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EVALUATION OF PLUS GRADES OF PERFORMANCE GRADED (PG) ASPHALT BINDER

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PREFACE

The research reported herein reviews the state of the plus grades of performance graded (PG) asphalt binder. The purpose of this work is to provide updated guidance to the New Mexico Department of Transportation (NMDOT) for the use of polymer modified binders (PMBs) for asphalt pavement, with a focus on the evaluation of PMB properties, binder specifications for PMBs, cost analysis, and recommendations.

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ABSTRACT

The Western Transportation Institute (WTI) conducted research on behalf of the New Mexico Department of Transportation (NMDOT) to document current knowledge and practice related to evaluation of plus grades of performance graded (PG) asphalt binder, with a focus on the scenarios of interest to NMDOT. This synthesis mainly includes a discussion of the following issues: history of polymer modified binders (PMBs) for asphalt pavement, selection of polymer for asphalt modification, evaluation of PMB properties, binder specifications for PMBs, cost analysis, recommendations, and future work. Recent years have seen the introduction of PG Plus Binders, the success of which hinges on the use of elastomer and/or rubber for binder modification. NMDOT is strongly recommended to apply elastomer modification right now while optimizing the formulation and adopt MSCR into the binder specification and implement plus grades of PG asphalt binder, in light of very small cost increase (less than 5%) and significant performance improvements (over 20% life extension) in plus-grade asphalt pavement.

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EXECUTIVE SUMMARY

The Western Transportation Institute (WTI) conducted research on behalf of the New Mexico Department of Transportation (NMDOT) to document current knowledge and practice related to evaluation of plus grades of performance graded (PG) asphalt binder, with a focus on the scenarios of interest to NMDOT. This synthesis study mainly includes a discussion of the following issues: history of polymer modified binders (PMBs) for asphalt pavement, selection of polymer for asphalt modification, evaluation of PMB properties, binder specifications for PMBs, cost analysis, recommendations, and future work.

Some of the key findings from this study include:

- Appropriate polymer content and asphalt-polymer compatibility will lead to the formation of a continuous highly elastic polymer network in the asphalt matrix, improving the cracking resistance of asphalt pavement at low service temperatures and its rutting resistance at high service temperatures.
- However, the elastomer modification tends to not increase the aging resistance of asphalt pavement as much as plastomeric modification without periodic fog sealing, for which one application is about 1% of the cost of a 3″ HMA mill and fill. *Rubber* modification results in better rutting resistance and higher ductility of the asphalt pavement, but the modifier is sensitive to decomposition and oxygen absorption.
- The content of added polymer in the asphalt matrix is an import factor that influences the properties of PMB. In most cases, the content of plastomers and elastomers are at the low and medium levels (no more than 7wt.%), while the rubbers are usually at the high content level (typically 15 to 20 wt.%).
- The storage stability of the SBS modified asphalt (a common plus-grade binder) is typically improved by adding sulfur or alternative vulcanization accelerator.
- The vast majority of states focused on elastomers (SBS, SB, SBR) or crumb rubber as polymer modifier (i.e., for plus grade PG asphalt binder) and have performance based binder specifications as their specification calls out either MSCR or elastic recovery.
- Different states have different requirements on the elastic recovery, flash point, solubility, and dynamic shear, but the requirements for rotational viscosity, creep stiffness and *m*-value, and mass change are similar. The current requirements for polymer modified asphalt in New Mexico are very limited.
- A 2005 Asphalt Institute study analyzed field performance of asphalt pavement from 84 sites across North America and found that the polymer modified asphalt

pavements showed significantly less rutting depth and less percentages of thermal cracking or fatigue cracking than neat asphalts.

- To ensure cost-effective polymer modification for PMBs, it is important to adopt reasonable design of asphalt pavement and implement good quality control of the modification process.
- In Arizona, crumb rubber is commonly used in asphalt pavement. For the PG 76-22 TR+ binder, a minimum 2 wt.% of SBS and 8 wt.% of crumb rubber are required. The benefits include: a) Reduced reflective cracking via improved elastic properties (**elastic recovery of at least 55** % at 10°C); b) Increased aging resistance; c) Increased durability; d) Reduced noise; e) Improved cost-effectiveness.
- In Florida, according to the Accelerated Pavement Testing (APT) method, the rutting and fatigue cracking performance of HMA mixtures (with neat PG67-22) were improved by the SBS modification.
- In Texas, plus grade PG asphalt binders (e.g., SBS co-block polymer-modified PG 76-22, PG 70-22, PG 58-34, and PG 58-40) exhibited outstanding benefits, relative to neat asphalt binders. Most of the elastomer modified binders have **as much as a 40** % **less hardening rate** than the neat binders. If the air voids in the Texas asphalt pavements are kept stable (lower than 2 wt.%), these reduced hardening rates can translate to 15 to 20 years of service life extension for asphalt pavement.
- In Oklahoma, three asphalt binders (PG 64-22, PG 70-28, PG 76-28 with an elastomer modifier (SBS) and two anti-stripping additives (Adhere HP-Plus and Perma Tac Plus) were used to evaluate the modification effects. After the change of grade, the PG 76-28 can reach the level of PG 82-28.
- In Colorado field studies, though the rutting resistance of pavement constructed by polymer modified asphalt binders (EVA, SBR, or styrene block copolymer) was not remarkably increased, the cracking resistance was considerably enhanced in the sections constructed with modified asphalt binders. Compared with the control sections, the cracks in the modified sections decreased by 50 % for longitudinal and transverse cracking.
- In Mississippi, the addition of polymer was found beneficial to the pavement performance at both high and low temperatures. The field evaluation further confirmed the improved rutting performance of the modified binder sections, relative to the neat asphalt section.

According to the evaluation, the following suggestions were presented:

- **NMDOT is strongly recommended to adopt MSCR into the binder specification and implement plus grades of PG asphalt binder**, in light of very small cost increase and significant performance improvements in plus-grade asphalt pavement. To optimize the use of such binder in the State of New Mexico, NMDOT is recommended to investigate the appropriate use of PMBs that suit the local traffic and environmental conditions and the appropriate curing and mixing conditions to maximize long-term performance of such plus-grade binders in dense graded asphalt pavement.

- When it comes to the use of PMBs, agencies cannot simply rely on the use of properties (elastic recovery or MSCR) as a performance specification and ignore the prescriptive spec. (e.g., appropriate SBS content and molecular weight to ensure good compatibility with asphalt binder).
- The NMDOT specification of PMBs has been successfully applied in the OGFC. However, some requirements need to be modified before the PMB's will be optimized as dense graded mix binder.
- It is ideal to form double interlock continuous phases of both elastomer and plastomer in the asphalt matrix, if the additive dosage of the elastomers and plastomers at no more than 4 wt.% or use crumb rubber at 15 wt.% to 20 wt.% of asphalt binder..
- The asphalt source must be analyzed before mixing with polymers to guarantee their compatibility. Specifically for SBS block copolymer modification, the content of butadiene must be as high as 60 % to 70 % and the molecular weights of the styrene fraction must be higher than 10,000 to guarantee the polystyrene-rich domains. This is typically done by suppliers.
- Future research should focus on the NMDOT service environments and the unique challenges and constraints in the State of New Mexico:
    1) Identify commercial and/or innovative elastic polymer modified binders that meet the proposed NMDOT binder specification;
    2) Test engineering properties of interest in the laboratory in an accelerated manner (both binder and mixture);
    3) Monitor the asphalt pavement sections constructed with select plus grade binders and periodically assess their characteristics;
    4) Conduct life cycle assessment of cost and sustainability for the neat and plus grade asphalt pavements.

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

Extensive studies have shown that polymers (mainly plastomers, elastomers, and rubbers) play a significant role in the properties and performance of Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA). Through construction specifications, many state departments of transportation (DOTs) require that polymers be used in HMA or WMA, and have developed Performance-Graded (PG) Plus grading criteria for specific climatic zones of their state. New tests have been developed to better understand the long-term performance of polymer-modified binders (PMBs). Due to changes in service conditions such as increased tire pressure, maximum truck weight limits, and traffic volume, the stresses placed on pavements have increased. Thus, addressing the fatigue and cracking resistance of asphalt binders has become more critical than in previous decades. In addition to enhancing the intrinsic viscoelastic performance of asphalt binders, studies have shown that some PMBs can create SuperPave mixes with high resistance to fatigue and thermal cracking, or providing more effective anti-rutting performance.

The PG Asphalt Binder specification (AASHTOM 320 or ASTM-D6373), which grades asphalt binder performance, was developed for studying the performance of neat asphalt and may not characterize PMBs properly. In recent years, the “PG Plus” tests, which include elastic recovery, toughness, and tenacity, have been added into PG tests (AASHTO M320) by many state DOTs to ensure the elastic property improvements of PMBs. While the PG Plus tests confirmed the benefits of PMBs, they cannot provide specific percentage and type of polymers used, nor can they predict performance in the field.

To better characterize and understand the overall performance of elastic polymer modified binders, the Multiple Stress Creep Recovery (MSCR) test was recently added to AASHTO M320 to replace the PG Plus tests. Although the new MSCR has made progress in improving and understanding the rutting and fatigue behavior of asphalt binder, it fails to predict low-temperature cracking and aging behavior of PMBs. As a result, it is necessary to evaluate PG Plus Binders (also known as Polymer PG or PG+ or PG+ modifier) by developing correlations of polymer content, MSCR, and PG Plus tests.

PMBs have been studied extensively over the past decades, and most of the research results have proven that the addition of polymers has benefits to various performance parameters of asphalt binders. Recent years have seen the introduction of PG Plus Binders, the success of which hinges on the use of elastomer and/or rubber for binder modification. Before the field application of PG Plus binders can be optimized by agencies, there are concerns that must be resolved, such as:

- Balancing performance parameters and cost of PMBs for the intended service environment
- Determining which polymers have the best modification effect on the asphalt

binder so as to meet the performance requirements under the cost and other constraints

- Long-term pavement performance of the modified asphalt binders in the field

According to current literature, these questions have yet to be answered. As a result, it is important to evaluate polymers to make appropriate decisions as to how they may be used more effectively. Although an immediate shift to plus grades would be advantageous, there is an urgent need to synthesize all research findings on polymer modified asphalt to accurately evaluate how to most cost-effectively apply it in the State of New Mexico.

1.2 HISTORY OF POLYMER MODIFIED BINDERS

Asphalt binder (a.k.a., bitumen) is the main binder material currently used for highway pavement construction. It is estimated that approximately 102 million tons of asphalt are used every year, and 85 percent are used as binders in various pavements (*1*). Figure 1.1 shows the applications of asphalt by regions and for specific purposes. The properties of the produced asphalt are largely governed by their chemistry and compositions, which are closely related to the refinery processes and the sources of crude oil. How to most cost-effectively enhance its viscoelastic performance and durability is a challenge in pavement engineering. With the decreasing number of oil sources and the aim for maximum benefits, the production of high performance asphalt has been replaced by modifying the properties of relatively low standard asphalts with various approaches (*2*). The use of PMBs is generally considered an effective approach to enhancing the overall performance and durability of pavement. In this approach, the polymers are mechanically mixed with asphalt binder to modify the natural viscoelastic behavior of the bitumen and to achieve an improved strength and elasticity of the pavements.

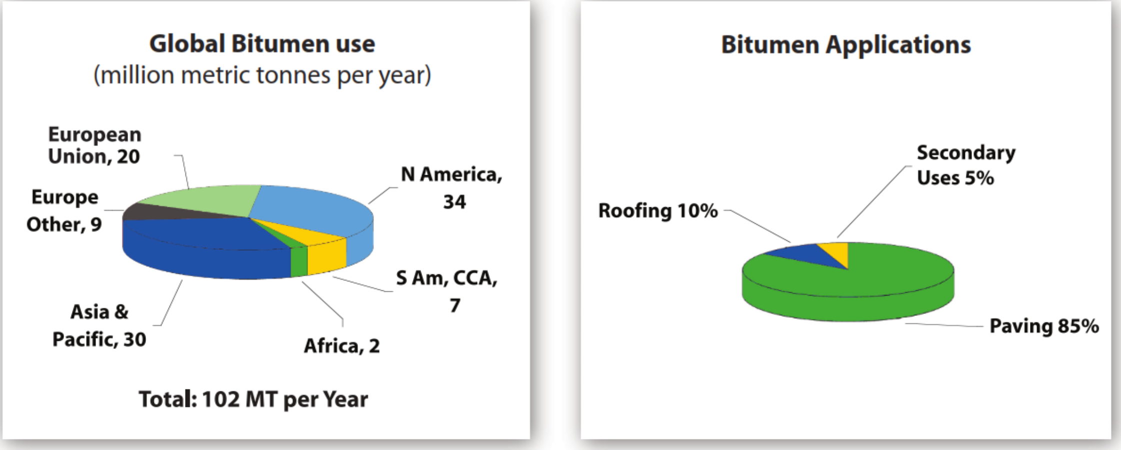


Figure 1 -1 Applications of asphalt by regions and purposes (*1*)

The purpose of Plus grade polymer addition in asphalt binder is to obtain 1) a soft blend at low service temperatures to reduce cracks, and 2) a stiff blend at high service temperatures to reduce rutting. Furthermore, the viscosity at layout temperatures would be reduced. Ideally, the stability, oxidation and aging resistance of PMB and the strength, abrasion resistance, and fatigue resistance of asphalt mixture should be increased with the polymer addition, while the structural thickness and life cycle cost of pavement should be reduced (*2*).

Several factors are considered as the main parameters influencing the final properties of the PMB, including polymer characteristics, asphalt characteristics, compatibility between the polymer and the asphalt, mixing conditions, and the polymer content added. The polymer must have strong compatibility with the asphalt to avoid phase separation during storage, transportation, construction, and service. The asphalt grade is another important factor that will influence the final properties of PMB. The asphalt characteristics are more complicated than polymers, as the asphalt constituents are inherently diverse in molecular weight, structure, viscosity, and density (*3, 4*).

Although limited studies systematically demonstrate the relationship between the chemical composition of asphalt binder and the final properties of PMB, some basic conclusions have been presented (*5*). First, the asphalt should contain enough oil content to help dissolve and expand the polymer. Second, the asphalt should contain a high level of condensed ingredients. For instance, the condensed aromatic hydrocarbons are compatible with polar aromatic polymers. The content of polymer modifier in the asphalt binder could range from 2 to 10 wt.%. Other factors also influence the final properties of PMB, including the physical form of the polymer (powder, crumb, or pallet), the mixing equipment, and the thermal history during mixing process (*6*).

The production of polymer modified asphalt began several decades ago. The well-known early case of PMB is the neoprene (polychloroprene) latex modification in North America in the 1950s (*7*). The asphalt modification by plastomers has a longer history than that by elastomers, as many plastomer modifications were commercially implemented before 1960 (*8*). **The first elastomer modification was developed with styrene-butadiene-styrene (SBS) in 1965** and has been widely used in Europe since the 1970s (*9, 10*). The styrene-ethylene/butylene-styrene (SEBS) modification was also developed in the 1970s (*11*). Research in the 1970s proved that some properties of the asphalt would improve with the addition of elastic polymers (*12*). Although the elastomer modified asphalt was previously reported to have a storage problem (*13*), its field construction in Texas exhibited positive performance.

During the 1980s, more polymers were developed with an increasing demand for thickness reduction in the pavement layer. Piazza (*14*) found that the mechanical and viscoelastic properties of bitumen, both at high and low temperatures, were noticeably improved by adding SBS and atactic polypropylene. The addition of SBS block copolymer prevented the stiffening of asphalt at low temperatures and thus led to the reduction of its brittleness. The addition of atactic polypropylene reduced the creep of the asphalt at room temperature. Kraus (*15*) reported phase separation and swelling of the polymer modified asphalt. Bowering (*16*) discussed the cost of the PMB and suggested that the high cost of construct PMB pavements may not be sufficiently justified by its improved service life and the reduced pavement thickness. In late 1980s, the Strategic

Highway Research Program (SHRP) developed the performance-based specification for neat asphalt based on rheology. A two-year case study in California (*17*) found the addition of polymer to increase the resistance of asphalt mixture to aging and cracking.

In the 1990s, after increased systematic investigations, the effects of various polymers on asphalt performance were reported. The mechanical properties, temperature sensitivity, storage stability, rheology, morphology, thermal performance, aging resistance, and durability were studied in many countries. For instance, **the addition of SBS polymer was found to result in the enhancement of asphalt mixture, in terms of elastic recovery, cracking resistance at low temperature, and rutting resistance at high temperature** (*18*, *19*, *20*, *21*, *22*). While some disadvantages of PMB were reported (e.g., thermal instability and phase separation) (*23*), these have been addressed with various approaches such as leveraging the synergizing effects of other polymers (*24*).

Since the 2000s, the research focus of the PMB changed from investigating properties to developing new methods to mitigate disadvantages and elucidating the modification mechanisms. For instance, sulfur vulcanization is one of the most popular approaches that have been widely investigated (*25*, *26*, *27*, *28*, *29*, *30*, *31*). In addition, adding antioxidants (*32*, *33*), using hydrophobic clay minerals (*34*, *35*), and functionalization (*36*, *37*, *38*) were also presented as effective methods to mitigate the problems of PMB.

1.3 REPORT STRUCTURE

Information in this report is presented as follows.

Chapter One has introduced the reader to the topic of PMBs and briefly introduced the history of their development.

Chapter Two presents information relevant to the selection of polymer for asphalt modification. It discusses the polymer types, advantages and disadvantages of various polymers, effect of polymer content, and compatibility and stability issues.

Chapter Three presents a compilation of case studies regarding the experience of various states with polymer modified asphalt pavement, followed by a summary of the PG Plus specifications of PMBs from various state DOTs. The relevant sections of the current NMDOT design policy are evaluated. The properties of plus grade PMBs are discussed with a focus on rheology, stiffness, elastic recovery, viscosity, ductility, toughness, rutting resistance, cracking resistance, aging resistance, storage stability, and long-term pavement performance.

Chapter Four presents the cost analysis for various PMBs.

Chapter Five provides a summary of key findings from all the previous chapters as well as suggestions for NMDOT, including a draft specification based on the information gathered in this study (detailed in Appendix A).

CHAPTER 2 SELECTION OF POLYMER FOR ASPHALT MODIFICATION

This chapter presents information relevant to the selection of polymer for asphalt modification. It discusses the polymer types, advantages and disadvantages of various polymers, effect of polymer content, and compatibility and stability issues.

2.1 POLYMER TYPES

The three main types of polymers for asphalt modification are plastomers, elastomers, and rubbers (natural rubber latex or crumb rubber). Note that rubbers can be categorized as a special type of elastomer; as such, PG Plus Binders typically feature the use of elastomer and/or rubber for binder modification. Figure 2-1 shows the physical appearance of a typical elastomer (SBS), a typical plastomer (EVA), and natural rubber latex (*39*).

