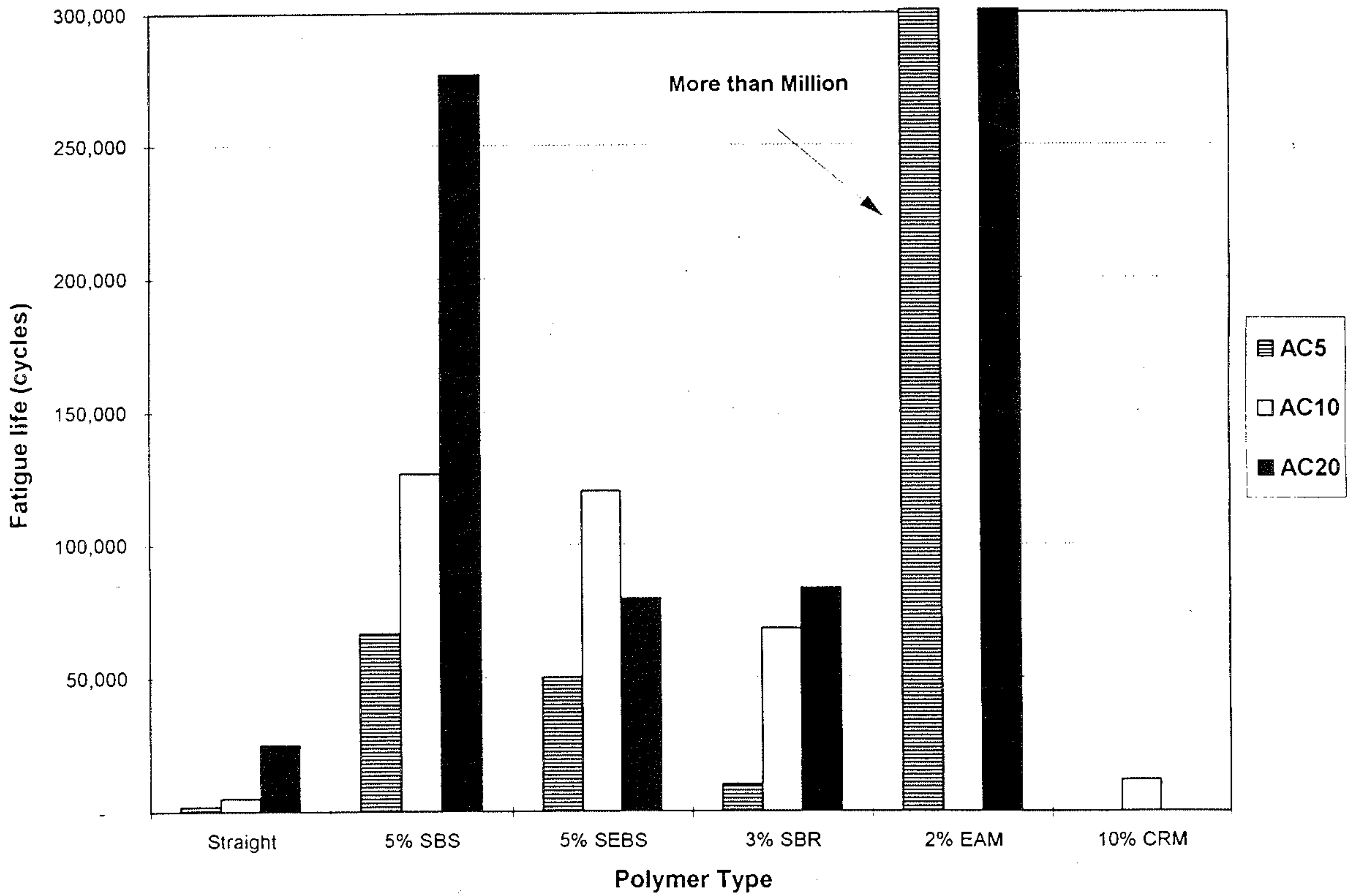
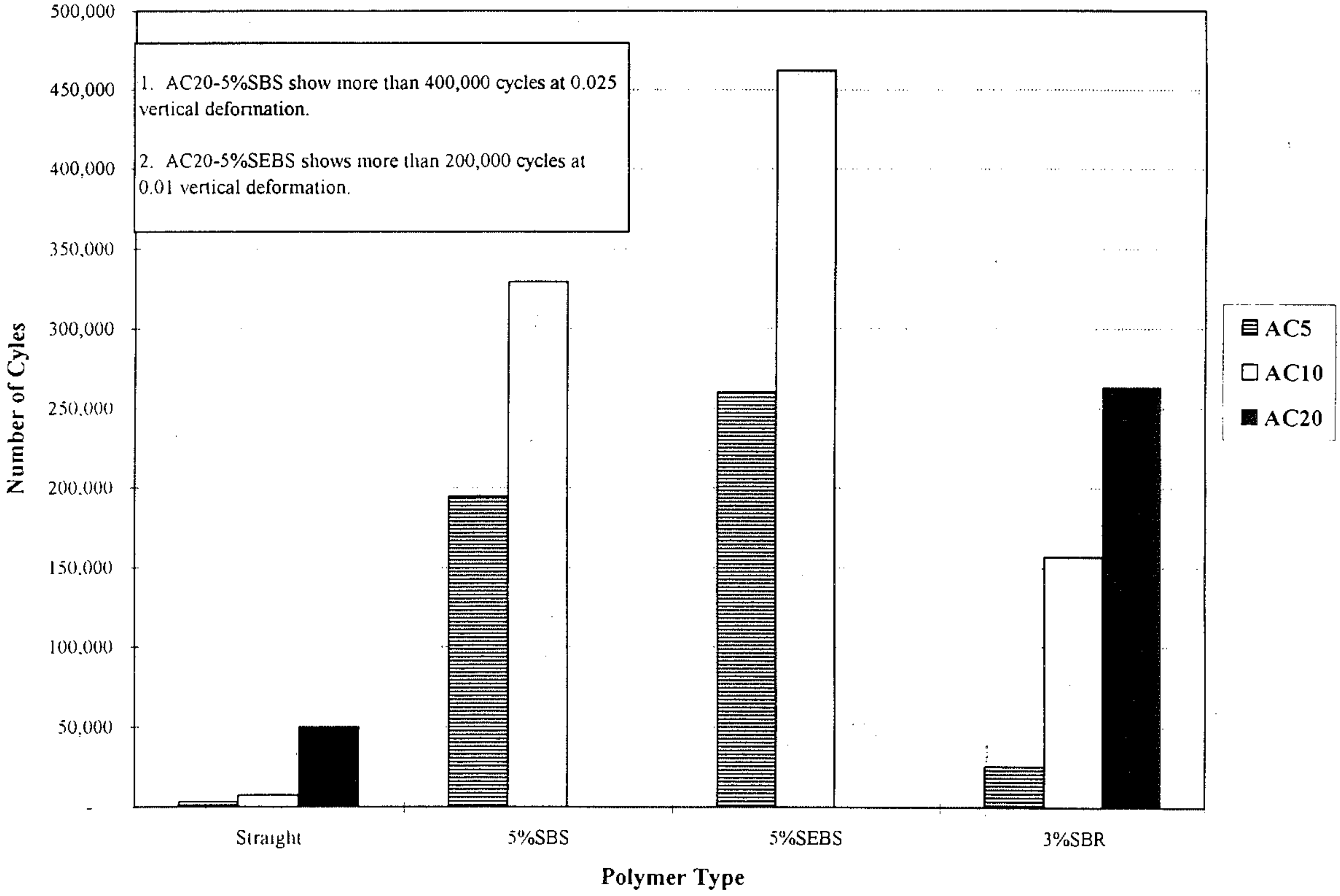


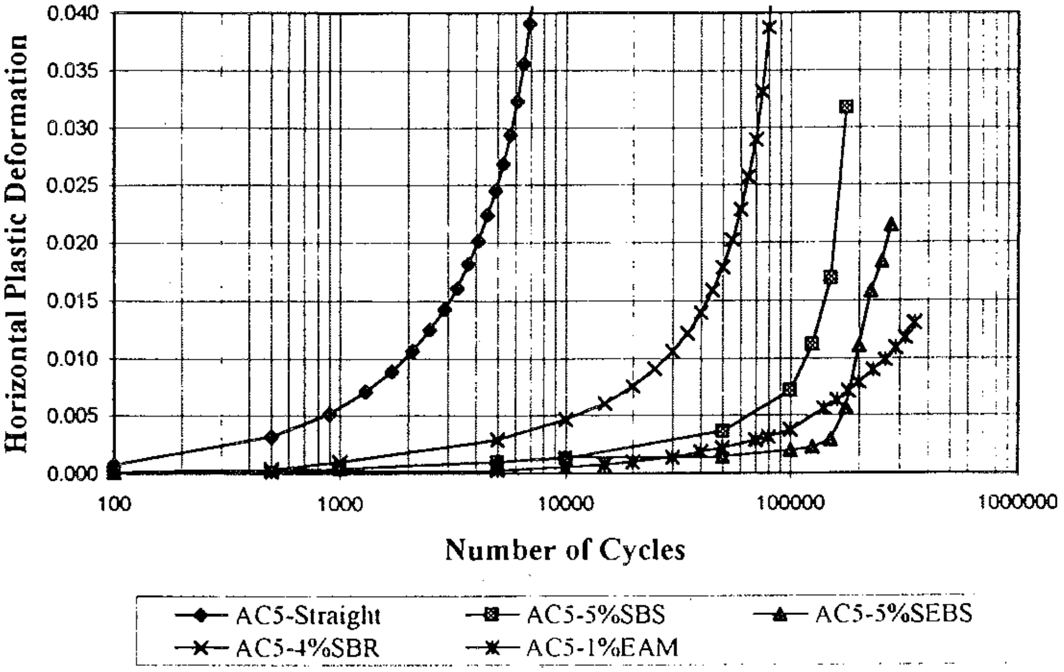
Figure III.56 Effect of polymer type on the fatigue life of PMA mixtures at 77° F.



1. AC20-5%SBS show more than 400,000 cycles at 0.025 vertical deformation.

2. AC20-5%SEBS shows more than 200,000 cycles at 0.01 vertical deformation.

Figure III.57 Effect of polymers on the deformation resistance of PMA mixtures at 77° F.