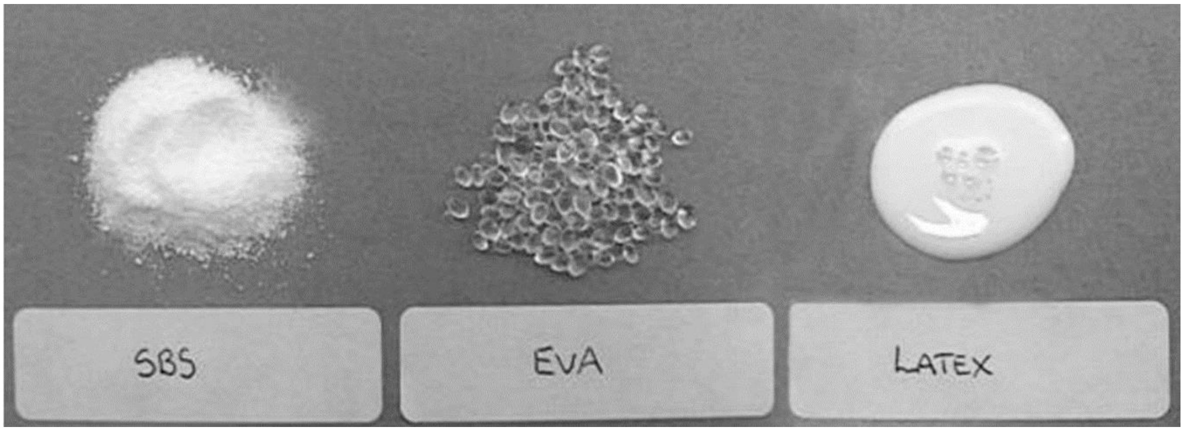


Figure 2- 1 Samples of polymers used in asphalt modification (*39*)

Typical plastomers include polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), ethylene-butyl acrylate (EBA), and ethylene-methacrylate (EMA). As they contain less elastic contents, plastomers tend to provide asphalt pavement with a relatively high early strength under load but may increase its risk of rutting and cracking failures (*21, 40, 41, 42, 43, 44, 45, 46*).

Typical elastomers include styrene-butadiene-styrene (SBS), styrene-butadiene-rubber (SBR), styrene-ethylene/butylene-styrene (SEBS), styrene-isoprene-styrene (SIS), and polybutadiene rubber. They are able to increase the asphalt pavement's resistance to permanent deformation (rutting). The rutting resistance improvement is attributable to the ability of elastomers to stretch under an external load and elastically recover once this load is removed (*9, 11, 47, 48*). The elastomer modification can **reduce the asphalt pavement's resistance to aging**, as the elastomer is more prone to decomposition than plastomers without periodic fog sealing (*23. 49, 50, 30, 51, 52, 53, 54, 33*).

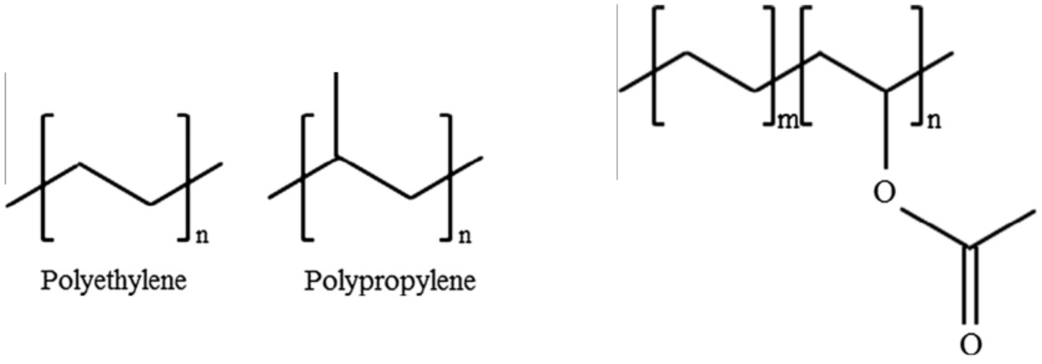
Natural rubber latex and reclaimed rubber (e.g., crumb rubber) are two primary rubber modifiers used in asphalt pavement. The use of rubber in asphalt pavement can improve its ductility, elasticity, rutting resistance, and properties under cyclical loads (*55*, *56*, *57*, *58*, *59*, *60*, *61*). The use of reclaimed rubber, however, is hindered by the difficulty of dissolving and dispersing it in the asphalt matrix.

The factors that govern the modification effect are complicated. Firstly, these include chemical composition, structure, average molecular weight, molecular weight distribution, and crystallization of the polymer. Specifically, **for SBS block copolymer**, there are basic requirements that must be satisfied before it can be used for modification. **The content of butadiene must be as high as 60** % **to 70** % **and the molecular weight of the styrene fraction must be higher than 10,000 to guarantee the polystyrene-rich domains** (*62*). Secondly, the original grade of the asphalt used in binders is another important factor dictating the performance of the polymer modified binder (PMB). Mechanical properties of the mixtures are largely affected by the original grade of the asphalt, and from a statistical perspective, the addition of polymer modifiers has little negative effect on low-temperature stiffness of the asphalt binders (*63*).

Plastomers

Polyolefin was the earliest plastomer used for asphalt modification. Many types of polyolefin, including high density polyethylene (HDPE), low density polyethylene (LDPE), and polypropylene have been investigated for applications, due to their relatively low cost (*64, 65, 66, 67, 68*). Once mixed with asphalt, polyolefin will swell in the light components of asphalt and form a dispersion phase in the continuous asphalt phase (*69*). By increasing the polyolefin content, the discrete polyolefin phase will be connected to form a continuous phase in the asphalt matrix. Optimum performance of plastomer modified asphalt can be attained if both polyolefin and asphalt are in a continuous phase (*10*). However, it has been reported that polyolefin is unable to enhance the elasticity of asphalt materials (*70*).

Currently, the widely used plastomers for asphalt modification are EVA and EBA (*71*, *72*, *73*). Unlike PE and PP, EVA has polar acetate groups as short branches that mitigate the close-packing of the ethylene-rich agglomerations and prevent the formation of crystals, thus enhancing the storage stability of EVA modified asphalt (*74, 75*). Figure 2-2 shows the typical structures of PE, PP, and EVA (*69*, *75*). The content of the vinyl acetate group is the key factor determining the properties of the modified asphalt. The modified asphalt with low EVA content will have a high degree of crystallization and thus feature properties similar to LDPE. As the EVA content increases, the crystallization risk will be mitigated. But too high an EVA content may negatively affect the compatibility between EVA and the asphalt and no longer benefit the properties of asphalt pavement. This phenomenon was proven based on the SuperPave testing methodology, which found that the resistance to low-temperature cracking increased with increased EVA content in the range of 2 wt.% to 4 wt.% but decreased with 6 wt.% EVA addition (*65*).



a) b)

Figure 2 -2 Structures of a) PE and PP, and b) EVA (*69, 75*)

Table 2-1 shows the physical properties of typical plastomers (the grade 18/150 indicates a melt flow index of 150 and an EVA content of 18 wt.%). As shown, the tensile strengths of the plastomers are relatively low (5 to 10.5 MPa), while the values of the elongation at break (25 °C) are relatively high (500 to 800 %).

Table 2-1 Physical properties of typical plastomers (*39*)

Property	EVA 18/150 grade	EVA 30/45 grade	LDPE	HDPE
Tensile strength, MPa	5	10.5	-	-
Density	-	-	0.91	0.94
Melt flow index, g/10 min	135-175	38-48	155	16-20
Elongation at break, percent @ 25 °C	500	800	-	-
Softening point, °C	95	107	-	-

Table 2-2 provides the typical properties of plastomer modified asphalt, which illustrates the effects of plastomer modification on the binder’s temperature susceptibility. As shown, the penetration of asphalt binder at 25 °C decreased significantly with a small plastomer addition. For instance, the 5 wt.% EVA addition by weight of 18/150 asphalt binder can decrease the binder penetration to 38 dmm. The softening point of asphalt binder increased significantly with a small plastomer addition. For instance, the 5 wt.% EVA addition by weight of 18/150 asphalt binder can increase the binder softening point up to 68 °C. All the plastomer modified binders show elongation break 50 % or higher at 25 °C. Finally, the two cases of 5 wt.% EVA addition decreased the Fraass breaking point from -10 °C to -18 °C, but the 4 wt.% LDPE addition increased it to -3 °C (*39*).

Table 2-2 Typical properties of plastomer modified asphalt binders (39)

Polymers	Penetration at 25 °C, dmm	Ring and ball softening point, °C	Elongation at break, percent @ 25 °C	Fraass breaking point, °C
70/100 grade asphalt (control)	70-100	43-51	20	-10
EVA 18/150 (5 wt.%)	38-48	58-68	50	-18
EVA 30/45 (5 wt.%)	55	57	50	-18
LDPE (4wt.%)	47	53	82	-3

Elastomers

In practice, SBS-type elastomers feature outstanding performance, reliability, and economy. SBS is typically composed of discrete rigid polystyrene (PS) domains dispersed in a flexible polybutadiene (PB) matrix, as shown in Figure 2-3. In the typical temperature range of in-service pavements, the PS blocks are glassy and account for the strength of SBS, whereas the PB blocks are amorphous and offer elasticity (*76*). At mild temperatures, the PS blocks tend to aggregate and form PS domains. This leads to the formation of crosslinking of PS and PB blocks (see Figure 2-3A), which is responsible for the improved elastic recovery performance of the SBS modified asphalt. With increased external temperatures, the kinetic energy may exceed the energy of intermolecular force and break the aggregation of PS blocks (see Figure 2-3B). After cooling, however, the physical crosslink between the PS and PB blocks will form again (see Figure 2-3C) and the strength and elasticity of SBS will be restored (*77*).

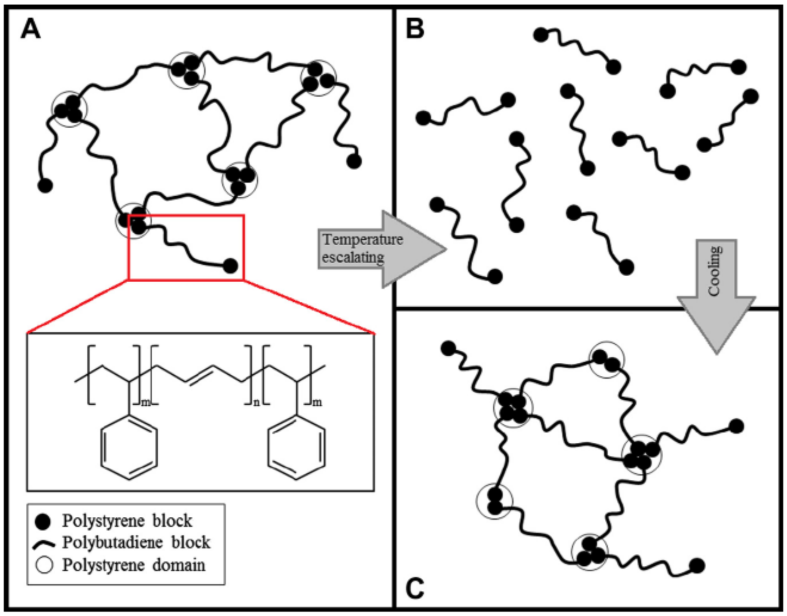


Figure 2- 3 Structure of SBS and schematic demonstration of reversible crosslinks in SBS (*10*)

Table 2-3 presents the physical properties of typical elastomers. Among them, the SEBS features the highest tensile strength of 35 MPa, while SBR features the lowest tensile strength of 0.5 MPa. SIS and SEBS feature the highest and lowest elongation at break, at 1,200 percent and 500 percent, respectively (*39*).

Table 2-3 Physical properties of typical elastomers (*39*)

Property	SBS	SEBS	SBR	SIS
Tensile strength, MPa	18	35	0.5	15
Elongation at break, percent @ 25 °C	800	500	900	1,200

Table 2-4 shows the typical properties of 160/220 grade asphalt modified by elastomers, which illustrates the benefits of elastomer modification on the binder's temperature susceptibility. As shown, the penetration of asphalt binder at 25 °C decreased significantly with a small elastomer addition. For instance, the 3 wt.% SEBS addition by weight of asphalt binder can decrease the binder penetration from 160 dmm to 60 dmm. The softening point of asphalt binder increased significantly with a small elastomer addition. For instance, the 5 wt.% SBS addition by weight of asphalt binder can increase the binder softening point up to 95 °C. All the elastomer modified binders show elastic recovery higher than 50 percent at 5 °C. Finally, the 1.5 wt.% polybutadiene rubber addition by weight of asphalt binder can decrease the Fraass breaking point from -15 °C to -30 °C (*39*).

Table 2- 4 Typical properties of 160/220 grade asphalt modified by elastomers (*39*)

Binder	Penetration at 25 °C, dmm	Ring and ball softening point, °C	Elastic recovery, percent @ 5 °C	Fraass breaking point, °C
160/220 grade asphalt (control)	160-220	35-43	N/d	-15
SBS (5 wt.%)	70-110	75-95	>50	-20
SEBS (3 wt.%)	60-100	65-85	>50	-18
SBR (5 wt.%)	100-130	56	>70	-15
Polybutadiene rubber (1.5 wt.%)	106	48	>80	-30

Rubbers

The use of crumb rubber in asphalt pavement applications started in the early 1960s in the U.S. (*55*). Dry process and wet process are the main methods for using crumb rubber to modify asphalt binder, and practical applications are focused on the wet process (*78*). The wet process entails the dispersion of crumb rubber particles in asphalt at 5 wt.% to 25 wt.% of asphalt to produce asphalt concrete mixture (*79*). The dry process entails the mixing of crumb rubber particles with the aggregates before producing the asphalt concrete mixture (*57*).

Many studies have shown that the asphalt pavement constructed with crumb rubber modified binder has multiple advantages relative to neat asphalt pavement, including enhanced mechanical properties, increased riding quality, decreased traffic noise, and increased rutting and cracking resistance. Furthermore, the value-added utilization of crumb rubber can mitigate environmental risks associated with waste tires disposal (*56, 80, 81*).

There are a few issues that hinder the widespread application of crumb rubber in asphalt pavement. Firstly, crumb rubber is not reactive and it is thus difficult to dissolve or fully disperse the crumb rubber particles in the asphalt matrix. In other words, there is a low-compatibility issue with the use of crumb rubber in asphalt that remains to be addressed. Secondly, the crumb rubber is prone to decomposition and oxygen absorption, which may negatively affect the long-term performance of the asphalt pavement.

2.2 ADVANTAGES AND DISADVANTAGES OF VARIOUS POLYMERS

All plastomers, elastomers, and rubbers provide advantages and disadvantages for their use as asphalt binder modifier. *Plastomers* typically bring positive benefits to high-temperature properties, aging resistance and storage stability. They provide compatibility with asphalt matrices with minimal viscosity change and are thermally stable. However, some bottleneck problems of plastomers, such as limited improvement in elasticity and in low-temperature properties and difficulty to be well-dispersed, have limited their widespread application in asphalt pavement. The performance of asphalt pavement modified by *elastomers* depends on the asphalt source, the asphalt-polymer compatibility, and the polymer content. Appropriate polymer content and asphalt-polymer compatibility will lead to the formation of a continuous highly elastic polymer network in the asphalt matrix, which increases the viscosity, stiffness, and elastic response of the binders, particularly at high service temperatures. The elastomers also improve the cracking resistance of asphalt pavement at low service temperatures. However, the elastomer modification tends to decrease the aging resistance of asphalt pavement, unless the elastomer is periodically fog-sealed. *Crumb rubber* modification results in better rutting resistance and higher ductility of the asphalt pavement, but the modifier is sensitive to decomposition and oxygen absorption. Table 2-5 provides advantages and disadvantages of the common polymers used for asphalt modification (*47, 48, 82, 37, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 81*).

Table 2- 5 Advantages and disadvantages of common polymers for asphalt modification

Polymer Type	Typical Product	Advantages	Disadvantages
Plastomers	PE	Improvements on high-temperature performance and aging resistance; high modulus; relative low cost	Limited stability and elasticity improvements; hard to disperse in asphalt; phase agglomeration problem
	PP	Little increase in viscosity; lower penetration and improved load resistance	Low thermal cracking resistance; low fatigue cracking resistance; little improvement on elasticity and mechanical properties
	EVA EMA	Relatively good storage stability and rutting resistance; good compatibility with asphalt matrix; minimal viscosity change; thermally stable; relative low cost	Little improvement on elastic recovery; limited enhancement in low-temperature properties
	EBA	Relatively high rutting resistance	Limited elastic recovery improvement and low-temperature properties
Elastomers	SBS SBR	High flexibility at low temperature; improvement on stiffness and elastic response; improved rutting resistance	Compatibility issue with asphalt (when used at high content without vulcanization); low aging resistivity; relatively high cost
	SIS	Reduced temperature sensitivity; improved rutting resistance	Relatively high cost; low resistance to heat and oxidation
	SEBS	High resistance to heat, oxidation, and ultraviolet degradation	Unstable during storage; reduced elasticity; high cost
Rubbers	Natural rubber	Relatively high ductility and elasticity; good properties under cyclical loads; improved rutting resistance	Prone to decomposition and oxygen absorption; low compatibility with asphalt; must be partially decomposed and mechanically homogenized
	Reclaimed tire rubber	Low maintenance cost; reduced reflective cracking; improved fatigue resistance, rutting resistance and durability	Hard to dissolve and disperse

2.3 EFFECT OF POLYMER CONTENT

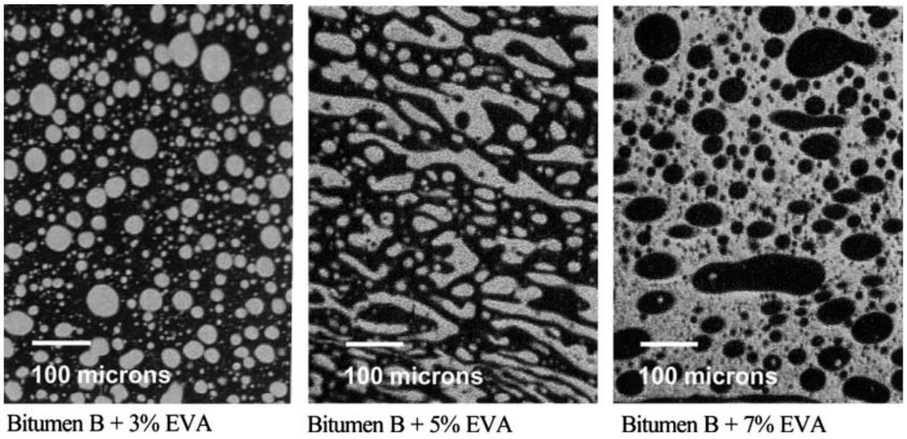
In addition to polymer type, another important factor that influences the final performance of polymer modified asphalt pavement is the content of added polymer (*95*). The typical PMBs can be divided into three groups, i.e., low polymer content (less than 4 wt.%), medium polymer content (4-7 wt.%), and high polymer content (7 wt.%).