a) AC5 Polymer Modified Asphalt Mixtures

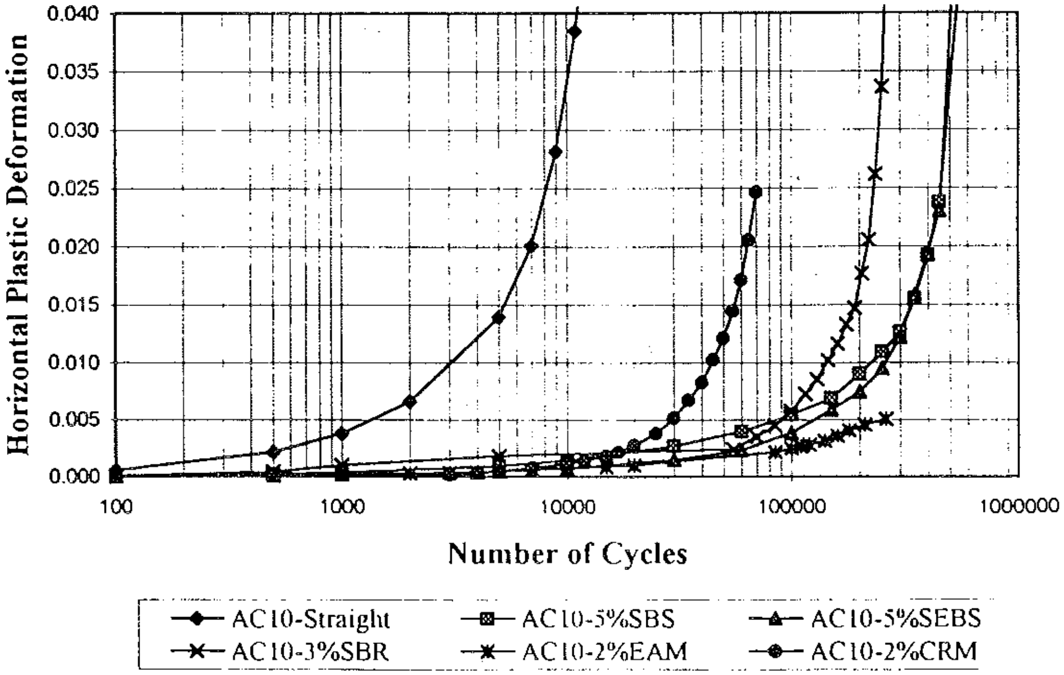
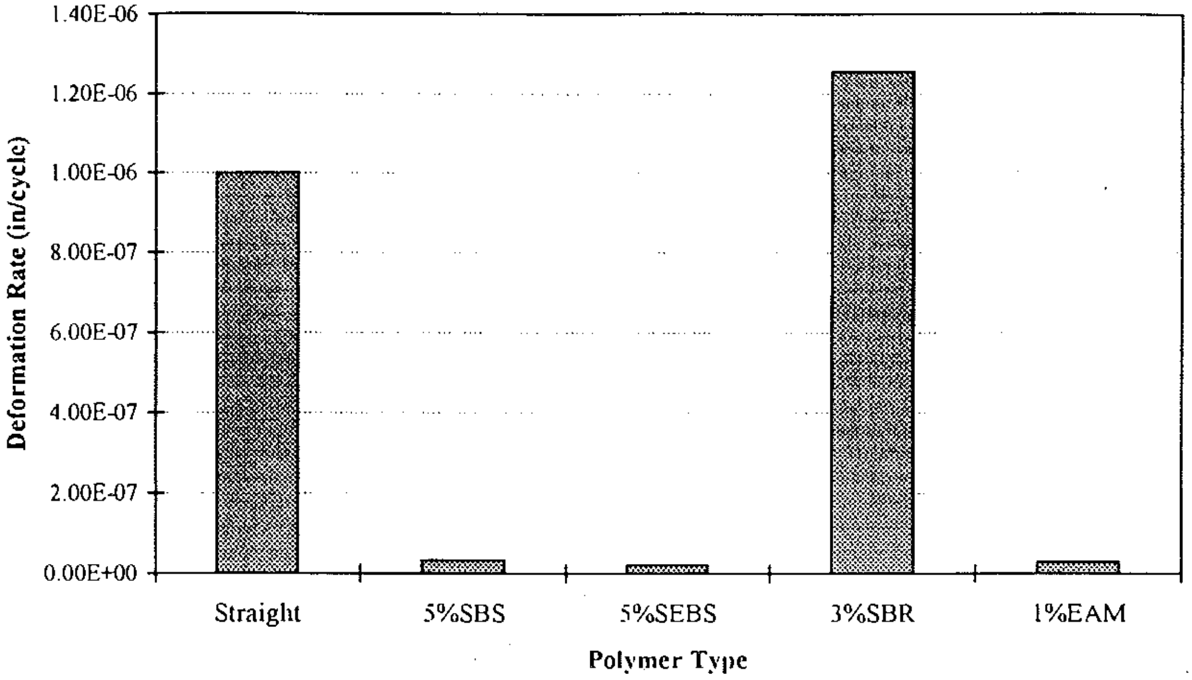

b) AC10 Polymer Modified Asphalt Mixtures

Figure III.58 Effect of polymers on the horizontal plastic deformation of AC5 and AC10 mixtures at 77° F.


a) AC5 Polymer Modified Asphalt Mixtures

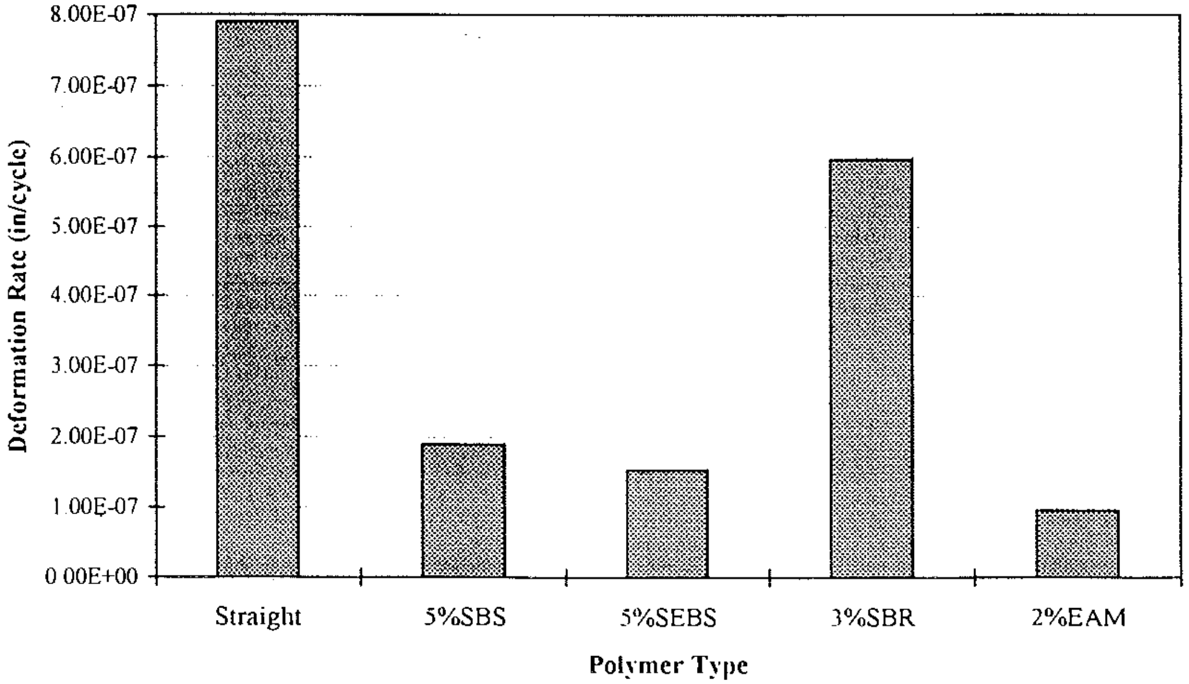

b) AC10 Polymer Modified Asphalt Mixtures

Figure III.59 Effect of polymers on the deformation rate of PMA mixtures at 77° F.

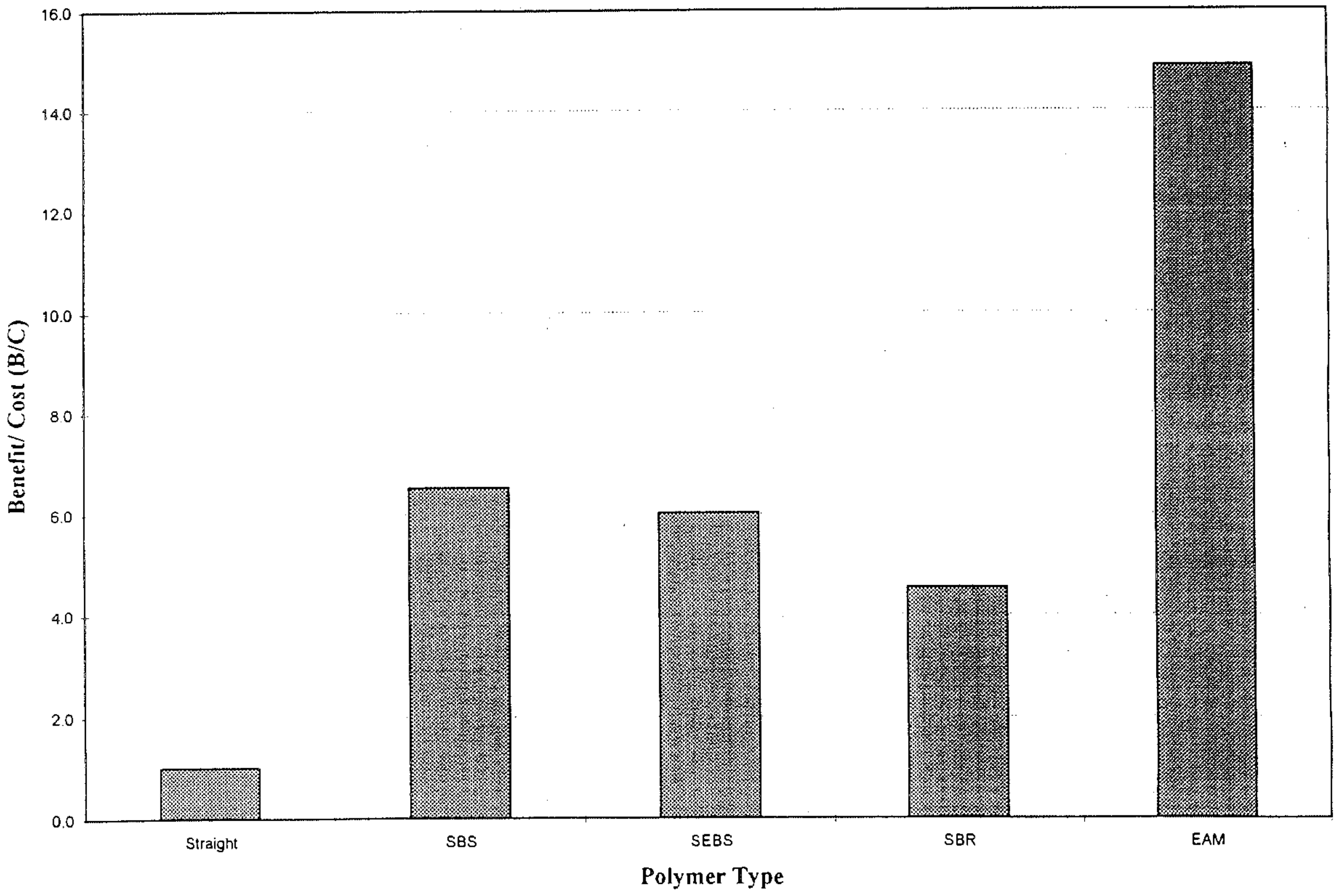


Figure III.60 Benefit- Cost ratio (B/C) of AC10 PMA mixtures.

Asphalt Binder	**Polymer Modifier**	**Processing Conditions**	**Features of modified Binders**	**Polymer phase Morphology**
AC5 AC10	SBS	350°C for 2 hr.	No change in binder network morphology.	Discrete polymer phases observed using fluorescent confocal LSM.
AC5 AC10	SEBS	350°C for 2 hr.	No change in binder network morphology	Discrete polymer phases observed using fluorescent confocal LSM.
AC5 AC10	SBR	350°C for 30 min.	Binder appears very soft. Undergoes plastic deformation easily.	String-like morphology of SBR observed using fluorescent confocal LSM.
AC5 AC10	Elvaloy	380°C for 2 hr.	Binder appears to have undergone considerable stiffening. Network structure of unmodified binder appears coarse. Modified binder with 1% Elvaloy has appearance similar to fresh binders.	Undetermined.
AC5 AC10	Crumb Rubber	350°C for 30 min.	Binder viscosity is very high. No change in network structure was observed. Binder network interacts with rubber particle surface.	Crumb Rubber remains particulate and interacts with the binder network. Observed using the ESEM.

Table II.1 Qualitative summary of polymer modified binder processing conditions, binder characteristics and polymer phase morphology.

Material	**Net Air- void content**	**Method Used**
AC5	1.28 %	Image Analysis
AC5 - 5%SBS	0.97 %	Image Analysis
AC10	1.33 %	Image Analysis
AC10 - 5% SBS	1.58 %	Image Analysis
AC10 - 5% SEBS	0.70 %	Image Analysis
AC5 - 0% SBR	4.21 %	Void Casting
AC5 - 5% SBR	4.89 %	Void Casting
AC5 - 0% ELVALOY	7.47 %	Void Casting
AC5 - 2% ELVALOY	5.23 %	Void Casting

Table II.2 Comparison between void analysis results obtained for various asphalt concrete mixes using both void image analysis and void casting methods.