When the polymer content is relatively low (e.g., **no more than 4** wt.% **of asphalt binder**), the polymer phase is well dispersed in the continuous asphalt matrix. At high service temperatures, the stiffness and modulus of polymer are typically higher than asphalt; as such, the polymer modification enhances the mechanical performance of asphalt pavement. At low service temperatures, the stiffness and modulus of the polymers are typically lower than asphalt; thus the low-temperature brittleness of asphalt pavement is mitigated by polymer modification. In summary, **adding low content of polymer can extend the service temperature range of asphalt pavement**.

Adding the polymer at a medium content is more complicated. Ideally, the modified binder should feature both the polymer and asphalt phases that are continuous and interconnected (e.g., 5 wt.% EVA in Figure 2-4 and 5 percent SBS in Figure 2-5). In reality, it is hard to achieve such results in a reproducible manner.

Adding the polymer at a high content (e.g., higher than 7 wt.% of asphalt binder) tends to work for roofing applications but is not desirable for pavement applications. In this case, the polymer, rather than the bitumen, is plastified by the oil content in the asphalt. The polymer phase becomes the continuous phase, and the asphalt phase becomes the second phase dispersed in the polymer matrix. As such, some performance parameters of the PMB (e.g., chemical resistance and aging resistance) may degrade (*96*).

Figure 2-4 shows the fluorescent images of EVA modified asphalt with various EVA contents (*96*). Remarkable microstructure differences can be observed with different EVA content in the bitumen samples. The low EVA content (3 wt.%) image shows isolated EVA dispersion in the continuous asphalt matrix; the medium EVA content (5 wt.%) image shows the interconnection in both EVA and asphalt phase; and the high EVA content (7 wt.%) image shows isolated asphalt dispersion in the continuous EVA matrix.



Bitumen B + 3% EVA Bitumen B + 5% EVA Bitumen B + 7% EVA

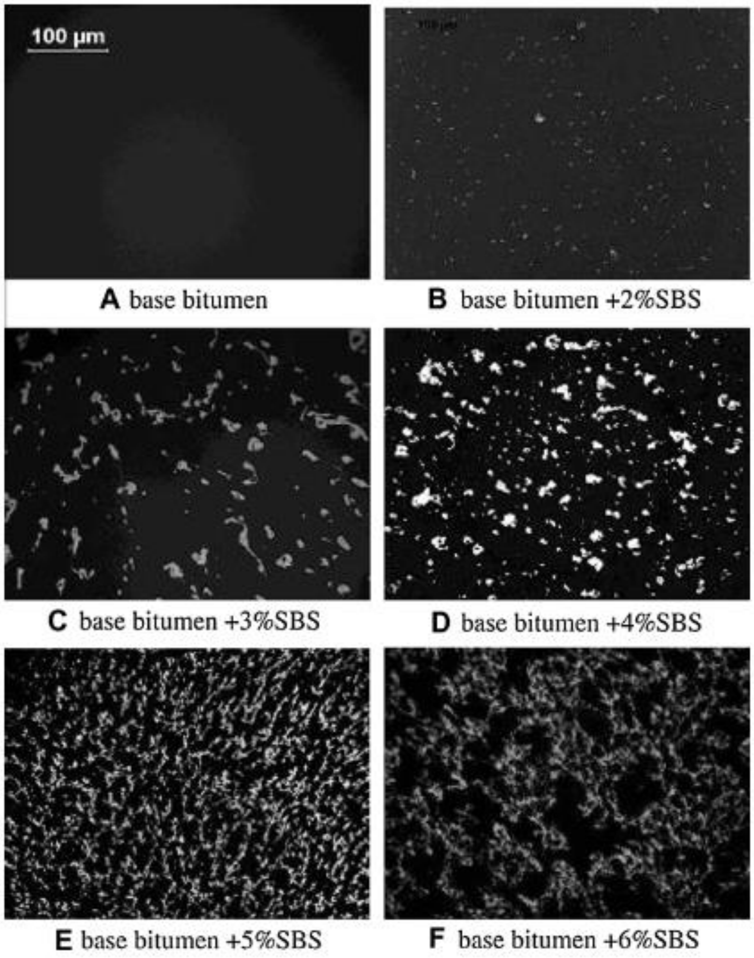
Figure 2- 4 Fluorescent images of asphalt modified with various EVA contents (*96*)

Figure 2-5 shows the fluorescent images of SBS modified asphalt with various SBS content (*72*). Similar to EVA modified asphalt binders, phase inversion can be observed with the increase in SBS content. When the SBS content is low, the isolated SBS phase is discretely dispersed in the asphalt matrix. As the SBS content increases to 5 wt.% of asphalt, the binder forms an ideal double interlock continuous phases of both SBS polymer and the asphalt. Once the SBS amorphous network forms in the asphalt matrix, the complex modulus, viscosity, elastic response, and low-temperature cracking resistance of the asphalt pavement are enhanced accordingly. As the SBS content increases to 6 wt.% of asphalt, the asphalt phase becomes discretely dispersed in the polymer matrix, which will negatively affect some properties of the asphalt pavement.

Champion et al. (*95*) used confocal laser scanning microscopy to study the morphology of various PMBs, including either copolymers from ethylene and EMA, EBA, or EVA or diblock or star-shape triblock SB or SBS as the polymer modifier. They reported that “the 4 to 6 wt.% blends display an heterogeneous structure with a polymer-rich dispersed phase based on initial polymer swollen by the aromatic fractions of the asphalt”. They also employed the linear elastic fracture mechanics (LEFM) method to study the low-temperature fracture behavior of the PMBs and found that the binder modification by the 4% cross-linked SB and the corresponding physical blend (non-crosslinked) led to better fracture properties. The asphalts modified by the elastomers generally exhibited better fracture performance than those by the plastomers, due to “more efficient energy dissipation during crack propagation.”

Note that there are emerging SBS products that may enable their use in asphalt binder at higher contents, known as “highly modified” binders. Kuennen (*97*) reported that the use of a SBS product at 7.5 wt.% by the Oklahoma DOT for three different asphalt mixes on I-40 (PG 76-28 E), aimed to reduce the required pavement thickness. This new type of SBS was manufactured by *Houston-based Kraton Performance Polymer, Inc., and some consider it still too early to draw conclusions about the performance of such SBS modified asphalt pavement until more field data become available.*

SBS modified asphalt binders have been extensively studied. It was claimed that the formation of the critical network between asphalt and polymer is the key factor to determining the optimum SBS content. The dominant phase will be inversed as the SBS content exceeds 5 wt.% (*28*). Figure 2-6 shows the softening point and penetration depth of an asphalt binder as a function of SBS content. With increasing SBS content, the softening point increases and the penetration depth decreases.



A base bitumen

B base bitumen +2%SBS

C base bitumen +3%SBS

D base bitumen +4%SBS

E base bitumen +5%SBS

F base bitumen +6%SBS

Figure 2- 5 Fluorescent images of asphalt modified asphalt with various SBS contents (*72*)

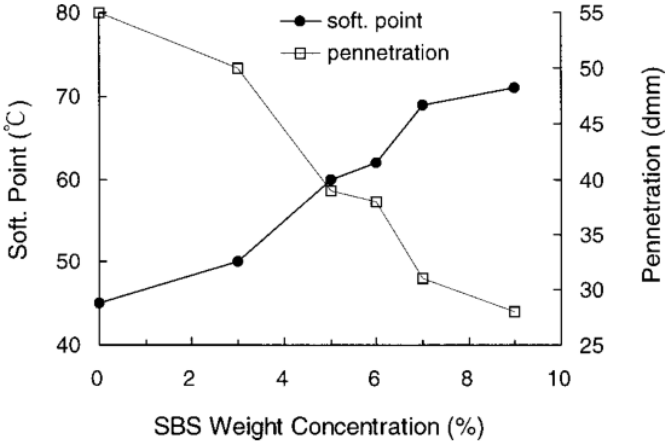


Figure 2- 6 Softening point and penetration depth of asphalt binder as a function of SBS content (*28*)

Studies so far have suggested keeping the EVA content at no more than 4 wt.% of asphalt. Two penetration grade (60/70 and 150/200) asphalts modified by recycled EVA were investigated by García-Morales (*82*). In this study, Oscillatory shear tests were carried out in the temperature range of -10 °C to 75 °C. It was found that the modified binders performed well at both low and high service temperatures. It was recommended that the maximum content of the EVA be 9 wt.%, since this is the threshold EVA content beyond which the binder microstructure started to change significantly (*82*). Based on the SuperPave testing methodology, however, Ameri (*65*) revealed that the low-temperature cracking resistance of an asphalt pavement was maximized with 4 wt.% EVA content and degraded with the increase of EVA content to 6 wt.%.

Some studies compared the effects of adding various contents of SBS or EVA to modify asphalt pavement and found the performance enhancement to vary with the polymer type and content (*98, 71*). Adding different contents of SBS and EVA for asphalt modification can lead to comparable properties of asphalt bitumen (see Figure 2-7, Table 2-6, and Table 2-7), and is anticipated to result in comparable performance of asphalt pavement at both low and high service temperatures.

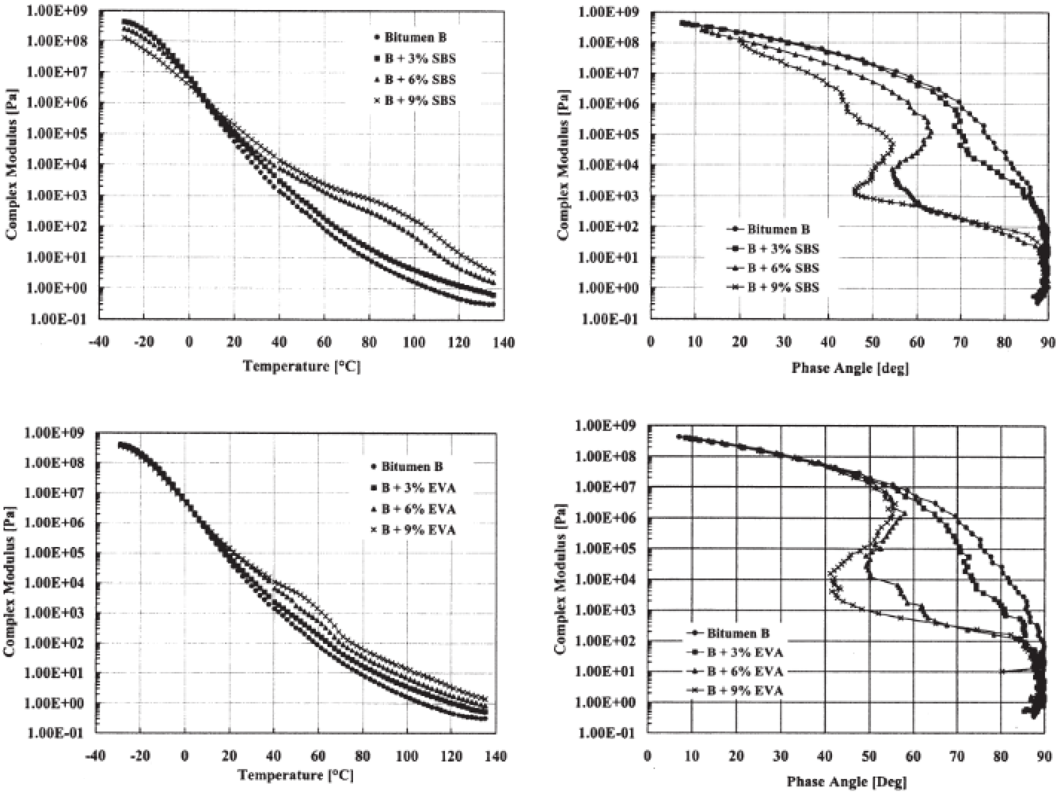


Figure 2- 7 Effect of polymer content on rheological properties of the modified binders (*98*)

Table 2- 6 Conventional properties of polymer modified bitumen (*71*)

Property	Type	Content (%)						
		0	2	3	4	5	6	7
Penetration (1/10 mm)	SBS Kraton D-1101	63	61	51	49	48	48	-
Softening point (°C)		49	50	54	57	67	69	-
Penetration index (PI)		-0.92	-0.73	-0.16	0.35	2.18	2.46	-
Change of mass (%)		0.07	0.06	0.06	0.07	0.07	0.07	-
Retained penetration after TFOT (%)		51	41	31	24	21	21	-
Softening point difference after TFOT (°C)		2	4	4	2	3	2	-
Storage stability (°C)		-	3	3	2	3	2	-
Penetration (1/10 mm)	Evatane 2805	63	-	53	52	49	48	47
Softening point (°C)		49	-	54	57	59	61	62
Penetration index (PI)		-0.92	-	-0.13	0.49	0.79	1.14	1.24
Change of mass (%)		0.07	-	0.04	0.06	0.05	0.07	0.06
Retained penetration after TFOT (%)		51	-	30	31	32	33	34
Softening point difference after TFOT (°C)		2	-	6	6	5	4	5
Storage stability (°C)		-	-	1	1	0	1	2

Table 2- 7 Rotational viscosities to SBS and EVA modification (*98*)

Property	Type	Content (%)						
		0	2	3	4	5	6	7
Brookfield viscosity at 135 °C (Pa s)	SBS Kraton D-1101	0.51	0.55	0.62	0.76	1.20	1.50	-
Modification index (η_{PMB}/η_{base})		1	1.08	1.22	1.49	2.35	2.94	-
Brookfield viscosity at 135 °C (Pa s)	Evatane 2805	0.51	-	0.98	1.24	2.16	2.98	3.41
Modification index (η_{PMB}/η_{base})		1	-	1.92	2.43	4.24	5.84	6.69

Table 2-8 summarizes the properties of asphalt pavement modified by various polymers at low, medium, or high content. As shown, most of the plastomers and elastomers are used as asphalt modifier at the low and medium content levels while rubbers are used at the high content level.

Table 2- 3 Properties of asphalt pavement modified by various polymers at low, medium, or high content

Polymer type	Low content (< 4 %)	Medium content (4 -7 %)	High content (>7 %)
PE	1 wt.% PE addition leads to high performance but low stability (*91*)		
EVA	Improves low-temperature cracking resistance with dosage of 2 wt.% to 4 wt.% (*65*)		The results of linear viscoelasticity investigation suggest keeping the EVA content no more than 9 percent (*82*)
SBS	Increases aging resistance with addition of 2 wt.%-3 wt.% (*99*); Improves stability and compatibility with 4 wt.% addition (*100*); Increases UV resistance with addition of 4 wt.% (*50*)	Increases softening point, viscosity, and complex modulus and decreases penetration depth with increased SBS content from 0 percent - 9 percent (*28*)	
SBR	Increases aging resistance with addition of 2 wt.%-3 wt.% (*99*)		
SEBS	Improves stability and compatibility with 4 wt.% addition (*100*)		
Rubber			Hardening rate decreases with increased rubber content in the range of 10 wt.%-20 wt.% (*101*); Increases aging resistance (*99*); Storage stability, and low and high service properties were improved; viscosity and temperature susceptibility were reduced with increased content of crumb rubber from 5 wt.% to 40 wt.% (*101);* Increases recovery capability with dosage of 8 wt.% to 12 wt.% (*60*) High viscosity of the rubber modified binder results in separation with content increased from 10 wt.% to 20 wt.%.

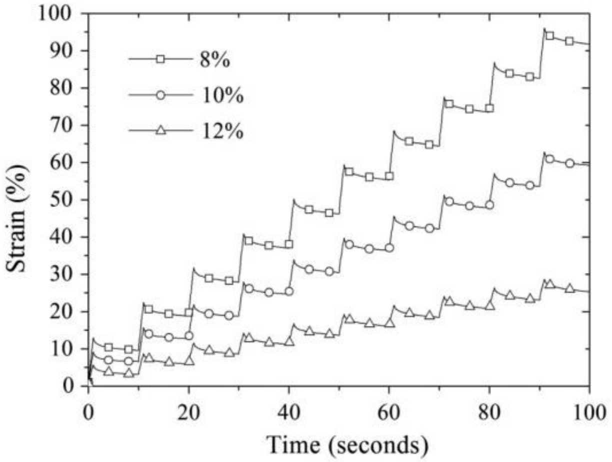


Figure 2- 8 Strain of asphalt pavement as a function of time, with crumb rubber added at three different contents (*60*)

There are many studies that used crumb rubber in asphalt without adding any SBS (*38, 102*). However, for an Arizona case study (Kliewer, ADOT), a 2 wt.% SBS amount was required for the asphalt binder with 20 wt.% crumb rubber. The addition of SBS certainly increases the cost of the PMB but likely improves the compatibility between crumb rubber and asphalt and thus the long-term performance of the asphalt pavement.

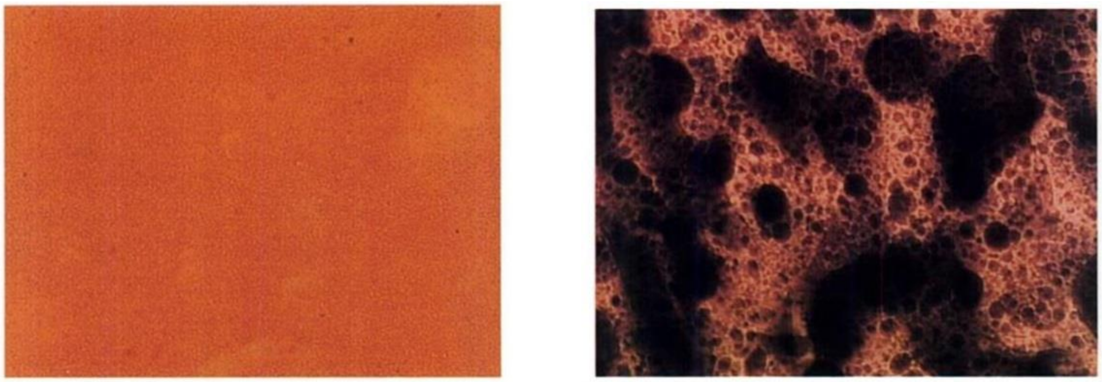
2.4 COMPATIBILITY AND STABILITY

The first priority to guarantee performance of PMB in the field is the degree of compatibility between the polymer and the asphalt. Strong compatibility will help prevent agglomeration of the polymers in the asphalt matrix during storage, pumping, construction, and service (*104, 100, 84, 105*). To obtain a stable system, several factors should be considered, including the content and size of the asphaltenes and polymers, and the aromaticity of the maltene phase. The high aromaticity content will lead to a reduction of the polystyrene domains and thus result in low softening points and will reduce flow resistance. The low content of aromaticity will result in a low flow resistance as well, due to the decreasing incorporation between the polymers and the asphalt.

Compatibility of the PMB is not only the producer’s concern but also the DOT user’s concern, as it would affect the proper storage and field handling of the PMB. The compatibility of PMBs can be tested following the ASTM D 7173 (Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt), even though there is no guarantee that this laboratory test method would reliably predict the long-term compatibility of polymer modified asphalt pavement in service.

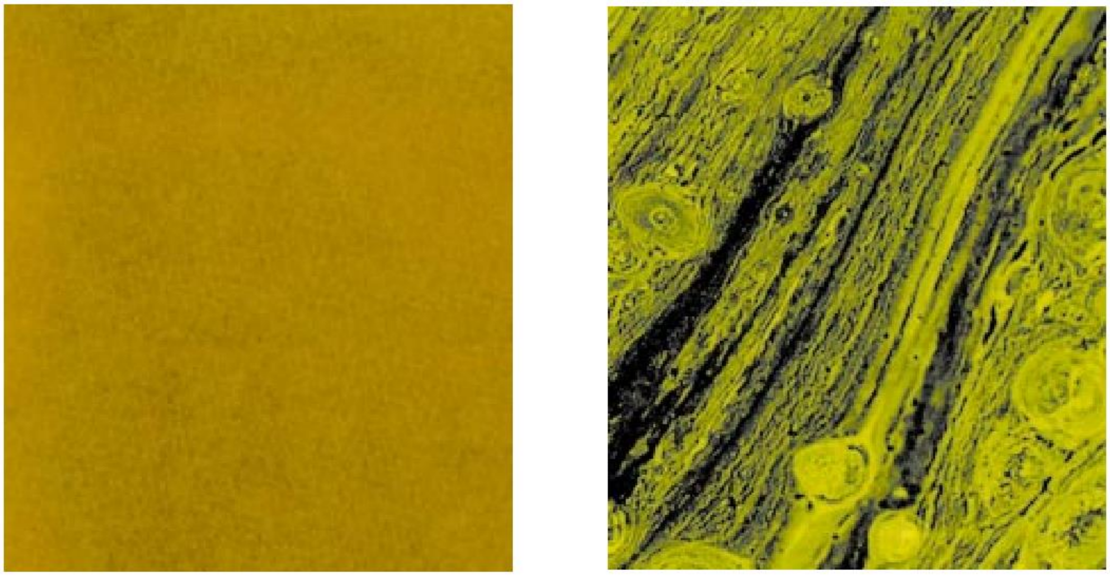
The polymers in the asphalt matrix can be divided into three groups: barely compatible (or incompatible), compatible, and highly compatible. If the polymers were incompatible in asphalt matrix, the colloidal equilibrium of the asphalt will be influenced and thus lead to a heterogeneous polymer-asphalt mixture with little cohesion and ductility. Polymers with medium compatibility in asphalt, in most cases, must be mixed with asphalt with special mechanical, thermal, or chemical equipment and a specific process to obtain the ideal dispersion condition. Although the high compatible polymers can be mixed in the asphalt matrix with conventional equipment and methods, the degrees of the property enhancement is not guaranteed.

Figure 2-9 illustrates the typical microstructures of polymer modified asphalt with high compatibility and low compatibility (*106*). As seen in this figure, the contrast between the two phases cannot be observed in high compatible PMB (a), while the other shows remarkable contrast between the polymer phase and the asphalt phase (b). Figure 2-10 shows the similar microstructures of 4 wt.% SBS modified asphalt binder (*106*). Similar to Figure 2-9, the contrast of the compatible image shows little difference between the SBS phase and the asphalt phase, while the incompatible shows obvious contrast between these two phases, suggesting their incompatibility.



a) b)

Figure 2- 9 Microstructures of a) compatible polymers and b) incompatible polymers in asphalt matrix (*106*)



a) b)

Figure 2- 10 Microstructures of 4 wt.% SBS modified asphalt a) compatible system and b) incompatible system (*106*)

In addition to the compatibility, storage stability is another important factor which must be considered before PMB can be implemented in the field. Specific to SBS modification, due to the low compatibility between the SBS polymer and the asphalt, the storage stability problem exists in the SBS modified asphalt. It was determined by Wen (*27*) that the high-temperature storage stability of the SBS modified asphalt is not strong until sulfur is added to mitigate the problem. Figure 2-11 shows the morphology of SBS-modified asphalt with increased storage time in an hour at 160°C in this study. As demonstrated in this figure, the well dispersed SBS will become isolated agglomerates with increased storage time at high temperature (*27*).

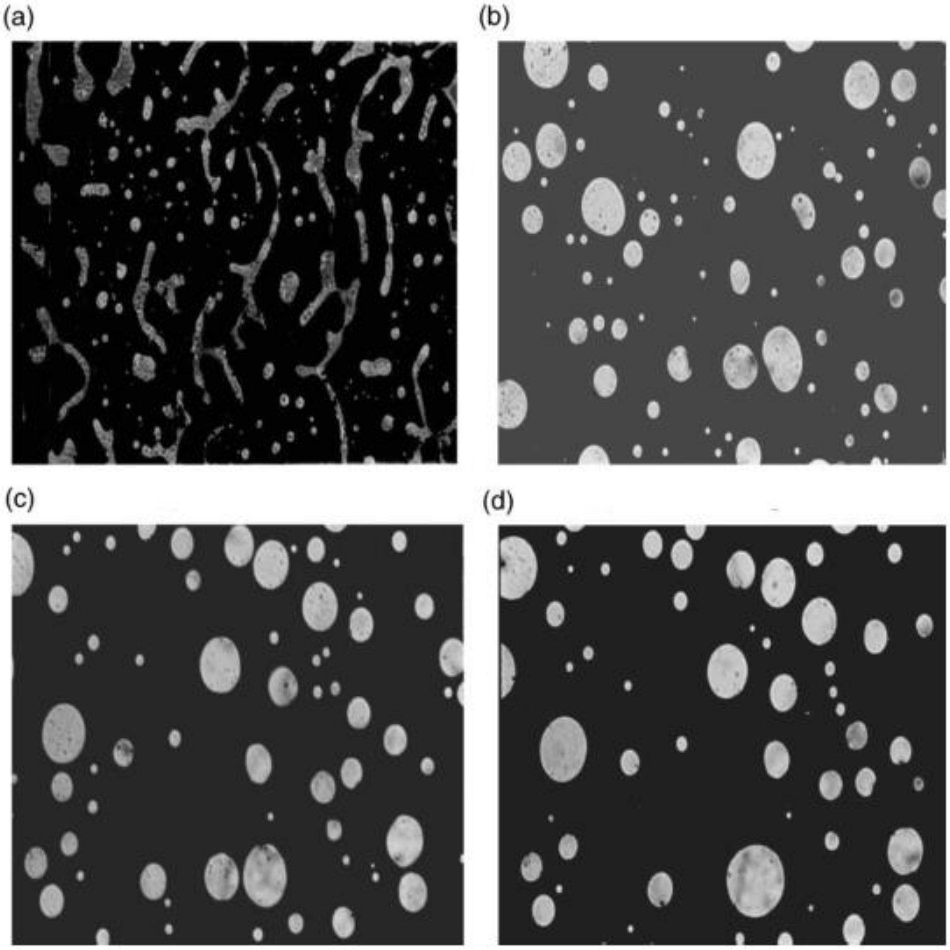


Figure 2- 11 Morphology development of SBS-modified asphalt with increased storage time at 160°C (*27*)

2.5 SULFUR VULCANIZATION OF PMBS

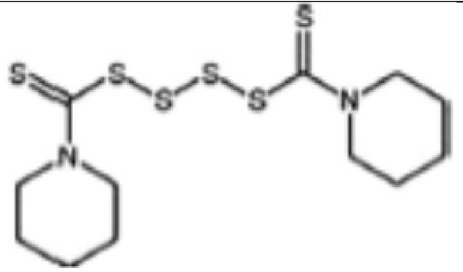
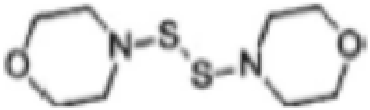
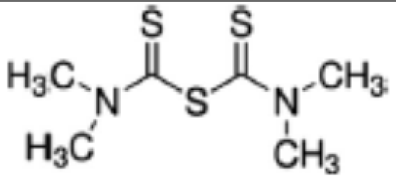
The sulfur vulcanization of PMBs (especially SBS) has been applied by the industry for more than three decades, and it has been proven to benefit the storage stability of PMBs (*107, 108*) and enhance the high-temperature properties of asphalt pavement (*109*). Nonetheless, from the published literature, it is hard to reach the conclusion that sulfur modification is the standard with SBS. While it may be true in practice, the literature rarely mentions whether or not the SBS has been modified by sulfur or by what type of sulfur when the performance of SBS modified binders is discussed.

The sulfur vulcanization treatment to PMBs is only effective to unsaturated polymers such as SBS, and it works via two main mechanisms. One modification mechanism is through the chemical crosslinking of polymer molecules, whereas the other mechanism is through the chemical coupling of polymer and asphalt via sulfide or polysulfide bonds (*27*). The formation of chemical bonds benefits the high-temperature stability of PMBs as they are stronger than physical bonds. The coupling effect between polymer and asphalt reduces the risk of phase separation as it contributes to stable polymer networks.

The linking of SBS and sulfur is resulted from the double bonds and substitution of allylic hydrogen atoms (*110*). While the treatment of SBS modified asphalt by elemental sulfur brings great benefits to the storage stability and other properties such as elasticity, deformation resistance, and rheology of PMBs, it also brought some shortcomings that initially limited its widespread applications in the field. First, some studies show that the sulfur vulcanization may lead to high susceptibility to oxidative aging. Second, hydrogen sulfide, a poisonous gas for both human health and natural environment, will be generated at high temperatures (*111, 112*). Finally, the sulfurized polymer modified asphalt pavement is more difficult to be reclaimed and recycled.

To address these issues, Table 2-9 lists the type and structure of innovative vulcanization accelerators as alternative to elemental sulfur (*107*). In most of them, the presence of S double bonds is responsible for performance enhancement of the SBS modified asphalt binder.

Table 2- 4 Type and structure of sulfur sources by means of additives

Additive	Molecular formula	Molecular weight
Dipentamethylenethiuram tetrasulfide (DPMTT)		384.66
4, 4’-dithiodimorpholine (DTDM)		2036.35
Tetramethylthiuram monosulfide (TMTMS)		208.37

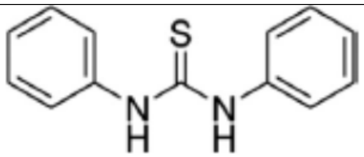
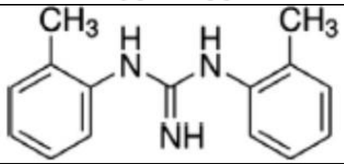
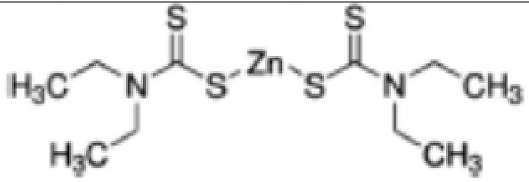
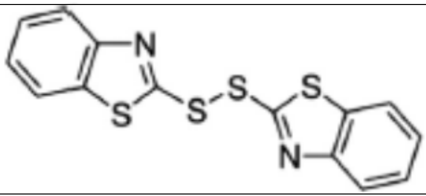
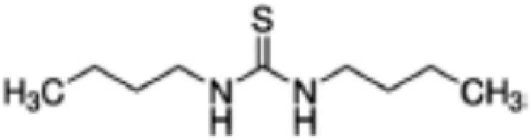
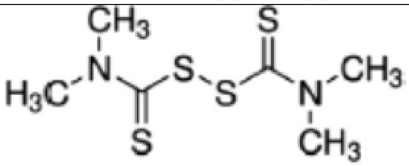
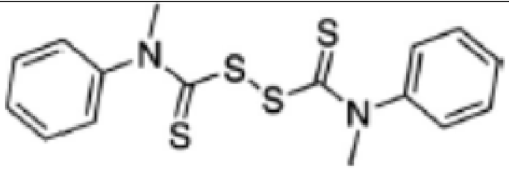
N, N’-diphenylthiourea (DPT)		228.31
1, 3’-Di-o-tolylguanidine (DoTG)		239.32
Zinc diethyldithiocarbamate (ZDTC)		361.93
2, 2’- dithiobis (benzothiazole) (DTBT		332.49
N, N’-dibutylthiourea (DBTU)		188.33
Tetramethylthiuram disulfide (TMTDS)		240.43
Dimethyl diphenyl thiuram disulfide (DMDTS)		364.575

Figure 2.12 and Figure 2.13 give the comparison of an SBS modified asphalt binder with or without vulcanization accelerator, which shows that the addition of vulcanization accelerator effectively addressed the compatibility issue of the SBS modified asphalt binder.

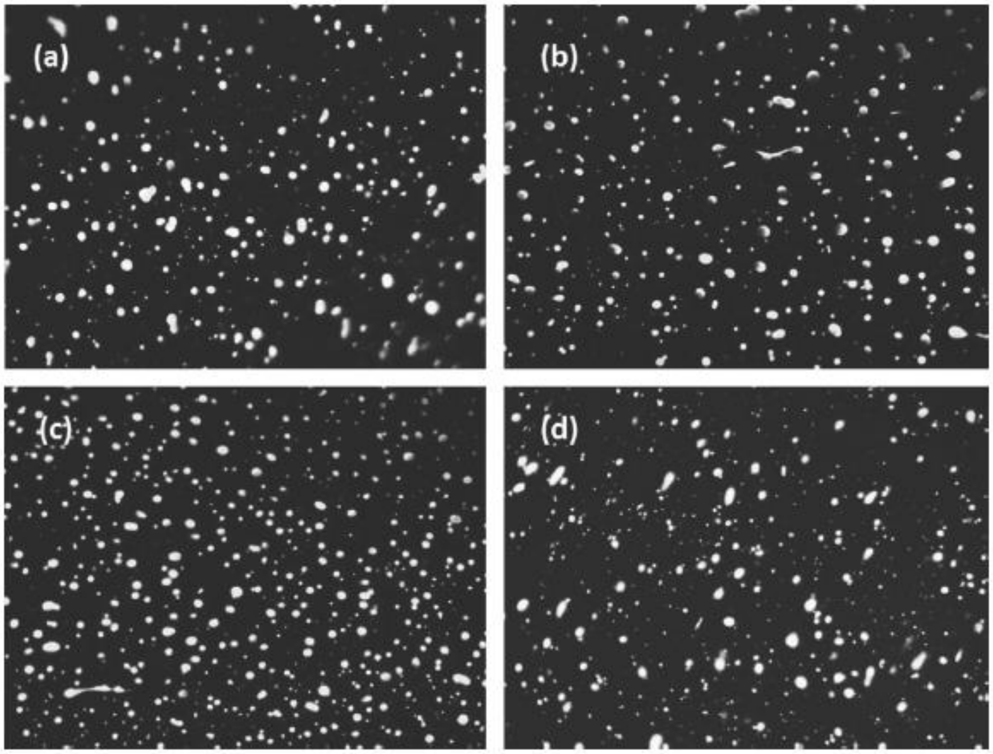


Figure 2- 12 Fluorescence micrographs of SBS modified asphalt binder without vulcanization accelerators (*107*)

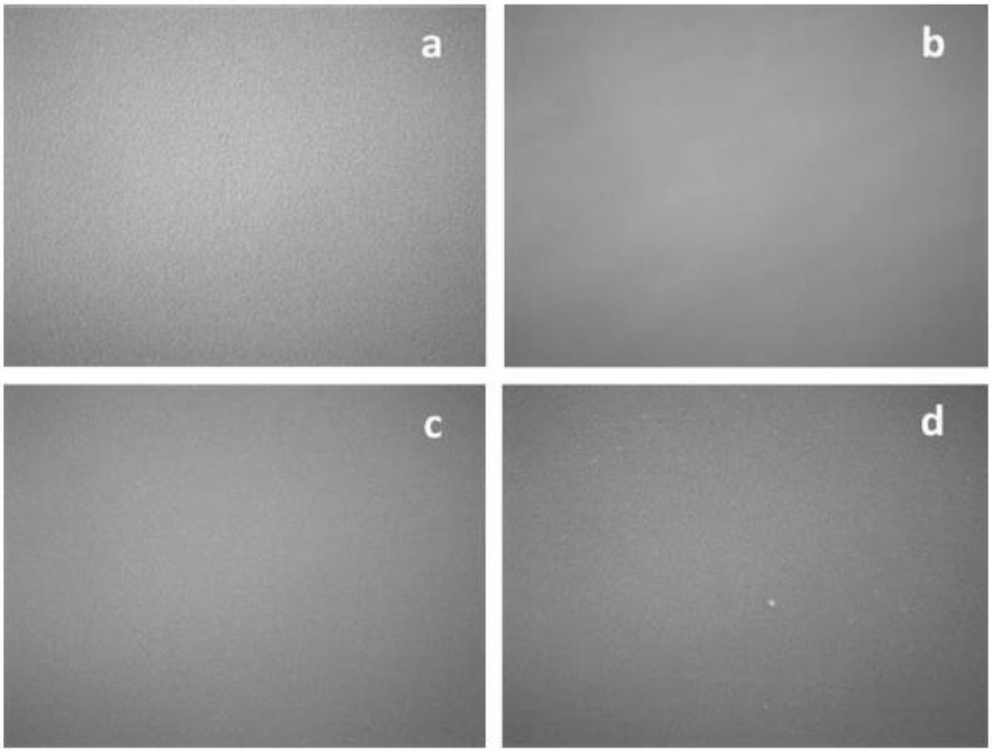


Figure 2- 13 Fluorescence micrographs of SBS modified asphalt binder with vulcanization accelerators (*107*)

2.6 KEY FINDINGS

- All plastomers, elastomers, and rubbers provide advantages and disadvantages for their use as asphalt binder modifier. Recent years have seen the introduction of PG Plus Binders, the success of which hinges on the use of elastomer and/or rubber for binder modification. The performance of asphalt pavement modified by *elastomers* depends on the asphalt source, the asphalt-polymer compatibility, and the polymer content. Appropriate polymer content and asphalt-polymer compatibility will lead to the formation of a continuous highly elastic polymer network in the asphalt matrix, which improves the cracking resistance of asphalt pavement at low service temperatures and its rutting resistance at high service temperatures. However, the elastomer modification tends to decrease the aging resistance of asphalt pavement However, the elastomer modification tends to decrease the aging resistance of asphalt pavement without periodic (e.g. semi-annual) fog-sealing. *Rubber* modification results in better rutting resistance and higher ductility of the asphalt pavement, but the modifier is sensitive to decomposition and oxygen absorption.
- The content of added polymer in the asphalt matrix is an import factor that influences the properties of PMB. It can be divided into low content (less than 4 wt.%), medium content (4-7 wt.%, and high content (more than 7 wt.%). In most cases, the content of plastomers and elastomers are at the low and medium levels, while the rubbers are usually at the high content level.
- Compatibility between asphalt and modifiers will prevent agglomeration of the polymers in the asphalt matrix during storage, pumping, construction, and service. The content and size of the asphaltenes and polymers, and the aromaticity of the maltene phase are the main factors that determine the compatibility. High aromaticity content will 1) lead to a reduction of the polystyrene domains, 2) result in low softening points, and 3) reduce flow resistance. The low content of aromaticity will result in a low flow resistance as well.
- The storage stability of the SBS modified asphalt (a common plus-grade binder) is typically improved by adding sulfur or alternative vulcanization accelerator. Well-dispersed SBS will become isolated agglomerates with increasing storage time at high temperature.