Table II.3 **Overall Lap-Shear Properties of Various Asphalt Binders Against Granitic Rock Substrate (Average of two measurements). Shaded Row Indicates the Optimum Polymer Concentration.**

BINDER SYSTEM		wt %	LAP-SHEAR STRENGTH, N					ELASTIC STRAIN ENERGY, N.mm				
			20°C	10°C	0°C	-10°C	-20°C	20°C	10°C	0°C	-10°C	-20°C
AC-5/ SBS	FRESH	0	160	600	1389	1189	1600	40	200	630	200	230
		1		360		2600	2195		80		1400	580
		2	80	440	1300	1600	1900	30	110	420	340	350
		3	80	490	1100	1000	1900	75	560	750	150	250
		4	60	400	890	1200	2000	50	100	220	540	280
		5	90	460	1000	1300	1400	110	70	200	280	130
	AGED	1	160	450	1350	1400	1000	30	100	350	150	110
		3	200	400	1000	1400	1200	150	90	320	200	200
		6	190		1100		2300	175		730		740
AC-5/ SEBS	FRESH	0	160	600	1389	1189	1600	40	200	630	200	230
		1		441		2000	1300		120		950	210
		2	143	618	1450	1100	2000	50	140	580	310	400
		3	90	510	1000	1500	1700	40	150	345	320	330
		4	115	600	1400	1200	1700	80	240	800	250	400
		5	110	600	1200	1400	1750	80	280	640	300	300
		6	130	640	1400	1600	1400	100	440	790	520	180
AC-5/ SBR	FRESH	0		348	1523	2000	1500		100	800	370	275
		1		341	1519	2050	1300		90	1140	500	190
		3		278	1300	2080	1740		60	650	1200	625
		5		267	1000	2795	2000		50	900	2000	725
	AGED	0			1830	1700	1500			550	350	180
		1			1708	1750	1140			830	300	175
		3			1322	2400	1100			550	1600	200
		5			1054	2400	3700			850	1952	2400
AC-5/ Elvaloy	FRESH	0		468	1425	1750	1170		140	650	440	190
		1		200	1440	2900	1550		35	340	1350	400
		2		419	1391	2000	1500		85	370	480	540
		3		370	1142	2700	1450		310	800	1050	340
	AGED	0		942	1700	934			450	420	100	
		1		854	1750	1750			735	1000	350	
		2		760	1750	1740			300	720	280	
		3		830	1730	996			400	710	210	
AC-5/ CRM GF80A 74 μm	FRESH	0	82		1500	2200	1500	20		1200	1750	500
		5	53		1150	1100	1600	35		700	380	430
		10	58		1050	2200	1650	20		480	1180	505
		15	58		1100	2500	2000	25		630	1850	670
		20	90		1200	2000	1850	25		770	1560	560
	AGED	0	270		1500	2200	1100	100		900	2050	295
		5	320		976	980	650	140		245	250	105
		10	300		1500	1750	1300	160		800	500	350
		15	280		1250	1950	1400	165		940	1200	350
		20	290		1100	2200	2200	145		670	1250	830

Table 2.3 Continued.

BINDER SYSTEM		wt ·%	LAP-SHEAR STRENGTH, N					ELASTIC STRAIN ENERGY, N.mm				
			20 C	10 C	0 C	-10 C	-20 C	20 C	10 C	0 C	-10C	-20 C
AC-10/ SBS	FRESH	0	235	800	1750	1106	1400	60	320	750	150	150
		2	100	600	1480	1900	1100	20	210	1200	330	150
		3	140	600	1300	2202	2400	20	630	1400	400	400
		4	170	690	1500	1500	1292	10	650	1300	370	200
		5	150	670	1300	1290	1100	30	130	400	200	140
		6	170	650	1470	1200	1349	50	450	930	230	180
	AGED	0	320	920	1300	900	850	145	260	210	70	130
		2	230		1200		1000	120		330		60
		3	300	570	1530	1200	1300	110	200	500	125	100
		5	330		1300		1450	210		375		120
		6	210		1500		1450	345		340		210
AC-10/ SEBS	FRESH	0	235	800	1750	1106	1400	60	320	750	150	150
		2	120	639	1500	1300	1450	30	120	900	220	200
		3	120	725	1645	1300	1800	30	220	915	260	240
		4	140	785	1655	1600	1600	80	380	1030	320	190
		5	200	800	1545	1650	1300	170	480	1050	340	190
		6	195	880	1760	1500	1200	150	500	530	320	190
AC-10 SBR	FRESH	0		605	1700	2300	1218		80	750	560	140
		1		560	1741	1050	1400		175	1000	245	270
		3		426	1456	1900	1430		170	850	445	190
		5		425	1304	2020	1500		100	1200	900	270
AC-10/ Elvaloy	FRESH	0		815	1800	1400	670		195	540	250	75
		1		720	1650	1600	670		195	800	240	85
		2		510	1532	1750	1120		190	1000	550	180
		3		700	2050	2100	1010		195	1250	600	150
	AGED	0		1030	1269	765			200	175	55	
		1		1288	1747	1000			380	250	130	
		2		1500	1700	1000			580	360	145	
		3		1156	1700	1100			810	300	160	
AC-10/ CRM GF80A 74 μm	FRESH	0	97		1700	1220	1300	20		1025	340	300
		5	70		1500	1800	1050	20		630	1600	420
		10	72		1500	2500	1279	45		950	1150	300
		15	131		2000	2300	1500	40		1210	1160	325
		20	131		1500	1400	1250	45		800	550	310
	AGED	0	390		1700	1200	600	320		750	410	110
		5	410		1150	800	650	150		420	170	130
		10	290		1220	1500	1000	210		720	460	160
		20	360		1300	2000	1750	190		850	1150	460

Material	**Average Fibril Length**	**Average Fibril Diameter at break**	**Fibril density relative to unmodified AC5**
AC5	~ 50-100 μm	~ 2 μm	
AC5 - SBS	~ 70-130 μm	~ 2 μm	++
AC5 - SEBS	~ 70-130 μm	~ 2 μm	++
AC5 - SBR	~ 1-2 mm	~ 700 nm	+++++
AC5 - Elvaloy	~ 70-100 μm	~ 2 μm	-
AC5 - Crumb Rubber	~ 600 μm	~ 2 μm	++

Table II.4 Qualitative summary of the changes seen in fracture morphology of asphalt concrete after polymer modification.

Sieve Size	Sieve Opening (mm)	%Passing	%Retained	Weight (gm)
3/8 inch	9.500	100	0	0
5/16 inch	7.700	99	1	32.5
No. 4	4.750	68	31	1007.5
No. 8	2.370	38	30	975
No. 16	1.180	26	12	390
No. 30	0.600	14	12	390
No. 50	0.300	10	4	130
No. 100	0.150	7	3	97.5
No. 200	0.075	4	3	97.5
Pan	Fly Ash	0	4	130
Total Weight of Aggregates				**3250**
Total Weight of Binder (5.7%)				**196.5**

Table II.5 Aggregate gradation used in fracture toughness test samples.

Composition	**J_{IC} Fracture Toughness (lb-in/in^2)**	**Remarks**
AC5-0% SEBS	1.5828	
AC5-3% SEBS	3.2774	Original AC5 asphalt binder used
AC5-5% SEBS	2.4018	
AC5 0% SBR	2.4699	
AC5 3% SBR	2.0468	Original AC5 asphalt binder used
AC5 5% SBR	1.6986	
AC5 0% Elvaloy	2.8713	
AC5 1% Elvaloy	2.8806	Original AC5 asphalt binder used
AC5 2% Elvaloy	2.7262	
AC5 0% CRM	3.0423	
AC5 5% CRM	2.684	New AC5 asphalt binder was used
AC5 10% CRM	3.4648	
AC5 0% SBS	4.3363	
AC5 3% SBS	3.4493	New AC5 asphalt binder was used
AC5 5% SBS	2.5697	

Table II.6 Results of J-contour integral fracture toughness measurements for polymer modified asphalt concrete at -10°C.

Table III.1 Specific gravity and absorption capacity of the aggregates.

	Size	Bulk S.G	Apparent S.G	Bulk S.G SSD	Absorbtion Capacity	% WT. of each Aggregate sizes	Bulk S.G of the Total Aggregates	Total S.G	Average Absorption Capacity (%)
Course Aggregate -1/2" to + #4sieve	1/2"	2.73	2.77	2.74	0.6	1	2.684	**2.651**	**1.10**
	+ 3/8"	2.69	2.75	2.71	0.8	18			
	+5/16"	2.68	2.75	2.7	0.92	18			
	+ #4	2.68	2.75	2.71	0.95	28			
Fine Aggragte -#4 to + #200sieve	+#8	2.661	2.768	2.7	1.45	13	2.651		
	+#16	2.655	2.78	2.7	1.69	6			
	+#30	2.629	2.75	2.67	1.71	5			
	+#50	2.648	2.745	2.68	1.34	2			
	+#100	2.64	2.728	2.67	1.22	2			
	+#200	2.65	2.782	2.7	1.79	2			
Fly Ash	- #200	2.29	---------	--------	-------	5	2.290		

100

Table III.2 Aggregate gradation and asphalt contents.

a) G7 gradation data.

Sieve size	Sieve opening (mm)	Gradation G7		weight retained (gr)	Cumulative weight retained
		Passing	Retained		
3/4 inch	19.000	100.0	0.0	0.0	0.0
1/2 inch	12.500	99.0	1.0	54.0	54.0
3/8 inch	9.500	81.0	18.0	972.0	1026.0
5/16	7.700	63.0	18.0	972.0	1998.0
No. 4	4.750	35.0	28.0	1512.0	3510.0
No. 8	2.370	22.0	13.0	702.0	4212.0
No. 16	1.180	16.0	6.0	324.0	4536.0
No. 30	0.600	11.0	5.0	270.0	4806.0
No. 50	0.300	9.0	2.0	108.0	4914.0
No. 100	0.150	7.0	2.0	108.0	5022.0
No. 200	0.075	5.0	2.0	108.0	5130.0
Pan	Fly ash	0	5	270.0	5400.0

b) Asphalt contents.

AC Content (percent)	AC weight required for 5400 gr batch	Total weight of the mix
4.00	225.00	5625.00
4.50	254.45	5654.45
5.00	284.21	5684.21
5.50	314.29	5714.29
6.00	344.68	5744.68
6.50	375.40	5775.40
7.00	406.45	5806.45

Table III.3 Summary of the results of the asphalt mix design for the straight and polymer modified asphalt mixtures.

Asphalt Grade	Polymer Type and Content	AC Content (% of the total mix by weight)	Maximum Theoratical S.G	Bulk Specific Gravity	Air Voids	V.M.A (%)	Stability (pounds)	Flow (0.1")	Optimum Asphalt Content (%)
AC 2.5	....	5.0	2.501	2.396	3.970	15.70	1425	10.80	5.30
		5.5	2.472	2.409	3.020	15.69	1478	10.90	
		6.0	2.456	2.402	2.100	16.36	1524	12.10	
		6.5	2.437	2.403	1.440	16.78	1331	10.90	
AC 5	....	4.5	2.520	2.353	6.620	17.02	1821	6.90	5.70
		5.0	2.500	2.376	4.970	16.65	1558	8.10	
		5.5	2.475	2.387	4.210	16.70	1561	7.40	
		6.0	2.465	2.382	3.290	17.32	1566	9.50	
		6.5	2.442	2.376	2.810	17.98	1366	9.30	
AC 5	5% SBS	5.0	2.505	2.398	4.240	16.32	2460	7.60	5.60
		5.5	2.489	2.392	3.420	16.11	2251	9.80	
		6.0	2.468	2.381	3.070	17.15	2294	8.50	
		6.5	2.484	2.379	2.450	17.63	1993	12.20	
AC 10	....	4.5	2.505	2.343	6.829	17.19	1906	8.10	5.70
		5.0	2.489	2.349	5.880	17.41	1484	12.70	
		5.5	2.484	2.386	3.936	16.54	1632	11.30	
		6.0	2.468	2.385	1.990	17.02	1388	16.60	
		6.5	2.438	2.398	1.710	17.15	1498	11.80	
AC 10	2%SBS	5.0	2.490	2.382	4.450	16.14	2556	9.60	5.70
		5.5	2.457	2.400	3.600	16.47	2254	11.20	
		6.0	2.448	2.397	2.700	16.50	2404	13.90	
		6.5	2.397	2.373	2.284	17.14	2074	13.60	
AC 20	....	5.0	2.478	2.393	4.250	16.00	1887	10.00	5.50
		5.5	2.475	2.398	3.300	16.25	1906	11.00	
		6.0	2.466	2.395	2.750	16.81	1942	11.90	
		6.5	2.463	2.388	2.220	17.47	1823	8.20	