CHAPTER 3 EVALUATION OF PMB PROPERTIES

This chapter presents a compilation of case studies regarding the experience of various states with polymer modified asphalt pavement, followed by a summary of the PG Plus specifications of PMBs from various state DOTs. The relevant sections of the current NMDOT design policy are evaluated. The properties of plus grade PMBs are discussed with a focus on rheology, stiffness, elastic recovery, viscosity, ductility, toughness, rutting resistance, cracking resistance, aging resistance, storage stability, and long-term pavement performance.

3.1 CASE STUDIES OF VARIOUS STATES

Arizona

In Arizona, crumb rubbers rather than elastomer or plastomer are most widely used for asphalt modification. PG 64-16 was used in hot climate area (Phoenix), PG 58-22 was used in moderate climate area (Prescott, Flagstaff), and PG52-28 was used in cold climate area (Alpine). A minimum of 20 wt.% crumb rubber is required by weight of asphalt to make pavement more durable and less noisy (Kliewer, ADOT).

The crumb rubber was added to asphalt at 180°C-205°C and cured for at least one hour for the reaction between asphalt and crumb rubber to occur at 165°C-190°C under agitation. Table 3-1 shows the typical properties of crumb rubber asphalt (CRA).

Table 3- 1 Typical properties of crumb rubber asphalt

Property	CRA-1	CRA-2	CRA-3
Base asphalt grade	PG 64-16	PG 58-22	PG 52-28
Rotational Viscosity	1.5-4.0	1.5-4.0	1.5-4.0
Penetration depth, 4°C, 200g, 60 sec,	10 min	15 min	25 min
Softening point, °C	57 min	54 min	52 min
Resilience, percent, 25°C	25 min	20 min	15 min

For the PG 76-22 TR+ binder, a minimum 2 wt.% of SBS and 8 wt.% of crumb rubber are required. The property requirements of this grade are listed as Table 3-2.

The benefits of crumb rubber modification to the asphalt pavement include: a) Reduced reflective cracking via improved elastic properties; b) Increased aging resistance; c) Increased durability; d) Reduced noise; e) Improved cost-effectiveness.

Table 3- 2 Typical properties of crumb rubber modified asphalt

Property	Test method	
Elastic recovery, 10°C, percent,	AASHTO T 314	55 min
Phase Angle 76°C and 10 rad/sec, degrees	AASHTO T 53	75 max
Softening point, °C	AASHTO T 301	60 min

Florida

According to the Accelerated Pavement Testing (APT) method, the neat PG67-22, SBS modified PG 76-22 (at about 3 wt.%), and SBS modified PG82-22 (at about 6 wt.%) were used and evaluated for rutting resistance and fatigue resistance. The rutting and fatigue cracking performance of hot mix asphalt (HMA) mixtures were both improved by the SBS modification. The PG82-22 binder remarkably reduced the damage rate of HMA, and it showed a relatively higher energy ratio than the PG76-22 binder, which indicates a relatively higher cracking resistance. (*113*)

Rutting Resistance

Figure 3-1 shows the rut depth as a function of the Heavy Vehicle Simulator (HVS) passes. As seen in this figure, the rut depth decreased with increased amount of SBS. Figure 3-2 shows the transverse rut profiles after 100,000 passes. After 100,000 passes, the rutting of the lane constructed with PG 76-22 and PG 82-22 binders decreased 50 percent and 80 percent compared with the lane without SBS modification. This figure also illustrates how the shear to wheel path area ratio remarkably decreased with increasing SBS content.

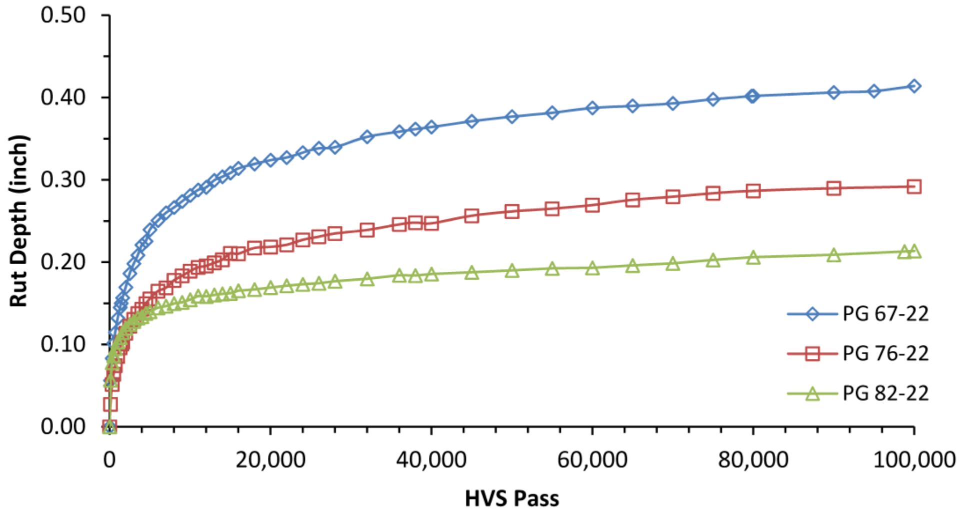


Figure 3- 1 APT rut depth as a function of HVS pass (*113*)

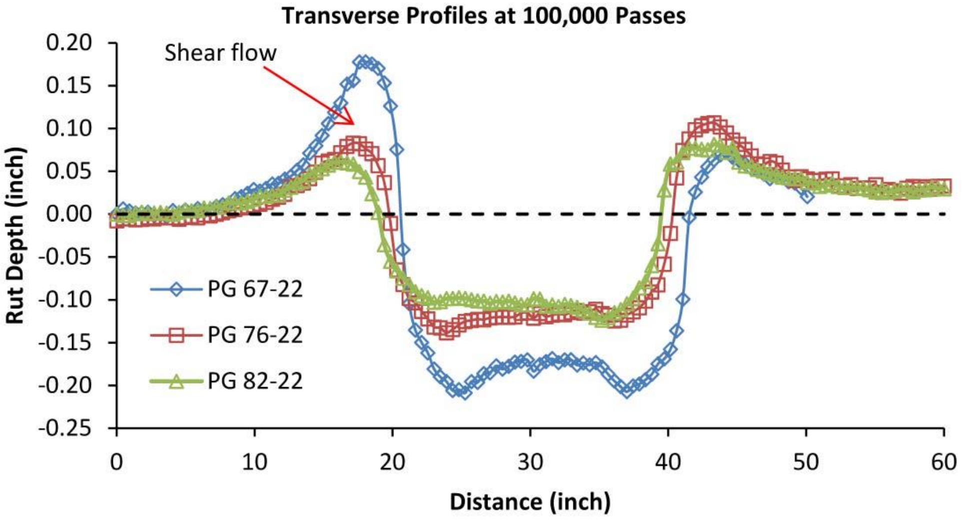


Figure 3- 2 Rut depth as a function of distance after 100,000 passes (*113*)

Fatigue Resistance

The average microtensile strain was measured at various times at the bottom of the HMA to obtain the response of the pavement in a wide temperature range. Little amount of fatigue cracks can be observed after more than 100,000 HVS passes. Figure 3-3 illustrates the tensile microstrain as a function of temperature after 100,000 passes. The PG 82-22 exhibited the lowest microstrain while PG 67-22 exhibited the highest. At 20°C, the fatigue resistance of the PG 82-22 and PG 76-22 binders was 20 times higher than the PG 67-22 binder. The fatigue life of the PG 82-22 binder was about 7 times higher than the PG 76-22 binder.

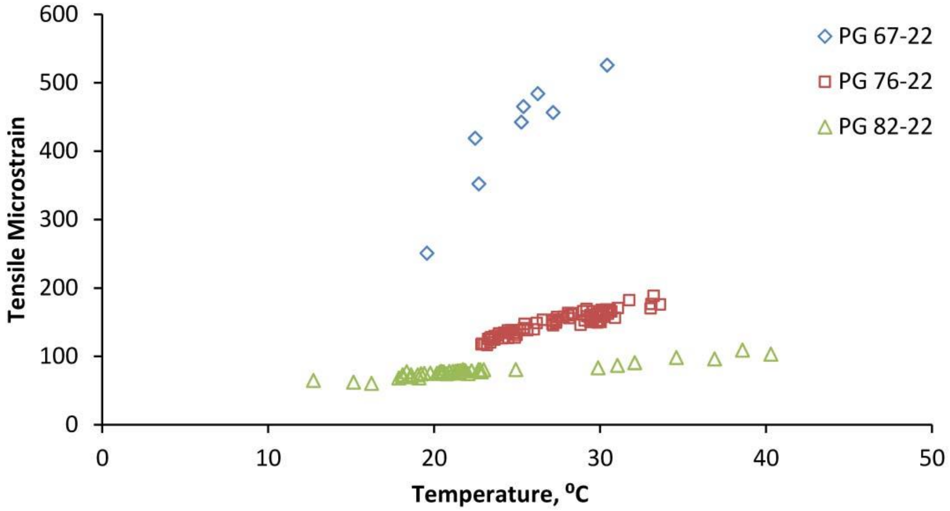


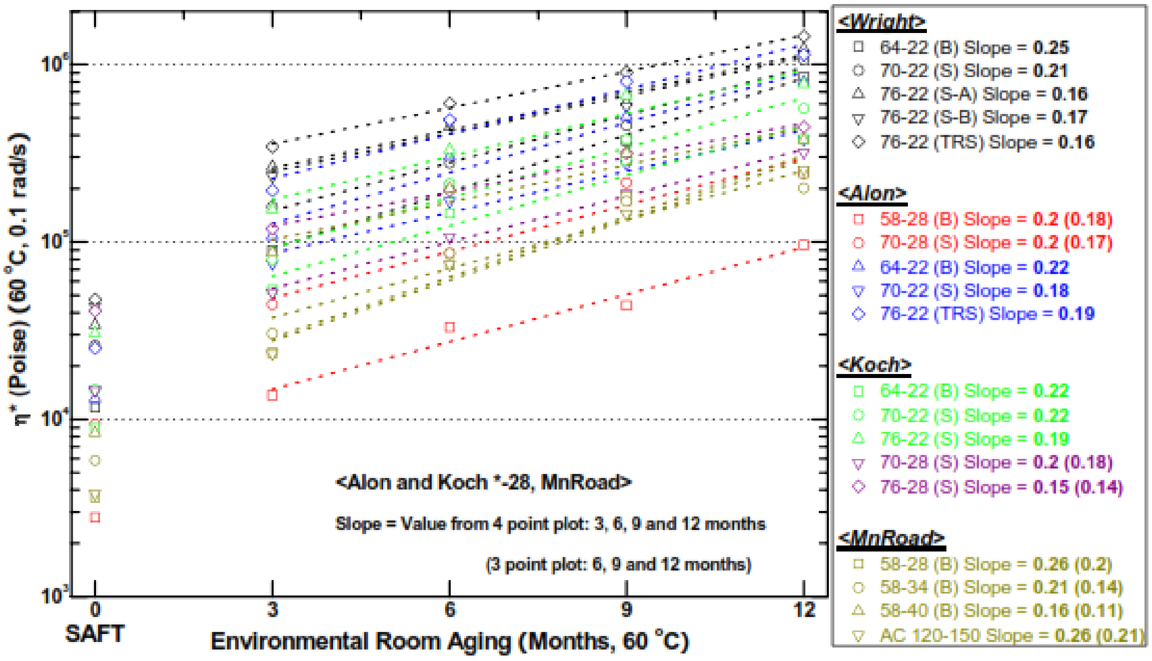
Figure 3- 3 Tensile microstrain of HMA as a function of temperature after 100,000 passes (*113*)

This study demonstrated that the PG 82-22 modified asphalt binder has a higher rutting and fatigue resistance than the standard asphalt binders currently used by the Florida DOT.

Texas

Three types of typical polymers, namely SBS, SBR, and tire rubber, were used for testing the modification effects. Same grade asphalt binder was used as a control. The base binders were primarily PG 64-22 asphalts, but also included one PG 58-28. The modified binders included the performance grade materials up to PG 76-22. The rheological properties and aging characteristics were investigated and it was determined that the ductility improved with polymer modifications if the oxidation was at a low level. The ductility improvement disappeared with increased oxidation levels. The binder stiffening and the polymer decomposition (due to oxidation) were the two main reasons for the degradation.

The hardening rate test results show that most of the modified binders have as much as a 40 percent less hardening rate than the neat binders. It was found that the hardening rate of the binders in the Texas pavement could be reduced, thus prolonging the service life of the pavement by 15 to 20 years, if the air voids in the pavements are stable (lower than 2 wt.%). A side effect of the SBS modified binder in Texas was a higher stiffness than neat asphalt binder at the beginning of the construction process, which is not good for workability. Figure 3-4 shows the hardening rate for environmental room (ER) aged binders from various resources, and Figure 3-5 shows the force ductility at 4°C for various binders.



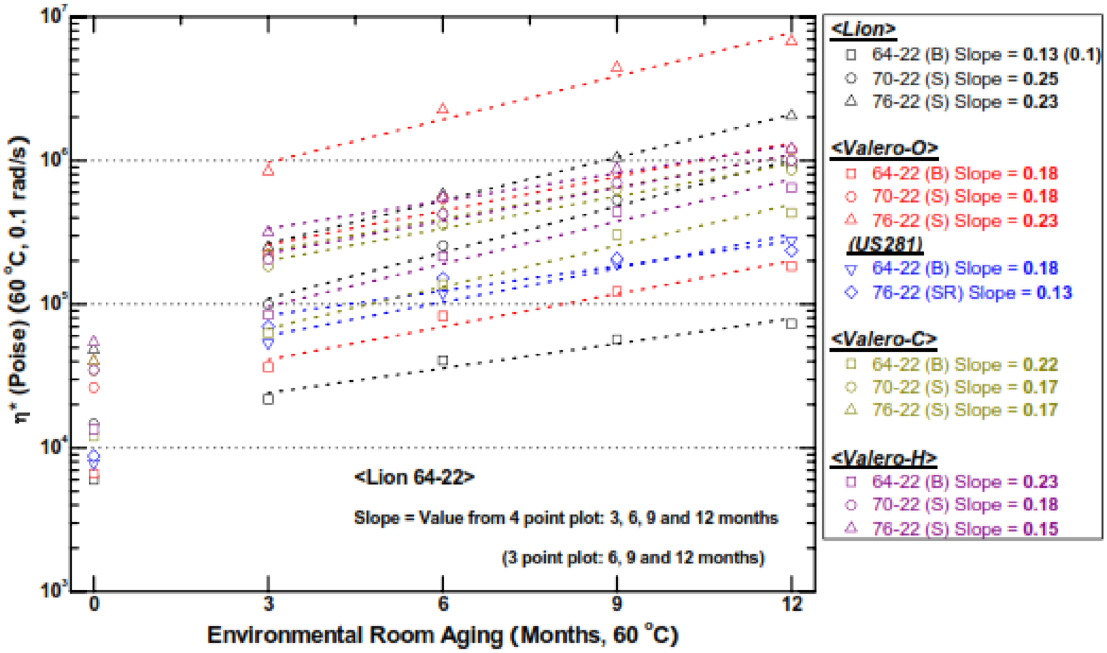
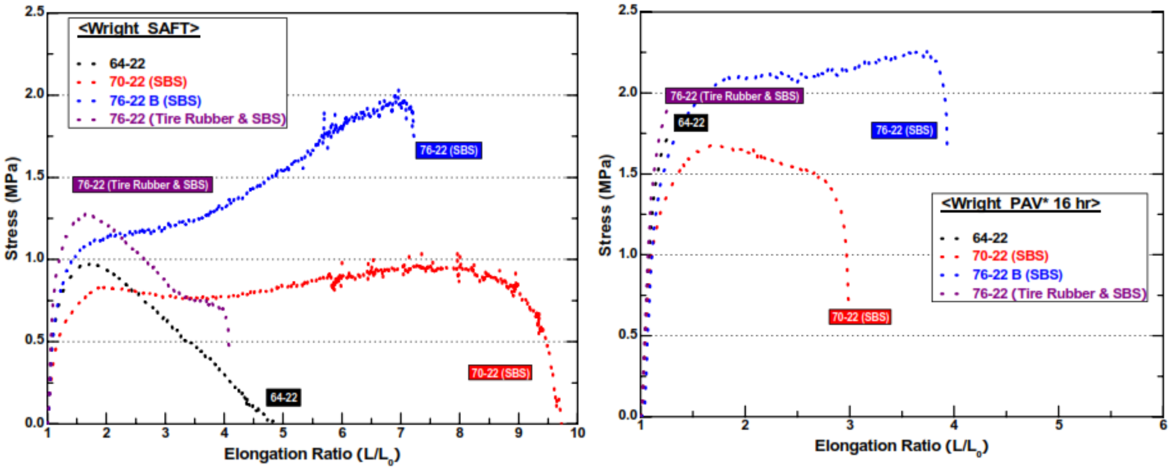
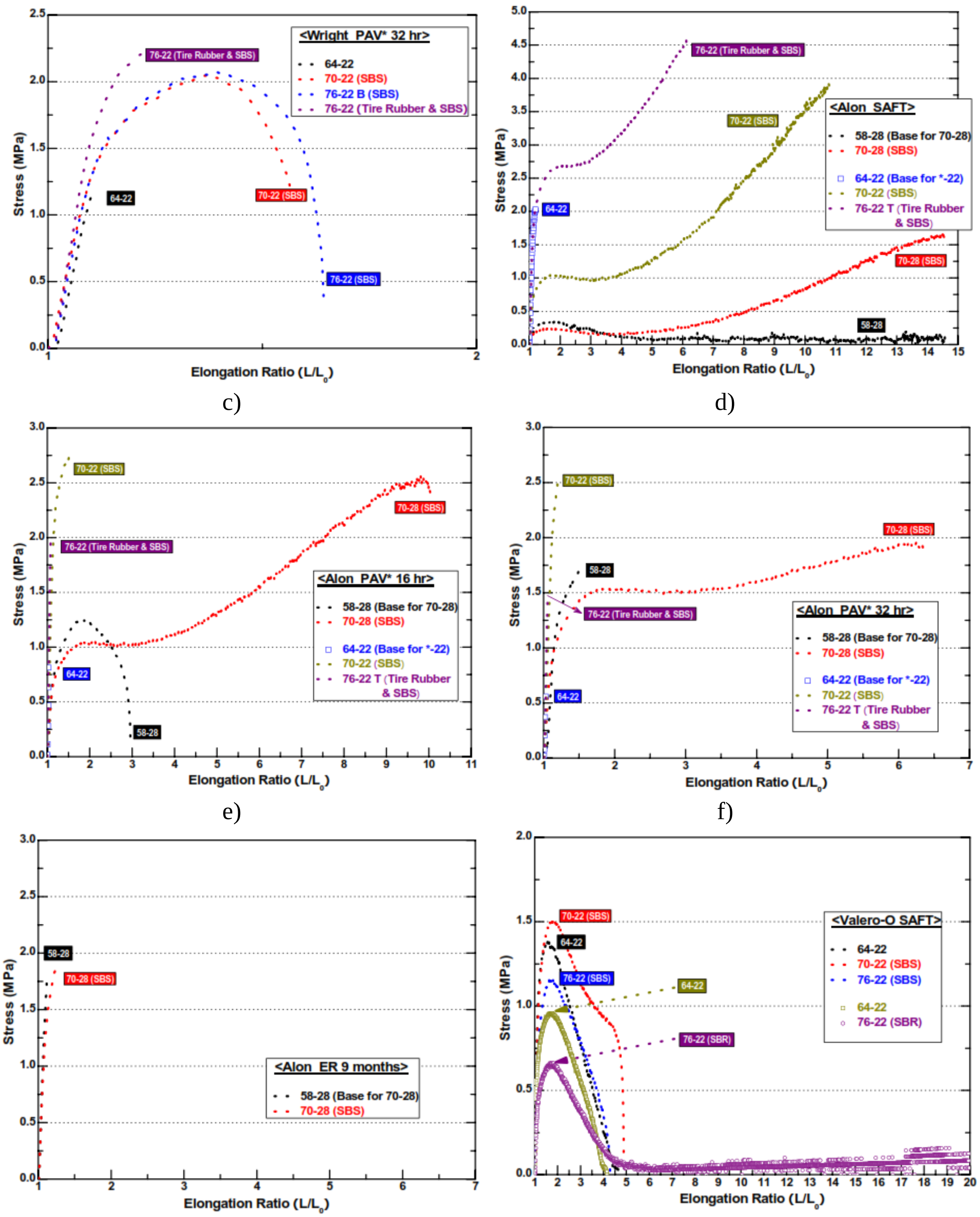