Table III.4 Summary of the indirect tensile strength test results of AC5 polymer modified asphalt mixtures at test temperature of 77°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Void	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3220051	2.35	5.10	1180	71	35	71	0.051	0.011	216
	3220052	2.37	4.25	1220	74	34	66	0.050	0.013	226
	3220053	2.33	5.90	1259	75	34	59	0.049	0.014	228
	3220054	2.36	4.45	1585	94	37	85	0.044	0.013	287
	3220055	2.36	4.53	1644	98	43	78	0.049	0.015	297
	3220056	2.39	3.23	1488	91	41	76	0.049	0.014	276
	3220057	2.36	4.41	1268	76	29	61	0.043	0.015	232
	3220058	2.35	4.97	1273	77	33	74	0.046	0.012	235
	3220059	2.37	4.37	1171	71	29	52	0.046	0.016	215
0%SEBS &SBS	3220014	2.34	5.54	1551	93	56	54	0.065	0.020	284
	3220015	2.35	4.81	1776	107	54	69	0.055	0.018	325
	3220016	2.35	5.05	1888	112	57	39	0.069	0.033	342
	3220017	2.33	5.66	1561	92	48	64	0.056	0.017	281
	3220018	2.36	4.45	1717	102	50	76	0.052	0.015	309
	3220019	2.38	3.84	1727	105	54	70	0.057	0.017	318
3% SBS	3221311	2.37	4.17	2249	134	51	114	0.044	0.014	406
	3221312	2.39	3.20	2088	126	70	102	0.058	0.014	382
	3221313	2.39	3.16	2259	135	76	42	0.073	0.037	412
4% SBS	3221411	2.39	3.04	2083	127	51	98	0.047	0.015	387
	3221412	2.38	3.73	2215	132	43	134	0.038	0.011	401
	3221413	2.38	3.77	1941	117	53	98	0.049	0.014	355
5%SBS	3221511	2.35	4.98	2390	144	49	165	0.039	0.010	438
	3221512	2.36	4.21	2351	142	64	126	0.049	0.013	432
	3221513	2.35	4.78	2546	155	58	135	0.043	0.013	471
7%SBS	3221711	2.34	5.11	1712	101	40	68	0.045	0.017	305
	3221712	2.36	4.34	1756	105	41	91	0.044	0.013	318
	3221713	2.35	4.79	1673	99	36	111	0.041	0.010	300

Table III.4 Summary of the indirect tensile strength test results of AC5 polymer modified asphalt mixtures at test temperature of 77^{o}F (continued).

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Void	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
3%SEBS	3222311	2.37	3.97	3234	198	75	154	0.046	0.015	604
	3222312	2.37	3.89	3122	192	71	186	0.043	0.012	583
	3222313	2.37	4.25	3278	199	80	171	0.047	0.013	604
	3222314	2.36	4.49	2483	151	57	108	0.044	0.016	461
	3222315	2.37	4.01	2639	163	60	135	0.043	0.014	496
	3222316	2.37	4.13	2644	161	58	132	0.044	0.014	490
4%SEBS	3222411	2.37	4.21	2288	136	51	132	0.043	0.012	413
	3222412	2.36	4.58	2146	127	45	128	0.039	0.011	384
	3222413	2.36	4.41	2356	140	58	111	0.047	0.015	426
5%SEBS	3222514	2.35	4.62	2098	128	55	95	0.047	0.015	389
	3222515	2.35	4.90	1902	115	59	72	0.058	0.018	349
	3222516	2.36	4.58	1912	117	56	81	0.053	0.016	355
	3222517	2.36	4.25	2678	163	63	83	0.051	0.023	497
	3222518	2.37	3.85	2698	164	60	125	0.044	0.015	500
	3222519	2.35	4.78	2634	161	60	133	0.044	0.014	489
7%SEBS	3222711	2.35	4.70	2341	138	48	109	0.042	0.015	421
	3222712	2.36	4.14	2161	128	51	108	0.043	0.014	391
	3222713	2.37	4.10	2346	139	49	86	0.045	0.019	423
0% SBR	3223011	2.36	4.57	1298	83	41	74	0.050	0.014	159
	3223012	2.37	4.25	1390	84	38	73	0.044	0.013	254
	3223013	2.38	3.88	1356	83	45	58	0.053	0.016	252
2% SBR	3223211	2.38	3.72	1537	94	44	72	0.046	0.015	285
	3223212	2.39	3.28	1566	96	44	111	0.044	0.010	291
	3223213	2.37	3.97	1650	106	48	90	0.048	0.014	322
3% SBR	3223311	2.35	4.74	1785	73	55	118	0.048	0.012	222
	3223312	2.37	4.21	1668	100	58	95	0.054	0.012	305
	3223313	2.35	4.82	...	...	...	...	...	...	...
4% SBR	3223411	2.35	4.21	1454	86	36	79	0.041	0.013	262
	3223412	2.39	4.58	1385	85	37	77	0.043	0.012	257
	3223413	2.34	4.41	1420	85	41	84	0.045	0.012	260
5% SBR	3223511	2.36	4.62	1488	88	45	97	0.046	0.010	268
	3223512	2.36	4.90	1488	90	49	65	0.053	0.016	276
	3223513	2.33	4.58	1439	85	40	67	0.043	0.015	259

Table III.4 Summary of the indirect tensile strength test results of AC5 polymer modified asphalt mixtures at test temperature of 77°F (continued).

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Void	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
0% EAM	3224011	2.34	5.54	2878	169	74	164	0.047	0.013	547
	3224012	2.36	4.77	3034	186	84	158	0.051	0.014	577
	3224013	2.40	3.15	2917	172	83	162	0.050	0.013	555
1% EAM	3224111	2.34	5.18	3327	198	87	175	0.048	0.014	633
	3234112	2.37	4.29	3434	207	83	202	0.046	0.012	653
	3224113	2.37	4.17	3195	194	80	168	0.047	0.014	608
2% EAM	3224211	2.36	4.53	3088	186	99	133	0.056	0.016	587
	3224212	2.33	5.75	2980	175	82	145	0.052	0.015	567
	3224213	2.36	4.49	3024	182	86	156	0.051	0.014	575
3% EAM	3224311	2.34	5.47	3020	181	84	143	0.052	0.015	574
	3224312	2.34	5.10	2898	172	73	151	0.048	0.014	551
	3224313	2.37	4.01	2859	175	86	119	0.056	0.018	544

Table III.5 Summary of the indirect tensile strength test results of AC10 polymer modified asphalt mixtures at test temperature of 77°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Void	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3230051	2.38	3.73	1610	96	41	107	0.045	0.010	294
	3230052	2.39	3.24	1688	101	48	88	0.051	0.013	308
	3230053	2.37	3.81	1620	97	50	78	0.055	0.014	296
0%SEBS &SBS	3230014	2.34	5.31	1844	109	49	98	0.048	0.013	332
	3230015	2.35	4.74	1917	115	53	95	0.051	0.014	351
	3230016	2.35	4.90	1873	112	60	82	0.057	0.016	341
	3230017	2.36	4.54	2800	168	81	128	0.053	0.015	510
	3230018	2.36	4.38	2810	169	84	115	0.055	0.017	515
	3230019	2.39	3.12	2824	171	83	84	0.057	0.023	521
2% SBS	3231211	2.38	3.57	2649	157	73	107	0.051	0.017	478
	3231212	2.38	3.41	2746	165	76	134	0.051	0.014	502
	3231213	2.37	4.06	2951	177	86	134	0.055	0.015	539
3% SBS	3231311	2.37	4.00	2863	172	79	145	0.051	0.013	524
	3231312	2.39	3.02	3043	182	77	153	0.047	0.014	556
	3231313	2.38	3.51	2985	176	88	110	0.056	0.018	535
4% SBS	3231411	2.36	4.34	2922	173	78	155	0.050	0.013	527
	3231412	2.38	3.65	2790	165	72	141	0.048	0.013	504
	3231413	2.37	3.94	3068	182	89	125	0.054	0.017	553
5%SBS	3231514	2.35	4.48	3049	183	96	78	0.064	0.028	559
	3231515	2.35	4.65	3020	184	87	149	0.053	0.014	560
	3231516	2.34	4.93	3346	202	78	205	0.044	0.011	613
	3231517	2.37	3.75	3059	186	88	135	0.054	0.016	567
	3231518	2.37	3.71	2893	177	98	72	0.068	0.013	540
	3231519	2.36	4.08	3000	176	83	123	0.052	0.017	537
7%SBS	3231711	2.37	3.84	2385	140	62	42	0.067	0.039	425
	3231712	2.38	3.31	2498	151	58	123	0.046	0.014	458
	3231713	2.36	4.16	2473	148	52	116	0.042	0.015	450

Table III.5 Summary of the indirect tensile strength test results of AC10 polymer modified asphalt mixtures at test temperature of 77°F (continued).

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Void	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
2%SEBS	3232211	2.39	3.12	3015	180	78	151	0.049	0.014	546
	3232212	2.37	3.73	3254	194	83	144	0.050	0.015	589
	3232213	2.37	4.10	2917	176	85	122	0.054	0.017	536
3%SEBS	3232314	2.36	4.36	2927	176	82	101	0.054	0.020	536
	3232315	2.37	4.08	3063	187	79	124	0.049	0.018	568
	3232316	2.36	4.28	2902	175	80	127	0.052	0.016	532
4%SEBS	3232411	2.37	4.06	3468	207	77	153	0.044	0.015	628
	3232412	2.38	3.33	3361	201	101	140	0.056	0.016	612
	3232413	2.36	4.22	3185	188	67	155	0.042	0.014	572
5% SEBS	3232514	2.34	4.93	2824	170	66	143	0.045	0.014	518
	3232515	2.35	4.73	2805	169	68	146	0.047	0.013	514
	3232516	2.34	4.89	2600	155	64	146	0.045	0.012	471
	3232517	2.36	4.12	3356	205	79	147	0.048	0.016	622
	3232518	2.37	3.71	3449	209	80	132	0.048	0.018	636
	3232519	2.35	4.65	3527	207	83	187	0.045	0.013	631
7%SEBS	3232711	2.37	3.80	3112	187	68	139	0.044	0.015	570
	3232712	2.38	3.55	...	...	...	...	...	...	...
	3232713	2.38	3.23	2659	156	72	102	0.051	0.018	475
0% SBR	3233011	2.34	5.06	2083	125	57	113	0.045	0.013	381
	3233012	2.36	4.54	2005	121	64	101	0.051	0.014	367
	3233013	2.37	4.17	2176	133	60	128	0.045	0.012	404
2% SBR	3233211	2.36	4.26	2132	127	60	133	0.045	0.011	387
	3233212	2.38	3.57	2068	126	68	129	0.052	0.011	384
	3233213	2.37	3.93	2159	132	66	143	0.047	0.011	420
3% SBR	3233311	2.35	4.70	2150	129	50	98	0.037	0.011	392
	3233312	2.36	4.30	2320	139	54	97	0.036	0.012	423
	3233313	2.37	3.85	2350	143	61	98	0.040	0.012	437
4% SBR	3233411	2.33	5.46	1995	116	53	99	0.044	0.013	354
	3233412	2.36	4.36	1951	116	56	101	0.046	0.013	352
	3233413	2.36	4.16	2029	124	59	121	0.046	0.012	377
5% SBR	3233511	2.35	4.83	2027	133	48	140	0.041	0.011	404
	3233512	2.34	5.07	2098	131	55	105	0.048	0.014	399
	3233513	2.35	4.87	1932	121	38	147	0.037	0.094	367

Table III.5 Summary of the indirect tensile strength test results of AC10 polymer modified asphalt mixtures at test temperature of 77°F (continued).

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Void	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
0% EAM	3234011	2.37	4.04	3454	212	93	192	0.050	0.013	657
	3234012	2.35	4.61	3629	220	92	156	0.048	0.017	690
	3234013	2.37	4.04	3259	199	114	133	0.061	0.018	620
1% EAM	3234111	2.37	3.85	3341	200	97	146	0.054	0.016	635
	3234112	2.36	4.34	3366	202	97	161	0.054	0.015	640
	3234113	2.39	3.20	3673	228	125	143	0.060	0.019	698
2% EAM	3234211	2.34	4.99	3820	233	96	193	0.047	0.014	726
	3234212	2.36	4.46	3912	234	106	155	0.052	0.018	744
	3234213	2.35	4.79	3776	227	99	148	0.052	0.018	718
3% EAM	3234311	2.34	5.05	3385	201	113	149	0.059	0.017	644
	3234312	2.34	5.13	3488	209	117	144	0.059	0.017	663
	3234313	2.38	3.39	3424	211	105	152	0.056	0.016	651
5% CRM	3235511	2.38	3.61	2025	123	56	63	0.046	0.016	374
	3235512	2.34	5.31	2050	122	62	60	0.051	0.017	372
	3235513	2.35	4.62	2125	126	59	66	0.045	0.016	385
10% CRM	32351011	2.36	4.46	3370	203	87	112	0.043	0.015	618
	32351012	2.37	3.85	3450	208	84	115	0.040	0.015	632
	32351013	2.37	4.01	3250	196	91	108	0.044	0.015	596
15% CRM	32351511	2.36	4.12	2280	139	50	88	0.035	0.013	423
	32351512	2.34	5.21	2220	132	57	74	0.041	0.015	402
	32351513	2.35	4.56	2320	138	49	89	0.037	0.013	420

Table III.6 Summary of mixing time & temperature and optimum polymer content for AC5 & AC10 polymer modified asphalt mixtures.

Polymer Type	Mixing Time (Hour)	Mixing Temperature (° F)	Optimum Polymer Content (%)
SBS	2	350	$5^{(AC5, AC10)}$
SEBS	2	350	$5^{(AC5, AC10)}$
SBR	1/2	350	$2^{AC5}, 3^{AC10}$
EAM	2	380	$1^{AC5}, 2^{AC10}$
CRM	1/2	350	10^{AC10}

Table III.7 Summary of the indirect tensile strength test results of AC5 polymer modified asphalt mixtures at test temperature of 140°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3120051	2.36	4.93	200	12	4.7	8	0.044	0.012	37
	3120052	2.40	4.32	185	11	3.1	9	0.036	0.01	34
	3120053	2.37	3.96	160	10	4.5	6	0.044	0.014	30
0%SEBS &SBS	3121011	2.38	4.53	215	13	4.6	11	0.032	0.01	40
	3121012	2.37	4.04	225	14	4.5	10	0.030	0.011	42
	3121013	2.37	4.77	250	16	5.2	13	0.032	0.01	47
5%SBS	3121511	2.35	3.44	245	15	6.0	18	0.032	0.007	45
	3121512	2.39	4.01	250	16	5.7	14	0.035	0.009	47
	3121513	2.36	4.21	285	17	6.1	20	0.035	0.007	53
5% SEBS	3122511	2.35	3.44	400	24	5.6	33	0.022	0.006	72
	3122512	2.34	4.01	405	24	5.9	23	0.023	0.009	74
	3122513	2.35	4.21	400	24	5.7	25	0.021	0.008	74
0% SBR	3123011	2.36	4.93	210	13	3.6	13	0.027	0.008	39
	3123012	2.36	4.32	220	13	3.7	14	0.027	0.008	40
	3123013	2.38	3.96	225	14	4.7	16	0.026	0.007	42
3% SBR	3123311	2.35	3.77	325	20	5.0	23	0.023	0.007	60
	3123312	2.31	3.85	350	21	4.8	29	0.020	0.006	63
	3123313	2.32	4.01	375	22	5.1	31	0.020	0.006	67
0% EAM	3124011	2.26	8.69	415	24	4.8	30	0.019	0.007	73
	3124012	2.26	8.77	450	25	5.6	32	0.021	0.007	76
	3124013	2.31	6.67	575	33	7.5	41	0.021	0.007	102
1% EAM	3124111	2.39	3.28	375	23	7.9	27	0.031	0.007	70
	3124112	2.40	3.11	400	25	9.1	25	0.030	0.008	75
	3124113	2.40	2.75	410	26	9.0	26	0.031	0.008	78

Table III.8 Summary of the indirect tensile strength test results of AC10 polymer modified asphalt mixtures at test temperature of 140°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3130051	2.36	4.25	225	14	4.9	9	0.038	0.012	37
	3130052	2.35	4.86	190	11	4.3	7	0.041	0.013	35
	3130053	2.35	4.82	200	12	4.4	10	0.032	0.01	36
	3130054	2.38	3.48	205	12	4.2	13	0.032	0.008	38
	3130055	2.38	3.57	210	13	3.9	15	0.029	0.007	39
	3130056	2.39	3.28	200	12	3.6	11	0.030	0.009	36
0%SEBS &SBS	3131011	2.36	4.34	375	23	7.4	21	0.028	0.009	70
	3131012	2.37	4.09	400	24	8.3	20	0.023	0.010	74
	3131013	2.38	3.61	385	23	8.4	21	0.033	0.009	71
5%SBS	3131511	2.36	4.20	310	19	5.2	19	0.025	0.008	56
	3131512	2.36	4.12	350	21	6.0	25	0.025	0.007	63
	3131513	2.37	4.04	310	19	5.2	19	0.025	0.008	57
5% SEBS	3132511	2.34	5.05	335	20	4.2	24	0.023	0.007	61
	3132512	2.35	4.81	400	24	5.9	29	0.020	0.007	73
	3132513	2.36	4.16	410	25	6.0	34	0.021	0.006	75
0% SBR	3133011	2.37	3.85	300	18	6.0	21	0.025	0.007	55
	3133012	2.38	3.73	340	21	6.7	28	0.026	0.006	64
	3133013	2.34	5.06	375	23	6.1	31	0.023	0.006	69
3% SBR	3133311	2.32	5.74	500	30	6.8	31	0.020	0.008	91
	3133312	2.28	7.65	440	26	5.2	37	0.018	0.006	78
	3133313	2.25	8.82	500	29	6.8	36	0.020	0.007	87
0%EAM	3134011	2.37	4.13	385	23	6.8	28	0.0260	0.007	71
	3134012	2.35	4.62	360	22	6.3	26	0.025	0.007	66
	3134013	2.37	3.81	390	24	4.4	24	0.029	0.008	72
2%EAM	3134211	2.38	3.61	445	27	7.7	28	0.025	0.008	83
	3134212	2.38	3.49	420	26	8.1	21	0.030	0.010	78
	3134213	2.38	3.57	475	29	7.8	30	0.025	0.008	87
10%CRM	31351011	2.37	3.81	325	20	5.0	15	0.029	0.011	60
	31351012	2.36	4.26	300	18	5.6	15	0.028	0.010	56
	31351013	2.38	3.57	350	21	5.0	19	0.026	0.009	65

Table III.9 Summary of the indirect tensile strength test results of AC20 polymer modified asphalt mixtures at test temperature of 140°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3140051	2.36	4.65	250	15	6	16	0.035	0.008	46
	3140052	2.38	3.68	225	14	6	13	0.036	0.009	42
	3140053	2.38	3.76	250	15	6	14	0.033	0.009	46
0%SBS	3141011	2.37	4.17	375	23	7	19	0.03	0.01	69
	3141012	2.36	4.61	425	25	7	27	0.026	0.008	77
	3141013	2.36	4.41	495	30	9	28	0.03	0.009	92
5%SBS	3141511	2.33	5.62	430	25	10	22	0.0330	0.0100	78
	3141512	2.33	5.74	410	24	8	21	0.0320	0.0100	74
	3141513	2.33	5.83	500	29	11	28	0.0260	0.0090	90
5%SEBS	3142511	2.34	5.42	650	41	9	30	0.026	0.011	120
	3142512	2.37	4.05	465	29	8	26	0.028	0.009	86
	3142513	2.37	3.96	465	29	9	23	0.031	0.01	86
0%SBR	3143011	2.37	4.17	250	15	5	16	0.031	0.008	46
	3143012	2.37	4.05	260	17	5	13	0.029	0.01	52
	3143013	2.38	3.84	275	17	5	17	0.029	0.008	51

Table III.9 Summary of the indirect tensile strength test results of AC20 polymer modified asphalt mixtures at test temperature of 140°F (continued).

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
3% SBR	3143301	2.38	3.80	360	22	9	18	0.038	0.01	67
	3143302	2.37	4.25	360	21	8	23	0.033	0.008	65
	3143303	2.38	3.80	400	24	7	25	0.026	0.008	74
0%EAM	3144011	2.36	4.37	450	27	9	23	0.03	0.01	82
	3144012	2.37	4.33	500	30	10	28	0.03	0.009	92
	3144013	2.35	4.89	550	33	9	39	0.025	0.007	100
2% EAM	3144211	2.37	4.33	600	37	11	30	0.035	0.01	110
	3144212	2.35	5.06	760	47	13	35	0.029	0.011	139
	3144213	-	-	-	-	-	-	-	-	-

Table III.10 Summary of the indirect tensile strength test results of oven aged AC10 polymer modified asphalt mixtures at test temperature of140 °F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3130021	2.38	3.57	130	8	3	4	0.043	0.015	24
	3130022	2.38	3.53	175	11	4	5	0.038	0.016	32
	3130023	2.38	3.48	240	15	4	8	0.036	0.015	45
5%SBS	3131521	2.35	4.48	325	19	6	18	0.030	0.009	59
	3131522	2.37	3.88	280	17	5	14	0.030	0.010	51
	3131523	2.37	3.88	305	19	6	15	0.029	0.010	57
3%SEBS	3132321	2.37	3.91	300	19	6	17	0.030	0.009	55
	3132322	2.38	3.51	285	18	5	14	0.027	0.010	53
	3132323	2.37	3.75	325	20	5	20	0.025	0.008	59
5% SEBS	3132521	2.36	4.24	319	20	6	7	0.041	0.022	58
	3132522	2.36	4.32	513	32	8	32	0.025	0.008	94
	3132523	2.36	4.12	525	33	7	44	0.021	0.006	97
3% SBR	3133321	2.38	3.51	315	19	5	18	0.026	0.009	57
	3133322	2.35	4.85	310	19	6	16	0.029	0.010	56
	3133323	2.35	4.56	300	18	6	19	0.029	0.008	54
2% EAM	3134221	2.38	3.41	475	30	9	26	0.028	0.009	87
	3134222	2.36	4.34	500	31	12	28	0.032	0.009	92
	3134223	2.38	3.57	570	36	9	41	0.03	0.007	105

Table III.11 Summary of the indirect tensile strength test results of oven aged AC20 polymer modified asphalt mixture at test temperature of140°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strengtb (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3140021	2.391	3.28	225	14	6	15	0.043	0.015	43
	3140022	2.375	3.92	260	16	5	26	0.035	0.010	49
	3140023	2.365	4.33	320	20	6	29	0.030	0.011	59
5%SBS	3141521	2.345	5.14	300	18	15	30	0.040	0.010	54
	3141522	2.369	4.17	400	24	13	36	0.040	0.011	73
	3141523	2.383	3.60	400	24	13	40	0.044	0.010	74
3%SEBS	3142321	2.385	3.52	320	20	10	25	0.037	0.013	60
	3142322	2.399	2.95	369	23	9	31	0.035	0.012	70
	3142323	2.383	3.60	350	21	8	32	0.034	0.011	65
5%SEBS	3142521	2.368	4.21	385	24.2	9	30	0.035	0.013	72
	3142522	2.378	3.80	370	23.2	7	37	0.030	0.010	68
	3142523	2.363	4.41	390	24.5	8	35	0.031	0.011	72
3% SBR	3143311	2.391	3.28	312	19	7	31	0.030	0.01	59
	3143312	2.388	3.40	325	20	6	33	0.029	0.01	60
	3143313	2.395	3.11	350	22	8	39	0.031	0.009	66
2% EAM	3144221	2.361	4.49	675	40	10	68	0.03	0.01	122
	3144222	2.354	4.77	825	49	17	75	0.033	0.011	151
	3144223	2.352	4.85	950	57	17	79	0.032	0.012	172

Table III.12 Summary of the percent increase or decrease of the ITST results of PMA mixtures with respect to processed mixtures at test temperature of 140°F.

a) ACS PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC5-5%SBS	14	26	10	55
AC5-5%SEBS	71	21	-29	145
AC5-2%SBR	8	8	0	21
AC5-1%EAM	-11	45	55	-24

b) AC10 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC10-5%SBS	-21	-31	-11	1
AC10-5%SEBS	-4	-32	-25	45
AC10-3%SBR	33	0	-24	30
AC10-2%EAM	17	36	0	2
AC10-10%CRM	-5	-17	0	-39

c) AC20 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC20-5%SBS	2	22	3	-4
AC20-5%SEBS	27	13	-3	8
AC20-3%SBR	38	59	7	47
AC20-2%EAM	40	28	14	7

Note: Negative sign indicates percent decrease.