Figure 3- 4 Hardening rate for ER aged binders from various resources (*114*)



a) b)



c)

d)

e)

f)

g)

h)

Figure 3- 5 Force Ductility at 4°C for a) SAFT Aged Wright Asphalts, b) PAV* 16 h Aged Wright Asphalts, c) PAV* 32 h Aged Wright Asphalts, d) SAFT Aged Alon Asphalts, e) PAV* 16 h Aged Alon Asphalts, f) PAV* 32 h Aged Alon Asphalts, g) ER 9 Month Aged Alon Asphalts, h) SAFT Aged Valero-Oklahoma Asphalts (*114*)

SBS co-block polymer-modified PG 76-22, PG 70-22, PG 58-34, and PG 58-40 provided the most reduction in the hardening rate and thus significantly improved the pavement durability. By adding polymers to neat asphalt, the SuperPave performance grade span can be increased by increasing the upper grade without harming the lower grade significantly. At the same time, polymer modification typically improves binder ductility, thereby providing a binder that is more durable to pavement stress and deformation. There is evidence that polymer modifiers may improve the aging characteristics of a binder, thereby delaying the deleterious impact of oxidative aging.

Oklahoma

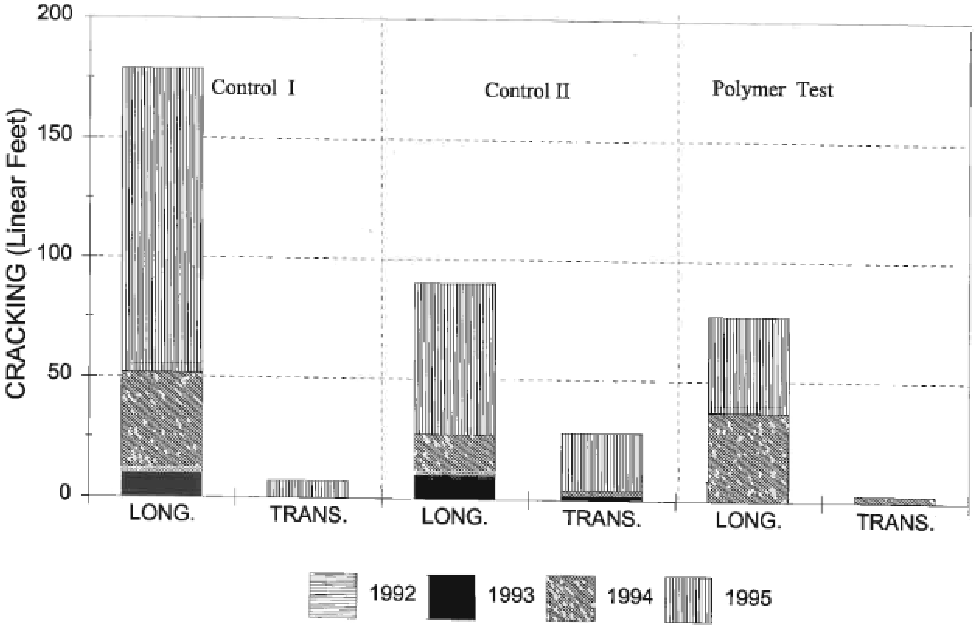
Three performance grade asphalt binders, namely PG 64-22, PG 70-28, and PG 76-28 with an elastomer modifier (i.e., SBS) and two anti-stripping additives (Adhere HP-Plus and Perma Tac Plus) were used to evaluate the modification effects. The testing results show that the grade changes of the PG 70-28 and PG 76-28 modified asphalt are more significant than the neat PG 64-22 asphalt with various anti-striping additives. The PG 64-22 binder increased 1.5°C on high grade temperature, while the PG 70-28 increased 3.2°C and the PG 76-28 increased 3.6°C. After the change of grade, the PG 76-28 can closely reach the level of PG 82-28. (*115*)

Kuennen (2012) reported that the use of a SBS product at 7.5 wt.% by the Oklahoma DOT for three different asphalt mixes on I-40 (PG 76-28 E), aimed to reduce the required pavement thickness. This new type of SBS was manufactured by Houston-based Kraton Performance Polymer, Inc., and some consider it still too early to draw conclusions about the performance of such SBS modified asphalt pavement until more field data become available.

Colorado

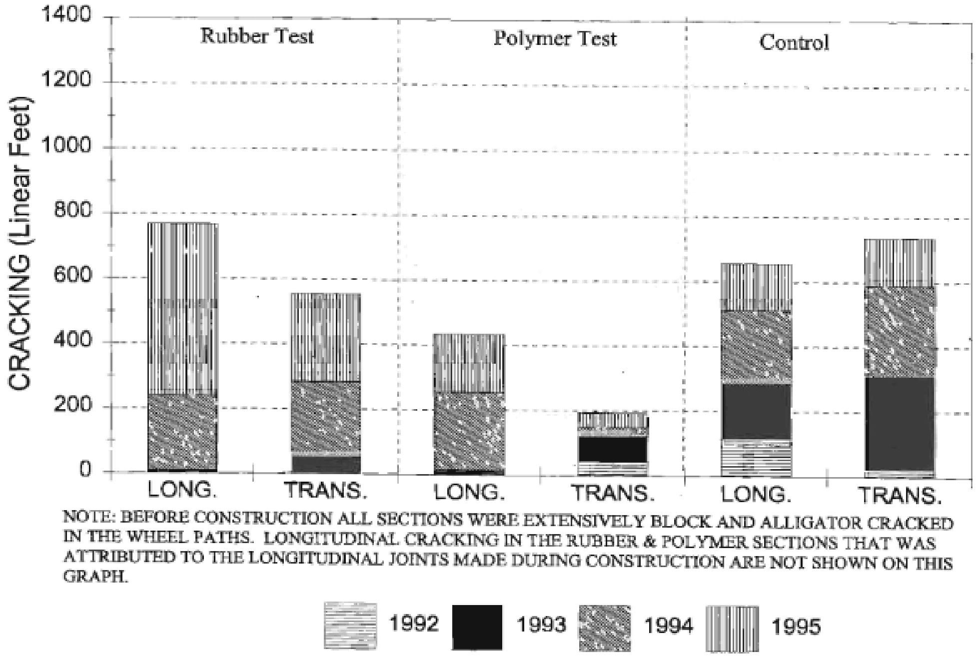
In Colorado field studies, three types of polymers were used as the modifiers for asphalt modifications. Type I was neat asphalt mixed with styrene block copolymer; type II was neat asphalt mixed with SBR or neoprene latex; and type III was neat asphalt mixed with EVA. The rutting resistance of pavement constructed by polymer modified asphalt binders was not remarkably increased. This was confirmed by the lack of change in the voids of the pavement cores during the four-year study period, in both modified sections and control sections. In contrast, the cracking resistance was remarkably enhanced in the sections constructed with modified asphalt binders. Compared with the control sections, the cracks in the modified sections decreased about 50 percent for longitudinal and transverse cracking (*116*).

Figure 3-6 shows the cracking distribution of polymer modified asphalt and control pavements from 1992 to 1995 at various locations.



CRACKING

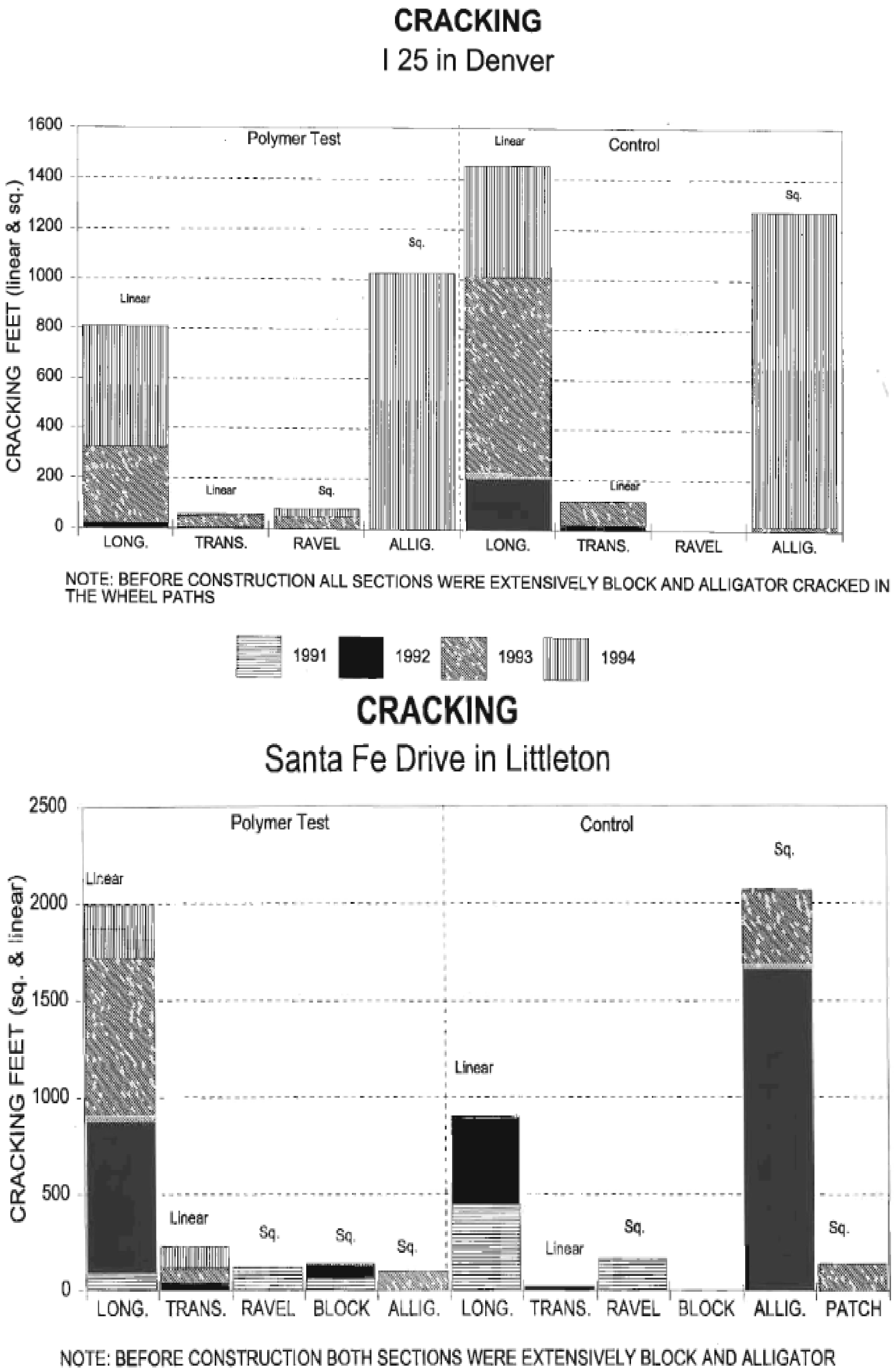
I 70 near Flagler



CRACKING

I 25 near Pueblo **(revised)**

NOTE: BEFORE CONSTRUCTION ALL SECTIONS WERE EXTENSIVELY BLOCK AND ALLIGATOR CRACKED IN THE WHEEL PATHS. LONGITUDINAL CRACKING IN THE RUBBER & POLYMER SECTIONS THAT WAS ATTRIBUTED TO THE LONGITUDINAL JOINTS MADE DURING CONSTRUCTION ARE NOT SHOWN ON THIS GRAPH.



CRACKING

I 25 in Denver

NOTE: BEFORE CONSTRUCTION ALL SECTIONS WERE EXTENSIVELY BLOCK AND ALLIGATOR CRACKED IN THE WHEEL PATHS

CRACKING

Santa Fe Drive in Littleton

NOTE: BEFORE CONSTRUCTION BOTH SECTIONS WERE EXTENSIVELY BLOCK AND ALLIGATOR

Figure 3- 6 Cracking distribution of polymer modified asphalt and control pavements from 1992 to 1995 at various locations (*116*).

Mississippi

The University of Mississippi conducted SuperPave binder tests in the laboratory and compared the PG 58-10 asphalt and modified asphalt binders from test sections along Interstate 55 in Mississippi (*117*). In this study, eight polymer modified binders were used to compare the high and low-temperature performances of pavements constructed with unmodified asphalt and polymer modified asphalt. The results show that the polymer addition was beneficial to the pavement performance at both high and low-temperatures. The field evaluation further confirmed the good performance of the polymer modified binder sections with respect to rutting, relative to neat asphalt section.

3.2 SUMMARY OF BINDER SPECIFICATIONS FROM STATE DOTS

The binder specifications of all 50 states have been reviewed and the information related to MSCR or elastic recovery of modified asphalt binder is summarized in Appendix B. The vast majority of states focused on elastomers (SBS, SB, SBR) or crumb rubber as polymer modifier (i.e., for plus grade PG asphalt binder). The vast majority of states have performance based binder specifications as their specification calls out either MSCR or elastic recovery, and about half of the states (23 out of the 50) specifies the use of polymer type or content in the asphalt binder. The vast majority of states have elastic recovery in their binder specification or in supplemental requirements, but only four states (Florida, Georgia, Nevada, and Oklahoma) have MSCR in their current binder specification. Nonetheless, many states are in the process of adopting MSCR into their binder specification. For instance, the North Central Asphalt User/Producer Group representing Iowa, Michigan, Minnesota, North Dakota, South Dakota, and Wisconsin DOTs and Nebraska Department of Roads (https://engineering.purdue.edu/~ncaupg/Activities/Combined%20State%20Binder%20Group.html,) Combined States Binder Group has established the requirements for minimum MSCR % Recovery to go effective in January 2015, as shown in Table 3-3 (Scott Schram, Iowa DOT, June 20, 2014 – unpublished data). Similarly, the North East Asphalt User/Producer Group representing Maine, Massachusetts, New Hampshire, Vermont, Rhode Island, and Connecticut DOTs (http://www.neaupg.uconn.edu/) are developing MSCR requirements to supplement their current binder specifications as well. For instance, the Connecticut DOT has the following special provision for bituminous concrete materials, specifically the requirements for “Modified Performance Grade (PG) Binder” (Robert G. Lauzon, Connecticut DOT, June 23, 2014 – unpublished data):

> “Unless otherwise noted, the asphalt binder shall be Performance Grade PG 76-22 asphalt modified with a Styrene-Butadiene-Styrene (SBS) polymer. The polymer modifier shall be added at either the refinery or terminal and delivered to the bituminous concrete production facility as homogenous blend. The stability of the modified binder shall be verified in accordance with ASTM D7173 using the Dynamic Shear Rheometer (DSR). The DSR G*/sin(δ) results from the top and bottom sections of the ASTM D7173 test shall not differ by more than 10%. The results of ASTM D7173 shall be included on the Certified Test Report. The

> binder shall meet the requirements of AASHTO M-320(M) and AASHTO R-29(M)."

The New Hampshire DOT has changed to the MSCR grades in 2014 and uses a PG 64E-28 grade for polymer modified asphalt binder, following the M332-14 and T350-14 specifications (Beran Black, New Hampshire DOT, June 23, 2014 – unpublished data).

Table 3- 3 Requirements for minimum MSCR % recovery established by the Combined States Binder Group

AASHTO M320 Grade	Test Temperature	
	58°C	64°C
52-34	0	0
58-28	0	0
64-22	0	0
58-34P	30	25
64-28P	30	25
64-34P	55	45
70-22P	55	45
70-28P	55	45
70-34P	75	75
76-28P	75	75
76-34P	75	75
82-22P	75	75

Note that many states have requirements for both specific properties (MSCR or elastic recovery) and polymer type or content in their binder specifications. The need for some prescriptive specifications is based on the fact that meeting the current binder property requirements cannot guarantee the long-term field performance of polymer modified asphalt pavement. This remains true despite the efforts of SuperPave and other studies to facilitate the paradigm shift from prescriptive specifications to performance based specifications.

Table 3-4 lists the descriptions and exclusions of binder specifications of the eight select State DOTs. As shown in the table, Arizona, Florida, and Texas have specific descriptions on the polymer modified asphalt, including polymer types, content ranges, and some grade requirements. Table 3-5 summarizes the PG Requirements for Performance-Graded Asphalt Binders. Basic property requirements on the specifications of various states are listed in this table. Table 3-6 gives the specific PG Requirements for Performance-Graded modified Asphalt Binders from various states.

Based on the evaluation of the states' specifications, the property requirements for PMBs are higher than neat asphalt binders. Arizona, Colorado, Florida, and Oklahoma have specific requirements for PMBs. The current requirements for PMBs for NMDOT are very limited. Different states have different requirements on the elastic recovery, flash point, solubility, & dynamic shear, but the requirements for rotational viscosity, creep stiffness and *m*-value, & mass change are similar. Florida has MSCR requirement on J_{nr} (percent) of 75 max at 67°C (Test method 19-10) in PG 76-22 (PMA), PG 76-22 (ARB), and PG 82-22 (PMA), and Oklahoma has MSCR requirement on J_{nr} (percent) of 95 min (Test method TP 70) in PG-76-28E.