Table III.13 Summary of the indirect tensile test strength results of AC20 polymer modified asphalt mixtures at test temperature of 77°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3240051	2.36	4.45	2000	122	51	67	0.041	372
	3240052	2.36	4.69	2225	134	52	86	0.040	408
	3240053	2.36	4.65	2050	123	50	85	0.038	376
0%SBS	3241011	2.36	4.61	2525	149	63	97	0.040	453
	3241012	2.35	5.10	2700	159	64	113	0.037	484
	3241013	2.37	4.05	2700	163	70	113	0.040	496
5%SBS	3241511	2.32	6.15	3634	227	99	131	0.055	691
	3241512	2.34	5.34	4000	250	109	180	0.051	761
	3241513	2.32	6.11	3898	244	96	198	0.047	741
3%SEBS	3242311	2.36	4.65	3618	226	103	185	0.052	687
	3242312	2.35	4.85	3820	239	103	153	0.053	726
	3242313	2.34	5.22	3502	219	86	189	0.046	666
5%SEBS	3242511	2.38	3.92	3900	245	85	139	0.036	725
	3242512	2.37	4.17	3950	243	85	141	0.038	717
	3242513	2.37	4.25	3825	235	79	147	0.037	694
0% SBR	3243011	2.37	4.21	2375	143	54	91	0.039	436
	3243012	2.37	4.09	2375	143	63	108	0.041	436
	3243013	2.38	3.60	2450	148	65	123	0.041	450
3% SBR	3243301	2.33	5.62	3093	193	83	144	0.049	588
	3243302	2.33	5.83	3180	199	96	160	0.053	605
	3243303	2.33	5.74	3083	193	71	168	0.044	586
0% EAM	3244211	2.38	3.80	3300	200	71	127	0.035	610
	3244212	2.36	4.45	3500	213	74	125	0.036	650
	3244213	2.38	3.76	3550	215	78	127	0.038	656
2% EAM	3244211	2.38	3.56	4100	249	100	137	0.040	757
	3244212	2.38	3.76	4500	274	110	141	0.038	836
	3244213	2.37	4.25	4725	288	109	139	0.040	878

Table III.14 Summary of the percent increase or decrease of the ITST results of PMA mixtures with respect to processed mixtures at test temperature of 77°F.

a) AC5 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC5-5%SBS	48	12	-23	125
AC5-5%SEBS	42	16	-12	56
AC5-2%SBR	18	10	4	56
AC5-1%EAM	13	4	4	13

b) AC10 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC10-5%SBS	39	38	4	33
AC10-5%SEBS	38	17	-9	49
AC10-3%SBR	9	-8	-19	-15
AC10-2%EAM	10	0	-6	2
AC10-10%CRM	60	46	-11	-2

c) AC20 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC20-5%SBS	53	53	31	58
AC20-5%SEBS	54	26	-5	33
AC20-3%SBR	34	38	23	45
AC20-2%EAM	29	43	8	10

Note: Negateive sign indicates percent decrease.

Table III.15 Summary of the indirect tensile strength test results of oven aged AC5 polymer modified asphalt mixtures at test temperature of 77°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3220021	2.36	4.57	1,434	87	53	66	0.063	266
	3220022	2.36	4.61	1,161	71	66	34	0.090	215
	3220023	2.37	4.24	1,517	93	53	77	0.057	283
	3220024	2.35	4.93	1,649	100	46	98	0.049	304
	3220025	2.37	4.32	1,449	88	54	58	0.063	269
	3220026	2.38	3.96	1,556	94	53	49	0.060	285
0%SEBS &SBS	3221021	2.36	4.53	1,527	92	43	67	0.050	280
	3221022	2.37	4.04	1,546	95	52	86	0.057	290
	3221023	2.36	4.77	1,546	93	67	45	0.076	282
	3222021	2.35	4.97	2,883	174	66	182	0.042	528
	3222022	2.37	4.20	2,405	147	83	89	0.061	446
	3222023	2.36	4.61	2,771	166	68	150	0.045	505
5%SBS	3221521	2.38	3.44	2,673	166	58	143	0.042	505
	3221522	2.37	4.01	2,571	157	58	111	0.045	477
	3221523	2.36	4.21	2,624	157	57	107	0.044	478
5% SEBS	3222521	2.36	4.25	3,054	183	61	158	0.040	556
	3222522	2.36	4.54	2,898	176	65	127	0.044	534
	3222523	2.39	3.36	2,990	182	63	160	0.040	555
0% SBR	3223021	2.35	4.93	1,644	98	49	66	0.055	300
	3223022	2.36	4.41	1,673	102	59	61	0.059	310
	3223023	2.36	4.69	1,532	93	80	31	0.095	284
3% SBR	3223321	2.37	3.97	1,659	102	55	106	0.054	312
	3223322	2.36	4.41	1,624	98	46	68	0.051	299
	3223323	2.35	4.78	1,610	98	54	64	0.056	297
0% EAM	3224021	2.38	3.60	2,293	138	55	123	0.046	420
	3224022	2.41	2.43	2,376	148	67	126	0.050	452
	3224023	2.40	2.91	2,498	153	77	122	0.056	466
1% EAM	3224121	2.38	3.64	2,956	179	74	127	0.050	545
	3234122	2.37	3.96	2,902	176	68	133	0.045	535
	3224123	2.38	3.92	2,854	174	63	179	0.041	529

Table III.16 Summary of theindirect tensile strength test results of oven aged AC10 polymer modified asphalt mixtures at test temperature of 77°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3230021	2.38	3.44	2060	124	57	137	0.0420	378
	3230022	2.33	5.59	2040	122	67	157	0.0400	372
	3230023	2.36	4.38	2000	120	50	182	0.0370	367
0%SEBS &SBS	3231021	2.38	3.77	2510	151	69	228	0.040	461
	3231022	2.34	5.15	3040	180	74	507	0.031	548
	3231023	2.37	3.81	3250	195	75	217	0.039	593
5%SBS	3231521	2.37	4.00	3000	182	71	300	0.035	554
	3231522	2.38	3.27	3050	187	79	254	0.040	570
	3231523	2.37	3.75	3200	192	72	267	0.035	584
5% SEBS	3232521	2.36	4.40	3000	181	61	300	0.031	551
	3232522	2.35	4.52	3500	208	73	250	0.036	635
	3232523	2.37	4.04	3100	187	69	221	0.040	569
0% SBR	3233021	2.39	3.24	2450	150	64	204	0.038	458
	3233022	2.36	4.38	2450	147	57	204	0.036	447
	3233023	2.38	3.69	2500	152	68	179	0.04	465
3% SBR	3233321	2.36	4.24	2450	147	67	204	0.04	447
	3233322	2.37	4.00	2600	158	52	236	0.035	480
	3233323	2.39	2.94	2650	165	72	265	0.04	502
0% EAM	3234021	2.36	4.58	3750	227	84	313	0.035	692
	3234022	2.33	5.47	4250	253	91	283	0.037	770
	3234023	2.34	5.06	4360	260	94	273	0.039	790
2% EAM	3234221	2.38	3.41	3375	206	72	281	0.036	626
	3234222	2.34	4.99	3775	225	81	343	0.034	684
	3234223	2.33	5.47	3750	223	69	341	0.031	679

Table III.17 Summary of the indirect tensile strength test results of oven aged AC20 polymer modified sphalt mixtures at test temperature of 77° F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Displacement at 1/2 load (in)	Compressive Strength (psi)
Straight	3240021	2.388	3.40	3,300	202	93	110	0.046	0.015	617
	3240022	2.385	3.52	3,600	222	81	120	0.038	0.015	677
	3240023	2.387	3.44	3,625	227	113	91	0.05	0.02	690
5%SBS	3241521	2.367	4.25	3,725	229	78	169	0.0350	0.0110	696
	3241522	2.339	5.38	3,650	217	77	130	0.0350	0.0140	662
	3241523	2.353	4.81	3,750	226	82	134	0.0370	0.0140	688
5%SEBS	3242521	2.372	4.05	3,250	202	84	102	0.041	0.016	597
	324222	2.363	4.41	3,260	204	83	116	0.038	0.014	602
	3242523	2.369	4.17	3,650	230	81	130	0.037	0.014	678
3% SBR	3243321	2.376	3.88	3,350	204	85	129	0.039	0.013	622
	3243322	2.393	3.20	3,675	225	90	153	0.040	0.012	687
	3243323	2.387	3.44	3,600	218	87	138	0.038	0.013	665
2% EAM	3244221	2.384	3.56	3,850	235	92	113	0.041	0.017	715
	3244222	2.380	3.72	4,500	273	90	150	0.04	0.015	831
	3244223	2.400	2.91	5,000	305	93	147	0.041	0.017	929

Table III.18 Summary of the indirect tensile strength test results of AC10 polymer modified asphalt mixtures at test temperature of 23° F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3430051	2.39	3.24	8000	497	187	222	0.040	1512
	3430052	2.33	5.59	8400	500	130	233	0.031	1521
	3430053	2.36	4.38	9010	549	180	237	0.041	1671
0%SEBS &SBS	3431011	2.38	3.73	8150	500	145	272	0.033	1521
	3431012	2.37	3.85	8500	512	145	236	0.034	1558
	3431013	2.37	3.81	8700	524	159	335	0.033	1594
5%SBS	3431511	2.38	3.35	9150	551	129	305	0.030	1677
	3431512	2.38	3.43	9300	564	137	291	0.030	1715
	3431513	2.38	3.59	9300	567	154	274	0.030	1726
5% SEBS	3432511	2.37	3.67	9250	561	170	210	0.040	1706
	3432512	2.37	3.92	9300	557	127	274	0.031	1695
	3432513	2.37	4.04	10000	602	144	313	0.029	1833
0% SBR	3433011	2.39	3.24	8950	546	125	320	0.028	1661
	3433012	2.38	3.77	8213	495	113	257	0.029	1505
	3433013	2.39	3.32	8730	529	130	336	0.028	1610
3% SBR	3433311	2.37	4.04	8050	526	146	224	0.036	1600
	3433312	2.37	3.75	9500	576	182	250	0.038	1752
	3433313	2.35	4.60	8400	500	152	191	0.039	1521
5% SBR	3433511	2.36	4.08	8950	546	135	280	0.031	1661
	3433512	2.36	4.20	8425	501	131	301	0.0290	1526
	3433513	2.36	4.16	8450	506	144	264	0.033	1540
0% EAM	3434011	2.40	2.96	8125	505	129	226	0.0340	1535
	3434012	2.37	3.85	8625	526	122	254	0.030	1600
	3434013	2.38	3.73	9350	570	166	234	0.039	1735
2% EAM	3434211	2.38	3.69	10500	640	169	328	0.032	1948
	3434212	2.36	4.42	10250	611	162	301	0.032	1856
	3434213	2.36	4.18	9750	580	147	271	0.032	1766
10% CRM	34351011	2.34	5.09	10400	630	231	200	0.046	1921
	34351012	2.34	5.21	8850	527	168	221	0.038	1605
	34351013	2.35	4.89	9250	551	164	243	0.035	1678

Table III.19 Summary of the indirect tensile strength test results of AC20 polymer modified asphalt mixtures. at test temperature of 23° F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3440051	2.36	4.41	9,850	586	207	235	0.042	1787
	3440052	2.36	4.61	9,200	551	158	256	0.035	1679
	3440053	2.35	4.85	8,700	518	149	218	0.035	1578
0%SBS	3441011	2.35	5.14	8,600	524	159	307	0.037	1598
	3441012	2.35	4.89	8,250	503	149	243	0.036	1533
	3441013	2.37	3.96	9,125	556	173	217	0.038	1595
5%SBS	3441511	2.31	6.47	8,900	517	151	223	0.0380	1577
	3441512	2.34	5.30	9,100	532	140	228	0.0340	1622
	3441513	2.32	6.19	9,400	546	161	235	0.0370	1665
5%SEBS	3442511	2.36	4.53	8,850	544	141	260	0.034	1605
	3442512	2.36	4.57	9,150	562	158	229	0.039	1660
	3442513	2.38	3.60	9,950	626	172	216	0.038	1849
0% SBR	3443011	2.36	4.45	8,200	500	148	241	0.036	1524
	3443012	2.35	4.81	6,900	416	138	182	0.04	1267
	3443013	2.36	4.49	8,600	512	134	253	0.031	1560
3% SBR	3443311	2.38	3.64	8,300	509	151	198	0.040	1552
	3443312	2.36	4.69	9,200	558	170	271	0.039	1699
	3443313	2.41	2.59	10,200	633	227	213	0.045	1931
0% EAM	3444011	2.35	4.85	8,925	538	165	235	0.037	1638
	3444012	2.36	4.53	9,100	555	164	217	0.036	1691
	3444013	2.35	4.94	8,900	536	160	223	0.036	1634
2% EAM	3444211	2.35	4.81	9,650	530	166	230	0.036	1751
	3444212	2.36	4.53	10,200	627	176	243	0.036	1850
	3444213	2.38	3.60	10,600	667	198	221	0.04	1969

Table III.20 Summary of the indirect tensile strength test results of oven aged AC10 polymer modified asphalt mixtures at test temperature of 23°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3430021	2.39	3.20	7,625	465	172	201	0.039	1,414
	3430022	2.37	4.01	8,050	488	124	224	0.032	1,484
	3430023	2.37	3.81	7,910	520	132	233	0.033	1,583
5%SBS	3431521	2.39	3.06	9,200	561	168	219	0.040	1,709
	3431522	2.38	3.59	9,250	564	156	243	0.035	1,719
	3431523	2.37	3.96	8,150	491	165	185	0.041	1,496
5% SEBS	3432521	2.36	4.36	9,450	562	165	236	0.035	1,711
	3432522	2.36	4.44	9,300	557	172	221	0.037	1,694
	3432523	2.37	4.00	8,900	536	160	247	0.036	1,631
3% SBR	3433321	2.38	3.51	10,050	625	140	279	0.031	1,845
	3433322	2.35	4.85	9,800	609	140	288	0.03	1,799
	3433323	2.35	4.56	9,600	597	149	320	0.031	1,762
2% EAM	3434221	2.38	3.41	10,200	618	194	255	0.04	1884
	3434222	2.37	3.85	10,000	606	180	238	0.038	1847
	3434223	2.38	3.33	10,200	622	194	268	0.038	1895

Table III.21 Summary of the indirect tensile strength test results of oven aged AC20 polymer modified asphalt mixtures at test temperature of 23°F.

Mix Type	Sample Designation Number	Specific Gravity	Percent Air Voids	Peak Load (lbs)	Tensile Strength (psi)	Toughness (lb.in)	Total Modulus (ksi)	Vertical Displacement (in)	Compressive Strength (psi)
Straight	3440021	2.383	3.60	9,250	567	157	220	0.037	1729
	3440022	2.389	3.36	8,775	535	141	244	0.034	1630
	3440023	2.374	3.96	9,150	558	147	241	0.034	1700
5%SBS	3441521	2.353	4.81	9,300	560	150	245	0.0350	1707
	3441522	2.350	4.94	9,700	577	177	243	0.0380	1759
	3441523	2.375	3.92	10,200	611	190	243	0.0390	1862
3%SEBS	3442321	2.375	3.92	9,450	576	151	295	0.032	1756
	3442322	2.377	3.84	7,675	468	119	192	0.035	1427
	3442323	2.388	3.40	9,400	577	158	247	0.035	1757
5%SEBS	3442521	2.356	4.69	8,700	524	143	242	0.034	1594
	3442522	2.362	4.45	9,700	592	153	255	0.034	1800
	3442523	2.361	4.49	7,600	461	121	271	0.03	1401
3% SBR	3443321	2.398	2.99	10,400	634	184	236	0.040	1932
	3443322	2.340	5.34	8,600	512	170	215	0.04	1560
	3443323	2.335	5.54	10,100	601	184	253	0.041	1832
2% EAM	3444221	2.343	5.22	10,400	615	190	260	0.037	1875
	3444222	2.327	5.87	9,800	583	179	245	0.037	1778
	3444223	2.368	4.21	10,400	634	182	248	0.038	1932

Table III.22 Summary of the percent increase or decrease of the ITST results of PMA mixtures with respect to processed mixtures at test temperature of 23°F.

a) AC10 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC10-5%SBS	10	-7	-9	3
AC10-5%SEBS	12	-2	0	-5
AC10-3%SBR	2	30	36	-27
AC10-2%EAM	14	14	-6	26
AC10-10%CRM	9	53	43	-27

b) AC20 PMA Mixtures

Mix Type	Tensile Strength	Toughness	Vertical Deformation	Total Modulus
AC20-5%SBS	1	-6	-3	-11
AC20-5%SEBS	9	-2	0	-8
AC20-3%SBR	7	31	14	1
AC20-2%EAM	15	10	3	3

Note: Negative sign indicates percent decrease.

Table III.23 Summary of the indirect cyclic load test results of AC5 PMA mixtures at test temperature of 77°F.

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Number of Cycles to Failure	Fatigue Life (cycles)	Horiz. Plastic Deform.	Resilient modulus (psi)
Straight	2220051	2.38	3.72	5,400	1,500	0.0153	213,546
	2220052	2.38	3.88	7,300	1,700	0.0130	203,908
	2220053	2.40	3.15	11,500	2,900	0.0143	215,976
0%SEBS & SBS	2220011	2.39	3.36	47,000	6,000	0.0053	325,589
	2220012	2.36	4.73	19,000	1,000	0.0010	318,925
	2220013	2.38	3.68	40,000	8,000	0.0092	313,784
3% SBS	2221311	2.40	2.71	55,000	19,000	0.0096	303,990
	2221312	2.40	3.04	89,000	30,000	0.0068	322,327
	2221313	2.39	3.24	68,000	25,000	0.0125	291,542
4% SBS	2221411	2.37	4.21	230,000	50,000	0.0008	304,375
	2221412	2.38	3.44	77,000	-	-	-
	2221413	2.39	3.16	110,000	40,000	0.0034	272,577
5% SBS	2221511	2.37	3.93	196,000	50,000	0.0036	335,775
	2221512	2.38	3.61	253,000	100,000	0.0019	425,176
	2221513	2.39	3.08	250,000	50,000	0.0005	430,233
7%SBS	2221711	2.38	3.69	123,000	50,000	0.0029	323,652
	2221712	2.36	4.30	111,000	30,000	0.0021	319,752
	2221713	2.36	4.30	106,000	30,000	0.0023	367,837
2% SEBS	2222211	2.36	4.41	129,000	30,000	0.0153	413,609
	2222212	2.36	4.45	135,000	40,000	0.0170	351,145
	2222213	2.37	4.09	77,000	-	-	-
3% SEBS	2222311	2.36	4.33	350,000	30,000	0.0007	344,530
	2222312	2.38	3.81	300,000	40,000	0.0088	422,332
	2222313	2.38	3.81	360,000	70,000	0.0043	347,886
4% SEBS	2222411	2.37	4.13	89,000	15,000	0.0031	536,757
	2222412	2.36	4.33	120,000	50,000	0.0081	417,242
	2222413	2.39	3.20	204,000	70,000	0.0124	411,205
5% SEBS	2222511	2.37	3.97	290,000	50,000	0.0015	408,013
	2222512	2.37	4.05	293,000	50,000	0.0014	338,402
	2222513	2.36	4.34	280,000	50,000	0.0005	430,233

Table III.23 Summary of the indirect cyclic load test results of AC5 PMA mixtures at test temperature of 77°F (continued).

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Number of Cycles to Failure	Fatigue Life (cycles)	Horiz. Plastic Deform.	Resilient modulus (psi)
7% SEBS	2222711	2.35	4.66	169,000	25,000	0.0032	336,350
	2222712	2.37	3.81	107,000	47,500	0.0052	361,649
	2222713	2.36	4.22	173,000	--	–	315,872
0% SBR	2223011	2.35	4.97	14,700	4,000	0.0115	279,434
	2223012	2.37	4.08	26,000	1,500	0.0037	297,707
	2223013	2.37	4.08	17,000	5,000	0.0160	261,726
2% SBR	2223211	2.37	4.29	14,500	1,000	0.0044	241,446
	2223212	2.36	4.65	5,900	1,000	0.0116	240,960
	2223213	2.38	3.72	13,000	3,000	0.0132	247,639
3% SBR	2223311	2.37	4.25	39,000	10,000	0.0086	365,614
	2223312	2.36	4.33	40,000	10,000	0.0167	300,548
	2223313	2.35	4.78	62,000			
4% SBR	2223411	2.35	4.78	55,000	20,000	0.0047	302,917
	2223412	2.34	5.18	15,000	5,000	0.0103	285,986
	2223413	2.37	4.17	98,000	20,000	0.0075	310,989
5% SBR	2223511	2.34	5.15	22,000	10,000	0.0041	293,276
	2223512	2.33	5.63	12,000	-	-	
	2223513	2.36	4.34	56,000	10,000	0.0057	271,187
0% EAM	2224011	2.34	5.50	91,000	20,000	0.0096	369,841
	2224012	2.37	4.25	142,000	15,000	0.0026	362,230
	2224013	2.33	5.70	184,000	40,000	0.0091	362,008
1% EAM	2224111	2.32	6.03	1,200,000	U	(0.00373)	370,237
	2224112	2.34	5.38	1,000,000	U	----------	414,185
	2224113	2.35	5.02	1,400,000	U	(0.002458)	440,455
2% EAM	2224211	2.35	5.02	1,500,000	U	(0.00278)	348,755
	2224212	2.34	5.18	1,040,000	U	---------	
	2224213	2.37	4.25	1,100,000	U	(0.00145)	440,013
3% EAM	2224311	2.34	5.22	1,200,000	350,000	0.006227	430,415
	2224312	2.34	5.14	250,000	U	(0.00361)	371,168
	2224313	2.35	4.90	178,000	U	(0.00362)	359,334

Note: The values in Parenthesis represent Horizontal Plastic Deformation (HPD) at 100,000 load cycles

Table III.24 Summary of the indirect cyclic load test results of AC10 PMA mixtures at test temperature of 77°F.

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Number of Cycles to Failure	Fatigue Life (cycles)	Horiz. Plastic Deform.	Resilient modulus (psi)
Straight	2230054	2.398	2.84	......	6,000	0.0142	236,307
	2230055	2.384	3.40	....	5,000	0.0139	274,120
	2230056	2.372	3.89	....	4,000	0.0137	290,168
0%SEBS & SBS	2230021	2.361	4.34	47,000	13,000	0.0151	355,374
	2230022	2.378	3.65	80,000	16,000	0.0095	355,398
	2230023	2.387	3.28	106,000	27,000	0.0101	392,579
3% SBS	2231311	2.375	3.67	163,000	-	-	-
	2231312	2.374	3.71	124,000	40,000	0.0100	321,030
	2231313	2.372	3.79	182,000	10,000	0.0019	339,756
4% SBS	2231411	2.334	5.31	191,000	25,000	0.0016	382,603
	2231412	2.331	5.44	122,000	10,000	0.0052	361,434
	2231413	2.348	4.75	------	70,000	0.0045	432,789
5% SBS	2231514	2.380	3.43	305,000	30,000	0.0019	418,142
	2231515	2.372	3.75	608,000	150,000	0.0069	330,837
	2231516	2.361	4.20	575,000	200,000	0.0197	355,420
2% SEBS	2232211	2.370	3.89	275,000	100,000	0.0095	515,824
	2232212	2.402	2.60	360,000	100,000	0.0114	409,875
	2232213	2.365	4.10	195,000	50,000	0.0050	385,997
4% SEBS	2232411	2.388	3.12	221,000	40,000	0.0020	457,524
	2232412	2.380	3.45	291,000	40,000	0.0014	405,149
	2232413	2.395	2.84	165,000	55,000	0.0084	382,907
5% SEBS	2232511	2.368	3.92	401,000	150,000	0.0068	346,660
	2232512	2.384	3.27	710,000	60,000	0.0023	569,369
	2232513	2.404	2.45	576,000	150,000	0.0045	396,834
7% SEBS	2232711	2.340	5.01	158,000	40,000	0.0048	473,683
	2232712	2.354	4.44	124,000	60,000	0.0318	401,883
	2232713	2.353	4.49	90,000	40,000	0.0024	391,829

Table III.24 Summary of the indirect cyclic load test results of AC10 PMA mixtures at test temperature of 77°F (continued).