Delaware has no specific requirement concerning plastomeric vs. elastomeric polymer modifiers. This is because elastomer is the default as there is no longer a plastomer supplier in the state. They just say "Asphalt Cement shall be prepared by refining of crude petroleum using methods conforming to industry standards. Asphalt Cement shall conform to requirements of AASHTO M 320."

Currently, NMDOT has its own specifications of the OGFC polymer-modified asphalt binder, and OGFC asphalt rubber binder formulation design (details are listed in Table 3-6). The NMDOT current design policy for both cases is reasonable in light of the knowledge available in the published domain and the field observations. In the OGFC polymer-modified asphalt binder specification, the PG 70-28R+ was used as the base and 5 wt.% tire rubber coupled with 2 wt.% SBS were added in it. It is required the performances have to satisfy AASHTO M 320 in addition to the requirement of the solubility, which should be higher than 97.5 percent (ASTM-D2042). In the OGFC asphalt rubber binder formulation design specification, the asphalt rubber binder shall contain a minimum of 10 wt.% tire rubber modifier and a minimum of 2 wt.% SBS polymer by weight of total formulation. The asphalt rubber binder shall conform to the requirement of AASHTO M 320, as well as the requirements with flash point>230 °C, elastic recovery>65 percent, solubility>98 percent, original DSR>1.00 KPa, RTFO aging>2.20 KPa, PAV aging<5000 KPa, creep stiffness<300 MPa, and *m*-value >0.300 (details are listed in Table 3-6).

Although the specification of polymer modified asphalt binder have been successfully applied in the OGFC of New Mexico, some requirements still need to be determined before the polymer modified asphalt can be optimized as dense graded mix binder. This is considering that the OGFC is only used as a highly porous surface and its stress condition, binder content, and porosity are considerably different from the dense graded mix. Changes are proposed to the specification for dense graded mix binder (see Appendix A), as a result of this study.

Table 3- 4 Summary of asphalt binder specifications from various state DOTs

States	Description	Polymer Modified Asphalts	Exclusions
Arizona	Shall be a Performance Grade (PG) asphalt binder conforming to requirements of AASHTO M 320. One-gallon sample required w/ C of A, seven days before production of asphaltic concrete. If binder is found to be non-compliant, the asphaltic concrete will be evaluated.	PG 76-22 TR+ and PG 70-22 TR+ shall contain a minimum of 8 wt.% crumb rubber and a minimum of 2 wt.% SBS polymer.	None
California	'Certificates of Compliance' shall accompany each shipment of asphalt to each job. Certificates shall include: shipment number, type of material, SG, refinery, consignee, destination, quantity, PO number, date, and statement of compliance.	None	Do not modify PG modified asphalt binder using polyphosphoric acid (PPA). Crumb rubber must be from automobile and truck tires and must be free from contaminants including fabric, metal, minerals and other non-rubber substances. PG modified asphalt binder modified with crumb rubber must be homogenous and must not contain visible particles of crumb rubber. The supplier of PG modified asphalt binder with crumb rubber must: 1) report the amount of crumb rubber by weight of asphalt binder and 2) certify a minimum of 10 wt.% of crumb rubber by weight of asphalt binder.
Colorado	Supplier must be certified in accordance with CP 11. Samples of PG Binder for acceptance shall be sampled on the project as stated in the Schedule of Field Materials Manual.	None	Asphalt shall not be Acid or Alkaline modified. Shall not contain any used oils that have not been re-refined or reprocessed. No modifiers shall be added that do not comply with environmental rules and regulations including 40 CFR Part 261.6(a)(3)(v) and 266/Subpart C. Modifiers shall not be carcinogenic.
Florida	"Superpave PG asphalt binders, identified as	All asphalt binders having a high-	None

	PG 52-28, 58-22, 67-22, 76-22 (PMA), 76-22 (ARB), and 8222, shall meet the requirements of 916-1. Where OG binder is used in mixes containing reclaimed asphalt pavement (RAP), the requirements of 334-2.3.1 and 334-2.3.5 must also be met. For all PG binder used in all hot mix asphalt, silicone may be added to the PG binder at the rate of 25 cm3 of silicone mixed to each 5,000 gallons of PG binder. The blending of the silicone with the PG binder shall be done by the supplier prior to the shipment. Unless FM 1-T 283 test results suggest otherwise, all PG binder for Friction Course mixes and for other HMA products containing RAP shall contain 0.5 wt.% heat stable anti-strip additive by weight of PG binder, added by the supplier during loading."	temperature designation of PG 67 or lower shall be prepared without modification. All PG asphalt binders having a high-temperature designation higher than PG 67 shall be produced with an SBS or SB polymer or ground tire rubber meeting the requirement of Section 919 (ARB). For modified binders, the original PF grade, the type of modifier and the amount added shall be indicated when applying for inclusion on the Qualified Products List.	
Oklahoma	Additional requirements for bitumen. PG 64-22 OK, PG 70-28 OK, & PG 76-28 OK shall meet the requirements for PG 64-22, PG 70-28, & PG 76-28 as shown in AASHTO M 320. Additionally, they must meet the requirements as shown below. PG 76-28 E must meet AASHTO MP 19 requirements.	None	None
Texas	Performance-Graded Asphalt Binders must be smooth and homogeneous, show no separation when tested in accordance with Tex-540-C, and meet Table 17 **(in TX spec)** requirements.	Separation testing is not required if: a modifier is introduced separately at the mix plant either by injection in the asphalt line or mixer, the binder is blended on site in continuously agitated tanks, or a binder acceptance is based on field samples taken from an in-line sampling port at the hot mix plant after the addition of modifiers.	None

Utah	Supply PGAB's under the Approved Supplier Certification (AC) System. Refer to the Utah Department of Transportation Minimum Sampling and Testing Guide, Section 509, Asphalt Binder Management Plan. As specified in AASHTO M 320 for all PGAB's having algebraic differences less than 92 degrees between the high and low design temperatures. For all PGAB's having algebraic differences equal to or greater than 98 degrees between the high and low design temperatures.	None	None
New Mexico	Performance-graded asphalt binder shall meet the requirements of AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder.	None	None

Table 3- 5 PG Requirements for Performance-Graded Asphalt Binders

States	Creep stiffness, MPa (PAV RESIDUE)	Elastic recovery, percent (RTFO RESIDUE)	Dynamic Shear, kPa (G*/sin δ)	Rotational Viscosity, Pa·s	*m*-value (PAV RESIDUE)	Solubility, percent	Mass change, percent (RTFO RESIDUE)	Flash point, °C
Arizona	300 max.@ 0°C, -6°C, -12°C. (Test method: T313) in PG 58-22, PG 64-16, PG 64-22, PG 70-10, PG 76-16, PG 70-22 TR+, PG 76-22 TR+.	-	1.00 min. (Test method: T315) in PG 58-22, PG 64-16, PG 64-22, PG 70-10, PG 76-16, PG 70-22 TR+, PG 76-22 TR+.	3.0 max. @ 135 °C (Test method: T316) in PG 58-22, PG 64-16, PG 64-22, PG 70-10, PG 76-16, PG 70-22 TR+, PG 76-22 TR+.	0.300 min.@ 0°C, -6°C, -12°C. (Test method: T313) in PG 58-22, PG 64-16, PG 64-22, PG 70-10, PG 76-16, PG 70-22 TR+, PG 76-22 TR+.	-	1.00 max. (Test method: T240) in PG 58-22, PG 64-16, PG 64-22, PG 70-10, PG 76-16, PG 70-22 TR+, PG 76-22 TR+.	230 °C min. (Test method: T48) in PG 58-22, PG 64-16, PG 64-22, PG 70-10, PG 76-16, PG 70-22 TR+, PG 76-22 TR+.
California	300 max.@ 0°C, -6°C, -12°C, -18°C. (Test method: T313) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.	-	1.00-2.00 min. (Test method: T315) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.	3.0 max. @ 135 °C (Test method: T316) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.	0.300 min.@ 0°C, -6°C, -12°C, -18°C. (Test method: T313) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.	99.0 min. (Test method: T44) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.	1.00 max. (Test method: T240) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.	230 °C min. (Test method: T48) in PG 58-22, PG 64-10, PG 64-16, PG 64-28, PG 70-10.
Colorado	300 max @ -12°C,	-	1.00 min. (Test method:	3.0 max. @ 135 °C (Test	0.300 min.@ -12°C,	-	1.00 max. (Test method: CP-L)	230 °C min. (Test method:

	-18°C, -24°C. (Test method: T313) in PG 58-28, PG 58-34, PG 64-22, PG 64-28, PG 70-28, PG 76-28.		T315) in PG 58-28, PG 58-34, PG 64-22, PG 64-28, PG 70-28, PG 76-28.	method: T316) in PG 58-28, PG 58-34, PG 64-22, PG 64-28, PG 70-28, PG 76-28.	-18°C, -24°C. (Test method: T313) in PG 58-28, PG 58-34, PG 64-22, PG 64-28, PG 70-28, PG 76-28.		in PG 58-28, PG 58-34, PG 64-22, PG 64-28, PG 70-28, PG 76-28.	T48) in PG 58-28, PG 58-34, PG 64-22, PG 64-28, PG 70-28, PG 76-28.
Florida	300 max @ -12°C, -18°C) in PG 58-22, PG 67-22. PG 52-28.	-	1.00 min. (Test method: T315) in PG 52-28, PG 58-22, PG 67-22.	3.0 max. @ 135 °C (Test method: T316) in PG 52-28, PG 58-22, PG 67-22.	0.300 min.@ -12°C, -18°C) in PG 52-28, PG 58-22, PG 67-22.	99.0 min. (Test method: T44) in PG 52-28, PG 58-22, PG 67-22.	1.00 max. (Test method: T240) in PG 52-28, PG 58-22, PG 67-22.	450 °C min. (Test method: T48) in PG 52-28, PG 58-22, PG 67-22.
Oklahoma	300 max @ -12°C, -18°C) in) in PG 64-22OK, PG 70-28OK, PG 76-28OK, PG 76-28E.	65 min @ 25 °C (Test method: D6084) in PG 70-28OK, 75 min @ 25 °C (Test method: D6084) in PG 76-28OK.	1.00 -2.50 min. (Test method: T315) in PG 64-22OK, PG 70-28OK, PG 76-28OK.	3.0 max. @ 135 °C (Test method: T316) in PG 64-22OK, PG 70-28OK, PG 76-28OK, PG 76-28E.	0.300 min.@ -12°C, -18°C) in PG 64-22OK, PG 70-28OK, PG 76-28OK, PG 76-28E.	99.0 min. (Test method: T44) in PG 64-22OK, PG 70-28OK, PG 76-28OK, PG 76-28E.	1.00 max. (Test method: T240) in PG 64-22OK, PG 70-28OK, PG 76-28OK, PG 76-28E.	260 °C min. (Test method: T48) in PG 64-22OK, PG 70-28OK, PG 76-28OK, PG 76-28E.
Texas	300 max. @ -6°C, -12°C -18°C, -24°C) in PG 58-22, PG 58-28, PG 58-34,	30 min @ 10 °C (Test method: D6084) in PG 58-34, PG 64-28, PG 70-22, PG 76-16,	1.00 min. (Test method: T315) in PG 58-22, PG 58-28, PG 58-34, PG 64-16, PG 64-22,	3.0 max. @ 135 °C (Test method: T316) in PG 58-22, PG 58-28, PG 58-34, PG 64-16, PG 64-22,	0.300 min.@ -6°C, -12°C -18°C, -24°C) in PG 58-22, PG 58-28, PG 58-34,	-	1.00 max. (Test method: TEX 541-C) in PG 58-22, PG 58-28, PG 58-34, PG 64-16, PG 64-22,	230 °C min. (Test method: T48) in PG 58-22, PG 58-28, PG 58-34, PG 64-16, PG 64-22,

	PG 64-16, PG 64-22, PG 64-28, PG 64-34, PG 70-16, PG 70-22, PG 70-28, PG 70-34, PG 76-16, PG 76-22, PG 76-28, PG 82-16, PG 82-22, PG 82-28.	50 min @ 10 °C (Test method: D6084) in PG 64-34, PG 70-28, PG 76-22, PG 82-16, 60 min @ 10 °C (Test method: D6084) in PG 70-34, PG 76-28, PG 82-22, 70 min @ 10 °C (Test method: D6084) in PG 76-34, PG 82-28.	PG 64-28, PG 64-34, PG 70-16, PG 70-22, PG 70-28, PG 70-34, PG 76-16, PG 76-22, PG 76-28, PG 82-16, PG 82-22, PG 82-28.	PG 64-28, PG 64-34, PG 70-16, PG 70-22, PG 70-28, PG 70-34, PG 76-16, PG 76-22, PG 76-28, PG 82-16, PG 82-22, PG 82-28.	PG 64-16, PG 64-22, PG 64-28, PG 64-34, PG 70-16, PG 70-22, PG 70-28, PG 70-34, PG 76-16, PG 76-22, PG 76-28, PG 82-16, PG 82-22, PG 82-28.		PG 64-28, PG 64-34, PG 70-16, PG 70-22, PG 70-28, PG 70-34, PG 76-16, PG 76-22, PG 76-28, PG 82-16, PG 82-22, PG 82-28.	PG 64-28, PG 64-34, PG 70-16, PG 70-22, PG 70-28, PG 70-34, PG 76-16, PG 76-22, PG 76-28, PG 82-16, PG 82-22, PG 82-28.
Utah	300 max. @ -18°C, -24°C) in PG 58-34, PG 64-28, PG 64-34, PG 70-28.	65 min @ 25 °C (Test method: T301) in PG 58-34, PG 64-28, 70 min @ 25 °C (Test method: T301) in PG 64-34, PG 70-28.	1.00 min. (Test method: T315) in PG 58-28, 1.30 min. (Test method: T315) in PG 58-34, PG 64-28, PG 64-34, PG 70-28.	3.0 max. @ 135 °C (Test method: T316) in PG 58-28, PG 58-34, PG 64-28, PG 64-34, PG 70-28.	0.300 min.@ -18°C, -24°C) in PG 58-28, PG 58-34, PG 64-28, PG 64-34, PG 70-28.	-	-	260 °C min. (Test method: T48) in PG 58-28, PG 58-34, PG 64-28, PG 64-34, PG 70-28.
New Mexico	300 max. @ -12°C,	-	1.00 min. (Test method:	3.0 max. @ 135 °C (Test	0.300 min.@ -18°C,	-	1.00 max. (Test method: T240)	230 °C min. (Test method:

	-18°C) in PG 58-28, PG 64-28, PG 64-22, PG 70-28, PG 70-22, PG 76-22, PG 82-22,		T315) in PG 58-28, PG 64-28, PG 64-22, PG 70-28, PG 70-22, PG 76-22, PG 82-22,	method: T316) in PG 58-28, PG 64-28, PG 64-22, PG 70-28, PG 70-22, PG 76-22, PG 82-22,	-12°C) in PG 58-28, PG 64-28, PG 64-22, PG 70-28, PG 70-22, PG 76-22, PG 82-22,		in PG 58-28, PG 64-28, PG 64-22, PG 70-28, PG 70-22, PG 76-22, PG 82-22,	T48) in PG 58-28, PG 64-28, PG 64-22, PG 70-28, PG 70-22, PG 76-22, PG 82-22,

Table 3- 6 PG Requirements for Performance-Graded Modified Asphalt Binders

State	Modification details	Resilience, percent	Elastic recovery, percent	Dynamic Shear, kPa (G*/sin δ)	Rotational Viscosity, Pa·s	Penetration depths, 0.1mm	Solubility, percent	Softening point, °C
Arizona	Minimum 8 wt.% GTR and Minimum 2 wt.% SBS Polymer Terminally Blended--- **(GTR+SBS)** PG Compliant Base Asphalt + Ground Tire Rubber (minimum 20 wt.% of asphalt binder)--- **(CRA)**	25 min @ 25 °C (Test method: D5329) in PG 64-16 20 min 25 °C (Test method: D5329) in PG 58-22 15 min 25 °C (Test method: D5329) in PG 52-28 **(CRA)**	55 min @ 10 °C (Test method: T301) in PG 70-22 TR+, PG 76-22 TR+. **(GTR+SBS)**	-	1.50-4.00 (Test method: AZ Spec.1009-2.03) in PG 64-16 **(CRA)**	10 min 4 °C (Test method: D5) in PG 64-16 15 min 4 °C (Test method: D5) in PG 58-22 25 min 4 °C (Test method: D5) in PG 52-28 **(CRA)**	97.5 min. (Test method: D2042) in PG 70-22 TR+, PG 76-22 TR+. **(GTR+SBS)**	54 °C min (Test method: T53) in PG 70-22 TR+, 60 °C min (Test method: T53) in PG 76-22 TR+. **(GTR+SBS)** 57 °C min (Test method: D36) in PG 64-16 54 °C min (Test method: D36) in PG 58-22 52 °C min (Test method: D36) in PG 52-28 **(CRA)**
California	Crumb rubber modification	300 max. (Test method:	75 min @ 25 °C (Test	1.00 min. (Test method:	3.0 max. @ 135 °C (Test	1.00 max. (Test method:	97.5 min. (Test method:	230 °C min. (Test method:

		T313) in PG 58-34M @ -24°C, PG 64-28M @ -18°C, PG 76-22M @ -12°C.	method: T301) in PG 58-34M, PG 64-28M, 65 min @ 25 °C in PG 76-22M.	T315) in PG 58-34M, PG 64-28M, PG 76-22M.	method: T316) in PG 58-34M, PG 64-28M, PG 76-22M.	T240) in PG 58-34M, PG 64-28M, PG 76-22M.	T44) in PG 58-34M, PG 64-28M, PG 76-22M.	T48) in PG 58-34M, PG 64-28M, PG 76-22M.
Colorado	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1
Florida	All PG asphalt binders having a high-temperature designation higher than PG 67 shall be produced with an SBS or SB polymer **(PMA)** or ground tire rubber meeting the requirement of Section 919 **(ARB).**	300 max @ -12°C) in PG 76-22 **(PMA),** PG 76-22, **(ARB),** PG 82-22, **(PMA).**	-	1.00 min. (Test method: T315) in PG 76-22 **(PMA),** PG 76-22, **(ARB),** PG 82-22, **(PMA).**	3.0 max. @ 135 °C (Test method: T316) in PG 76-22 **(PMA),** PG 76-22, **(ARB),** PG 82-22, **(PMA).**	1.00 max. (Test method: T240) in PG 76-22 **(PMA),** PG 76-22, **(ARB),** PG 82-22, **(PMA).**	99.0 min. (Test method: T44) in PG 76-22 **(PMA),** PG 82-22, **(PMA).**	450 °C min. (Test method: T48) in PG 76-22 **(PMA),** PG 76-22, **(ARB),** PG 82-22, **(PMA).**
Oklahoma	Type IV Polymer Modified Asphalt Binder is normally produced by modifying neat asphalt binders with polymer content (SBS-solid base) 3 wt.% min, and tire rubber 5	300 max @ -18°C) in **AC20-5TR**	55 min @ 25 °C (Test method: T301) in **AC20-5TR**	1.00 -2.50 @ 64 °C. (Test method: T315) in **AC20-5TR**	3.0 max. @ 135 °C (Test method: T316) in **AC20-5TR**	1.00 max. (Test method: T240) **AC20-5TR**	1.00 max. (Test method: T240) in **AC20-5TR**	260 °C min(Test method: T48) in **AC20-5TR**

	wt.% min. Separation of polymer, difference in $G^*/\sin \delta$ is 10 percent max (D5709).							
Texas	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1
Utah	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1	See table 3-1
New Mexico (OGFC Polymer modified asphalt binder)-(Table 402.2.6:1)	5 wt.% of Tire Rubber and 2 wt.% SBS content in PG 70-28R+	-	65 min @ 25 °C (Test method: T301) in PG 70-28R+	-	-	-	97.5 (Test method: D2042)	-
New Mexico (OGFC Asphalt rubber binder formulation design)-(Table 402.2.4:1)	Min 10 wt.% TRM and 2 wt.% SBS.	300 max. (Test method: T313)	65 min @ 10 °C (Test method: T301)	1.00 @ 70 °C. (Test method: T315) in			98 (Test method: T44)	230 °C min (Test method: T48)

3.3 PROPERTIES OF PMBS

3.3.1 Rheological Properties

The rheological properties of SBS modified asphalt were studied by Airey (*96*) from the United Kingdom. In this study, the linear SBS copolymer was mixed with asphalt from two crude oil sources with low (3 wt.%), medium (5 wt.%), and high content (7 wt.%). The results show that the rheological properties were improved by increasing the SBS content. At high temperature and low frequencies, the complex modulus and elastic response of the SBS modified polymers were both increased (*96*). This phenomenon has been validated by other studies as well (*118, 22, 119, 120*). Yilmaz's study from Turkey claims that the desired performance PG 70-34 level can be obtained with 3.8 wt.% SBS addition to PG 58-34 pure asphalt (*121*).