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Number of Cycles to Failure	Fatigue Life (cycles)	Horiz. Plastic Deform.	Resilient modulus (psi)
0% SBR	2233011	2.362	4.29	77,000	15,000	0.0045	319,216
	2233012	2.362	4.29	64,000	20,000	0.0164	371,701
	2233013	2.383	3.44	58,000	16,000	0.0125	312,321
2% SBR	2233211	2.344	4.95	225,000	50,000	0.0093	461,584
	2233212	2.384	3.33	220,000	45,000	0.0083	378,331
	2233213	2.371	3.85	294,000	50,000	0.0095	394,701
3% SBR	2233311	2.346	4.85	196,000	90,000	0.0135	434,567
	2233312	2.363	4.16	295,000	85,000	0.0045	457,505
	2233313	2.386	3.22	112,000	30,000	0.0058	417,993
4% SBR	2233411	2.333	5.37	68,000	40,000	0.0216	398513.6
	2233412	2.336	5.25	63,000	20,000	0.0163	350228.1
	2233413	2.365	4.08	71,000	40,000	0.0254	399880.9
5% SBR	2233511	2.335	5.27	22,000	40,000	0.0239	338610.3
	2233512	2.345	4.87	89,000	30,000	0.0091	398760.5
	2233513	2.362	4.18	110,000	10,000	0.0010	372265.8
0% EAM	2234011	2.368	3.92	340,000	20,000	.00223	362,725
	2234012	2.355	4.44	523,000	60,000	.00140	438,283
	2234013	2.373	3.71	300,000	100,000	.0119	504,538
1% EAM	2234111	2.354	4.54	200,000	U	(0.0050)	403,515
	2234112	2.364	4.14	200,000	U	(0.0093)	472,060
	2234113	2.348	4.79	200,000	U	(0.0064)	452,692
2% EAM	2234211	2.348	4.79	300,000	U	(0.0025)	479,887
	2234212	2.369	3.93	300,000	U	(0.0019)	454,999
	2234213	2.358	4.38	300,000	U	------	481,854
3% EAM	2234311	2.362	4.20	300,000	U	(0.0024)	442,635
	2234312	2.359	4.32	300,000	U	(0.0018)	333,161
	2234313	2.354	4.52	-	-	-	-

Table III.25 Summary of the indirect cyclic load test results of AC20 PMA mixtures at test temperature °F77

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Number of Cycles to Failure	Fatigue Life (cycles)	Horiz. Plastic Deform.	Resilient modulus (psi)
Straight	2240051	2.366	4.13	71,000	20,000	0.0116	410,135
	2240052	2.363	4.25	74,000	40,000	0.0189	416,953
	2240053	2.373	3.85	75,000	15,000	0.0096	434,829
0%SEBS & SBS	2240041	2.378	3.65	220,000	100,000	0.0111	494,604
	2240042	2.360	4.38	178,000	60,000	0.0165	453,565
	2240043	2.377	3.69	180,000	60,000	0.0054	463,208
5% SBS	2241511	2.320	6.00	240,500	110,000	0.0110	514,403
	2241512	2.335	5.39	1,065,000	500,000	0.0078	541,334
	2241513	2.334	5.43	860,000	220,000	0.0020	430,633
5% SEBS	2242511	2.360	4.38	400,000	-	-	409,608
	2242512	2.378	3.65	300,000	60,000	0.0008	457,551
	2242513	2.354	4.62	200,000	99,000	0.0018	426,505
3% SBR	2243301	2.363	4.25	459,000	140,000	0.0094	429,052
	2243302	2.359	4.42	227,000	90,000	0.0159	475,645
	2243303	2.390	3.16	631,000	20,000	0.0009	568,501
2% EAM	2244211	2.340	5.19	U	U	0.0002	326,314
	2244212	2.362	4.29	U	U	0.0008	393,032
	2244213	2.337	5.31	U	U	0.0044	332,208

Table III.26 Summary of the indirect cyclic load test results of AC5 PMA mixtures at test temperature °F 23

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Resilient modulus (psi)			Deformation rate (in/cycle)
				500	1,000	5,000	
Straight	2420051	2.36	4.77	774,493	913,271	1,026,678	3.12E-08
	2420052	2.37	4.33	761,615	799,665	859,985	1.43E-08
	2420053	2.35	4.85	699,540	775,414	774,977	1.73E-07
0%SEBS & SBS	2420011	2.36	4.77	609,534	612,766	637,272	5.90E-08
	2420012	2.34	5.30	514,659	525,888	596,065	4.27E-08
	2420013	2.37	4.33	511,694	517,196	545,087	3.27E-09
3% SBS	2421311	2.36	4.41	662,336	671,602	639,979	3.08E-08
	2421312	2.36	4.45	673,443	692,097	685,733	2.63E-08
	2421313	2.37	4.09	420,967	415,421	430,284	4.69E-09
4% SBS	2421411	2.34	5.14	660,523	588,284	552,967	1.20E-08
	2421412	2.34	5.35	631,335	631,289	640,514	3.73E-08
	2421413	2.35	4.66	897,458	1,101,863	1,190,630	4.76E-08
5% SBS	2421511	2.34	5.19	506,145	504,543	501,396	5.92E-09
	2421512	2.33	5.51	847,165	887,422	981,725	1.24E-08
	2421513	2.34	5.15	659,136	699,384	634,238	1.71E-08
7%SBS	2421711	2.36	4.38	833,335	884,224	848,956	8.16E-10
	2421712	2.37	4.06	770,652	784,412	706,617	1.72E-07
	2421713	2.37	3.93	568,707	585,651	585,519	6.76E-08
3% SEBS	2422311	2.36	4.57	1,134,272	1,109,584	1,114,385	-
	2422312	2.37	4.17	801,637	815,905	796,795	2.69E-08
	2422313	2.35	4.82	915,671	990,248	1,124,142	1.76E-08
5% SEBS	2422511	2.36	4.50	787,754	836,594	756,732	1.32E-07
	2422512	2.35	4.98	719,158	710,531	726,881	4.29E-09
	2422513	2.35	4.94	632,872	650,130	635,775	1.78E-08
7% SEBS	2422711	2.38	3.57	1,018,972	1,127,216	1,284,298	8.86E-08
	2422712	2.37	4.06	1,053,122	1,201,501	1,538,329	8.98E-09
	2422713	2.38	3.65	1,084,193	869,609	896,367	5.97E-07

Table III.27 Summary of the indirect cyclic load test results of AC10 PMA mixtures at test temperature of 23°F.

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Resilient modulus (psi)			Deformation rate (In/cycle)
				500	1,000	5,000	
Straight	2430051	2.36	4.42	582,008	627,239	582,312	2.03E-08
	2430052	2.36	4.38	651,477	676,250	765,989	-1.39E-08
	2430053	2.37	3.85	790,813	946,818	1,138,111	3.06E-08
0%SEBS & SBS	2430011	2.38	3.44	866,869	983,683	1,051,891	1.20E-08
	2430012	2.36	4.21	936,280	968,361	798,109	5.59E-07
	2430013	2.33	5.43	1,290,847	1,146,763	1,209,149	1.71E-07
3% SBS	2431311	2.38	3.69	1,502,005	1,703,050	1,800,817	1.88E-08
	2431312	2.37	3.97	524,106	537,150	520,178	1.08E-08
	2431313	2.36	4.30	805,790	877,745	957,929	1.39E-08
4% SBS	2431411	2.36	4.20	597,991	657,725	735,322	6.53E-09
	2431412	2.37	3.83	783,213	774,705	784,548	1.27E-08
	2431413	2.37	4.08	1,095,111	-	-	5.08E-07
5% SBS	2431511	2.36	4.26	631,170	650,873	699,062	2.82E-08
	2431512	2.37	3.85	880,007	929,148	823,503	2.86E-09
	2431513	2.37	3.73	912,951	944,293	947,405	4.06E-08
3% SEBS	2432311	2.36	4.34	1,014,128	1,235,769	1,595,923	2.78E-08
	2432312	2.37	4.06	-	-	-	-
	2432313	2.38	3.53	1,036,075	1,178,083	1,467,469	4.14E-08
5% SEBS	2432511	2.35	4.54	653,017	709,034	766,954	2.94E-08
	2432512	2.35	4.50	648,922	642,742	639,896	2.46E-08
	2432513	2.37	3.94	679,462	688,175	743,017	1.21E-07
0% SBR	2433011	2.40	2.88	-	-	-	-
	2433012	2.36	4.46	1,054,758	1,046,536	1,054,136	2.65E-09
	2433013	2.38	3.61	972,054	1,023,350	1,080,048	1.30E-08
3% SBR	2433311	2.36	4.30	-	-	-	-
	2433312	2.33	5.56	471,261	498,021	564,801	2.58E-07
	2433313	2.32	6.12	790,554	937,631	1,012,691	1.25E-09
0% EAM	2434011	2.37	3.89	442,211	414,490	…….	9.68E-08
	2434012	2.35	4.66	517,769	534,369	………	6.74E-08
	2434013	2.36	4.38	-	-	…….	-
2% EAM	2434211	2.34	5.27	425,185	517,510	663,844	1.88E-07
	2434212	2.34	4.99	451,217	457,209	466,163	1.00E-07
	2434213	2.37	3.93	573,674	556,328	559,623	2.71E-08

Table III.28 Summary of the indirect cyclic load test results of AC10 PMA mixtures at test temperature of 140°F.

MIX TYPE	Sample Designation Number	Specific Gravity	Percent Air voids	Resilient modulus (psi)	Deformation Rate (in/cycle)	Vertical Plastic Deformation (in)		
						0.03"	0.05"	0.07"
Straight	2130051	2.350	4.78	Less than 100 cycles				
	2130052	2.363	4.25					
	2130053	2.363	4.25					
5% SBS	2131511	2.368	3.94	81382	9.76E-04	59	81	96
	2131512	2.392	2.96	90959	2.50E-04	85	129	152
	2131513	2.389	3.08	97510	1.74E-04	90	125	146
3% SEBS	2132311	2.373	3.77	Less than 100 cycles				
	2132312	2.366	4.06					
	2132313	2.377	3.61					
5% SEBS	2132511	2.368	3.94	94545	2.65E-04	95	145	170
	2132512	2.392	2.96	91810	4.28E-04	80	110	135
	2132513	2.389	3.08	103515	3.40E-04	90	125	145
3% SBR	2133311	2.411	2.23	Less than 100 cycles				
	2133312	2.376	3.65					
	2133313	2.380	3.49					
2% EAM	2134211	2.381	3.45	92077	2.73E-04	95	125	145
	2134212	2.399	2.72	96186	1.88E-04	110	175	210
	2134213	2.376	3.65	96186	2.57E-04	100	145	160

Table III.29 Summarry of the percent increase or decrease in the resilient modulus of PMA mixtures.

AC5 PMA mixtures.

Mix Type	Unaged Samples			Oven Aged Samples		
	23° F	77° F	140° F	23° F	77° F	140° F
AC5-5%SBS	23	24	.....	.....	.....	.....
AC5-5%SEBS	31	42	.....	.....	.....	.....
AC5-2%SBR	.....	19	.....	.....	.....	.....
AC5-1%EAM	.....	12	.....	.....	.....	.....

AC10 PMA mixtures.

Mix Type	Unaged Samples			Oven Aged Samples		
	23° F	77° F	140° F	23° F	77° F	140° F
AC10-5%SBS	-22	7	.....	-8	48	.....
AC10-5%SEBS	-36	19	.....	1	106	.....
AC10-3%SBR	-38	31	.....	12	58	.....
AC10-2%EAM	1	9	.....	-18	45	.....
AC10-10%CRM	.....	1	.....	.....	.....	.....

AC20 PMA mixtures.

Mix Type	Unaged Samples			Oven Aged Samples		
	23° F	77° F	140° F	23° F	77° F	140° F
AC20-5%SBS	.....	18	.....	.....	.....	.....
AC20-5%SEBS	.....	-5	.....	.....	.....	.....
AC20-3%SBR	.....	17	.....	.....	.....	.....
AC20-2%EAM	.....	-17	.....	.....	.....	.....

Note:

1. AC10 oven aged and AC20 PMA mixtures are compared with respect to straight mixtures.

Table III.30 Benefit/Cost estimation of polymer modified asphalt mixtures.

Polymer	Percent of Polymer	Price per Ton (Dollars)		Increse in Cost	Unit Cost	Benefits			Net Benefit/Cost
		Polymer	Mixture	(%)		Fatigue life	Tensile strength	Toughness	(B/C)
Straight	0	0	30	0	1.00	1.00	1.00	1.00	1.0
SBS	5	1650	34	16	1.16	6.78	1.39	1.38	6.5
SEBS	5	1650	34	16	1.16	6.42	1.38	1.17	6.0
SBR	3	1650	32	10	1.10	4.88	1.09	1.00	4.5
EAM	2	3300	33	13	1.13	16.67	1.10	1.00	14.9