The rheological properties of asphalt modified by EVA were studied in Saudi Arabia (*122*). Hussein found that the rheological properties of base asphalt could be improved by polymer modifications. EVA modification decreases the flow activation energy. Temperature resistance to high-temperature deformations was achieved with low vinyl acetate content in EVA. A Spanish study by Gonzalez (*64*) investigated the asphalt modified with pure and recycled EVA. Based on the rheological property measurements, the risk of low-temperature cracking and high-temperature rutting were both reduced with the modification. It was also found that the content of EVA should not be too high and that an addition of 1 wt.% performed better than 3 wt.% (*64*).

Other investigations on the rheological properties of rubber modified asphalt were studied in Spain by Navarro *et.al.* (*123, 101*). These studies confirmed that the content of the added rubber is a main factor that influences the rheology and storage stability of the modified binders. The results of the linear viscoelastic measurements demonstrated an improvement of both low and high service properties. The viscosity was increased and the temperature susceptibility was reduced after modification. Furthermore, it was found that the high-temperature stability increased with increased rubber contents.

3.3.2 Creep Stiffness

The Bending Beam Rheometer (BBR) is used to accurately evaluate binder properties at low temperatures when asphalt binders are too stiff to reliably measure rheological properties. The rate of change of binder stiffness with time is represented by the *m*-value, which is the slope of the log stiffness versus log time curve from the BBR test results (*117*).

In a Swedish study, Lu (*124*) compared the creep stiffness of EVA, EBA, SBS, and SEBS on the performance of asphalt binders with low (3 wt.%), medium (6 wt.%), and high content (9 wt.%). Creep stiffness and creep rate were tested at several loading times ranging from 8 to 240 seconds. Table 3-7 shows the creep stiffness and the *m*-value of the binders with a loading time of 60s at different temperatures (*124*).

Table 3- 7 Creep stiffness and *m*-value of the binders with loading time of 60s at various temperatures (*124*)

Binder	Creep stiffness, MPa, @ -15°C	Creep stiffness, MPa, @ -25°C	Creep stiffness, MPa, @ -35°C	m-value, @ -15°C	m-value, @ -25°C	m-value, @ -35°C
Type A Asphalt	185	789	1590	0.45	0.26	0.09
A+6 wt.% SBS	123	482	884	0.40	0.23	0.12
A+6 wt.% SEBS	195	684	1140	0.38	0.20	0.11
A+6 wt.% EVA	180	790	2000	0.42	0.25	0.12
A+6 wt.% EBA	161	656	1620	0.41	0.26	0.13
Type B Asphalt	54	487	1560	0.61	0.35	0.15
B+6 wt.% SBS	55	371	921	0.52	0.30	0.15
B+6 wt.% SEBS	80	329	774	0.41	0.28	0.19
B+6 wt.% EVA	48	366	1240	0.54	0.38	0.18
B+6 wt.% EBA	38	298	1160	0.52	0.38	0.19
Type C Asphalt	99	437	931	0.49	0.32	0.19
C+6 wt.% SBS	95	295	491	0.42	0.27	0.18
C+6 wt.% SEBS	97	333	765	0.42	0.28	0.18
C+6 wt.% EVA	94	411	1040	0.44	0.32	0.19
C+6 wt.% EBA	60	167	875	0.35	0.16	0.20

3.3.3 Viscosity

Figure 3-7 shows the relationship between the SBS content and the viscosity of the modified asphalt. As shown, the viscosity of the two types of asphalt both increased with increasing SBS content (*28*).

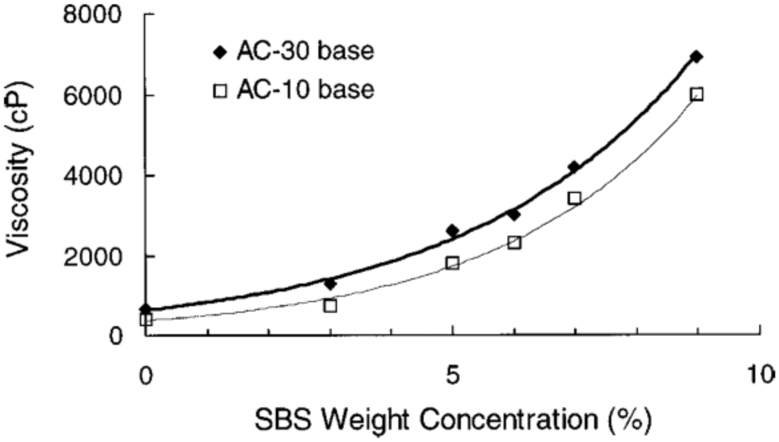


Figure 3- 7 Viscosity of SBS modified asphalt as a function of SBS content (*28*)

Figure 3-8 shows the zero-shear-limiting viscosity as a function of the EVA content at 25°C. The values of the zero-shear-limiting viscosity increase by increasing EVA content from 0 wt.% to 9 wt.%. In addition, the low penetration grade asphalt leads to a higher zero-shear-limiting viscosity value (*125*).

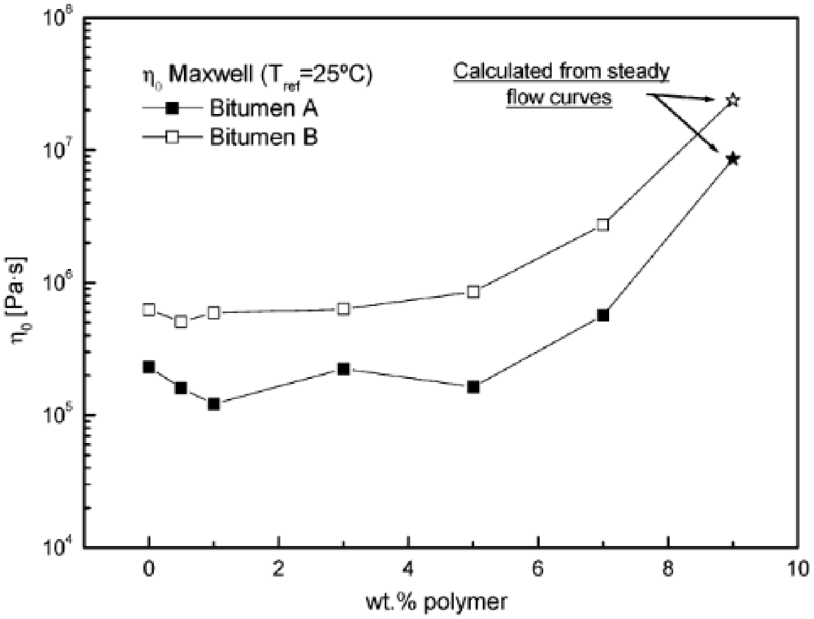


Figure 3- 8 Zero-shear-limiting viscosity as a function of the EVA content (*125*)

Figure 3-9 shows the dynamic viscosity as a function of the of base and modified asphalt binder with 1 wt.% RPE content at 30°C. The viscosity shows higher values of the modified asphalt than base asphalt (*99*).

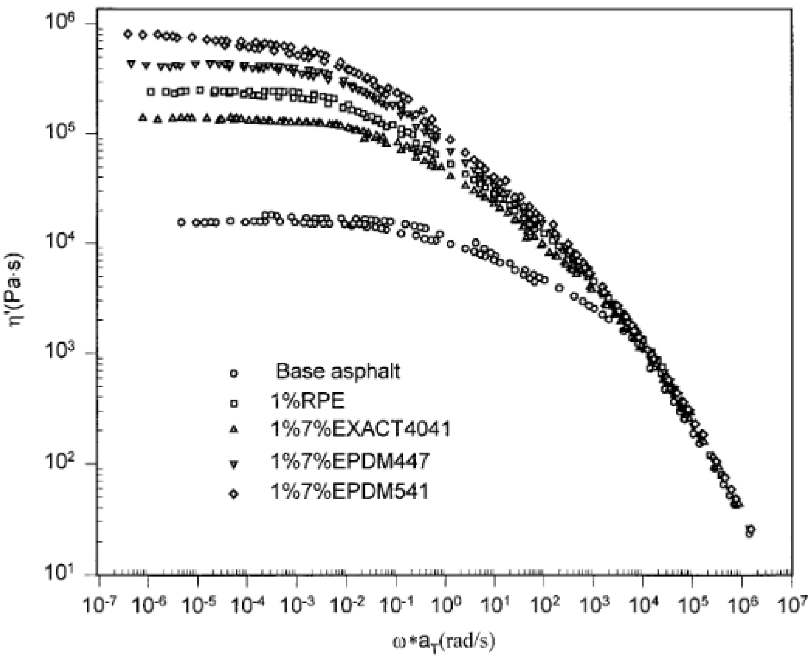


Figure 3- 9 Dynamic viscosity of base and modified asphalt (*99*)

3.3.4 Elastic Recovery

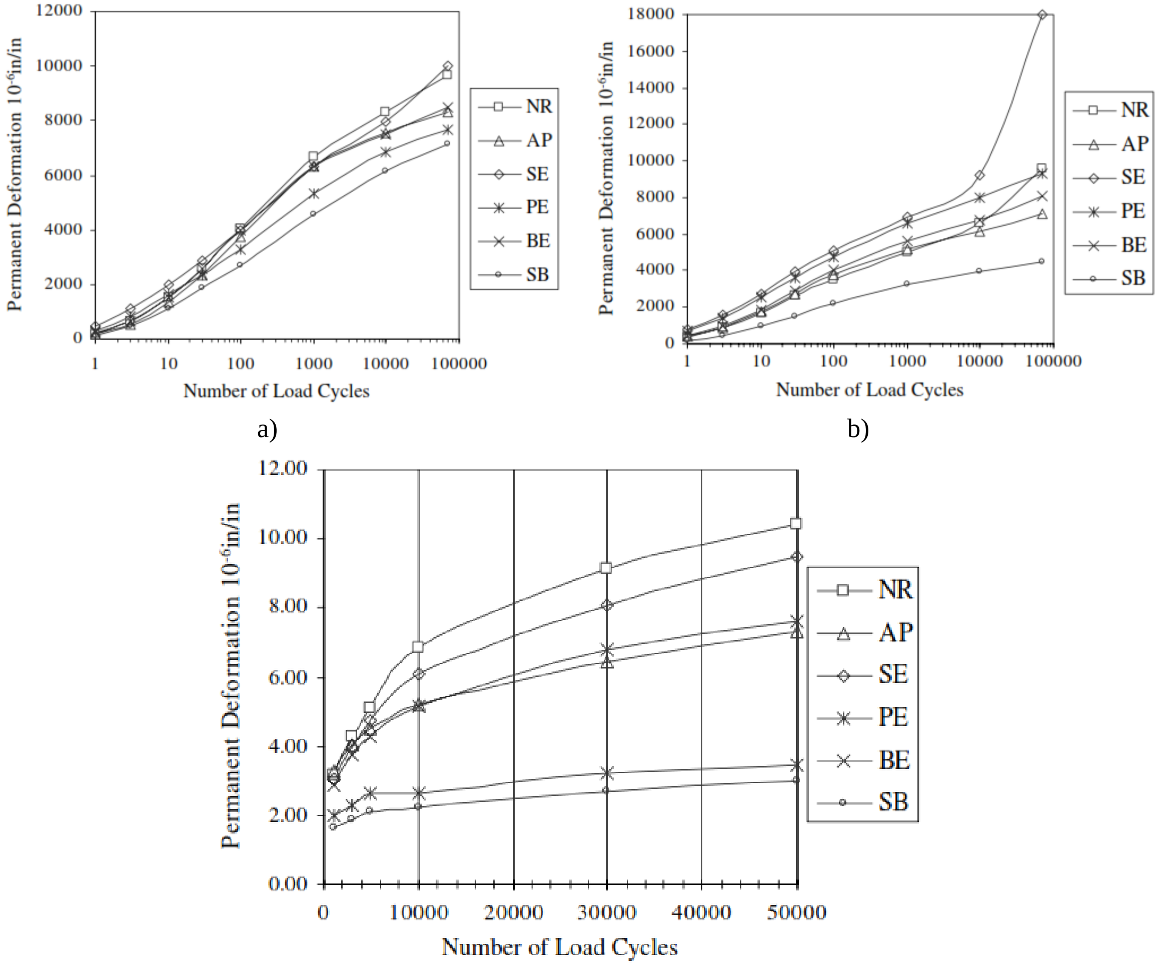
In general, the elastomer addition will increase the elasticity of the binders (*118, 26*). Airey (*96*) studied the elastic recovery of the SBS modified asphalt. Low (3 wt.%), medium (5 wt.%), and high content (7 wt.%) were mixed in two types of asphalts and prepared for the elastic recovery testing. Table 3-8 shows the results of the elastic recovery at 10°C of these six types of modified asphalt binders.

Table 3- 8 Elastic recovery the SBS modified binders at 10°C (*127*)

Binder	Elastic recovery, percent
Type A Asphalt	-
Type A Asphalt +3 wt.% SBS	68
Type A Asphalt +5 wt.% SBS	76
Type A Asphalt +7 wt.% SBS	81
Type B Asphalt	-
Type B Asphalt +3 wt.% SBS	71
Type B Asphalt +5 wt.% SBS	78
Type B Asphalt +7 wt.% SBS	80

3.3.5 Rutting Resistance

The rutting resistance of the polymer modified asphalt was investigated in Turkey. Six types of asphalt binders (neat asphalt binder, amorphous polyalphaolefin, cellulose fiber, polyolefin, bituminous cellulose fiber, and SBS modified asphalt binders) were investigated through indirect tensile strength, indirect tensile, static and repeated creep, and Laboratoire Central des Ponts et Chaussées (LCPC) wheel tracking tests to evaluate the performances of the modified asphalt binders. As the testing results demonstrated, the samples with the addition of 5 wt.% of asphalt binder had the greatest rutting resistance relative to the other five types of binders. Figure 3-10 shows the permanent deformation as a function of number of load cycles and Figure 3-11 represents the resilient modulus of various modified asphalt binders at different temperatures (*128*). Other studies have also shown that the rutting resistance of the elastomer modified asphalt is higher than neat asphalt binders (*129*, *126*).



a) b)

c)

Figure 3- 10 Permanent deformation as a function of number of load cycles at a) 25°C, and b) 40°C, and c) with LCPC wheel tracking tests (*128*)

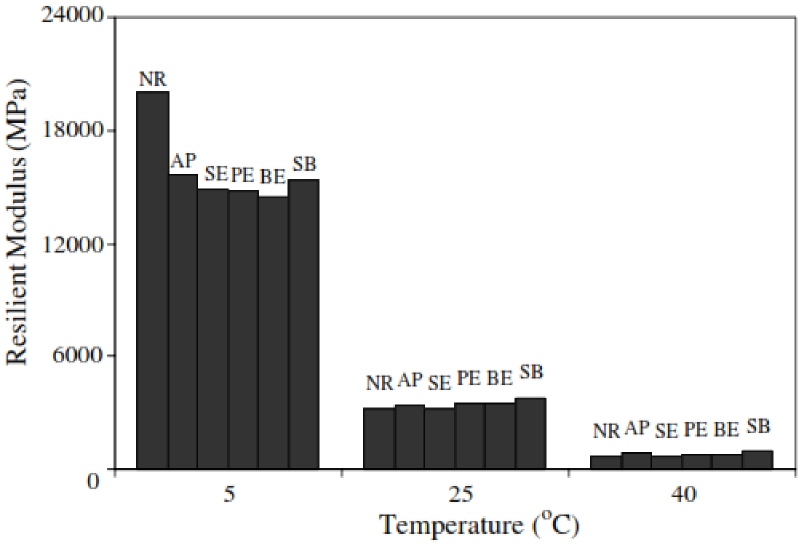


Figure 3- 11 Average resilient modulus of various asphalt at 5°C, 25°C, and 40°C (*128*)

3.3.6 Cracking Resistance

The cracking resistance of polymer modified asphalt binders has been studied extensively (*44*). Both elastomers and plastomers can increase the cracking resistance of asphalt binders (*20, 130*). However, in light of the complexity of the cracking categories, such as thermal cracking, fatigue crack, and reflective cracking, it is still in question as to which polymer has a better modification effect on the cracking resistance.

Kim (*131*) studied the cracking resistance of SBS (3 wt.%) modified asphalt concrete with a binder content of 6.1 wt.% and 7.2 wt.%. The SBS addition increased the cracking resistance, and the normalized resilient deformation was used to reflect the damage development of the mixture (*132*). If the rate of change is linear, the mixture is undergoing a microdamage process. The crack initiation occurs when the rate of change becomes non-linear. Figure 3-12 shows the normalized resilient deformation versus the number of load replications according to fracture test results. As shown in the figure, the SBS addition reduced the microdamage development rate, resulting in an increase of the number of loading repetitions for the occurrence of the initial cracks (*131*).

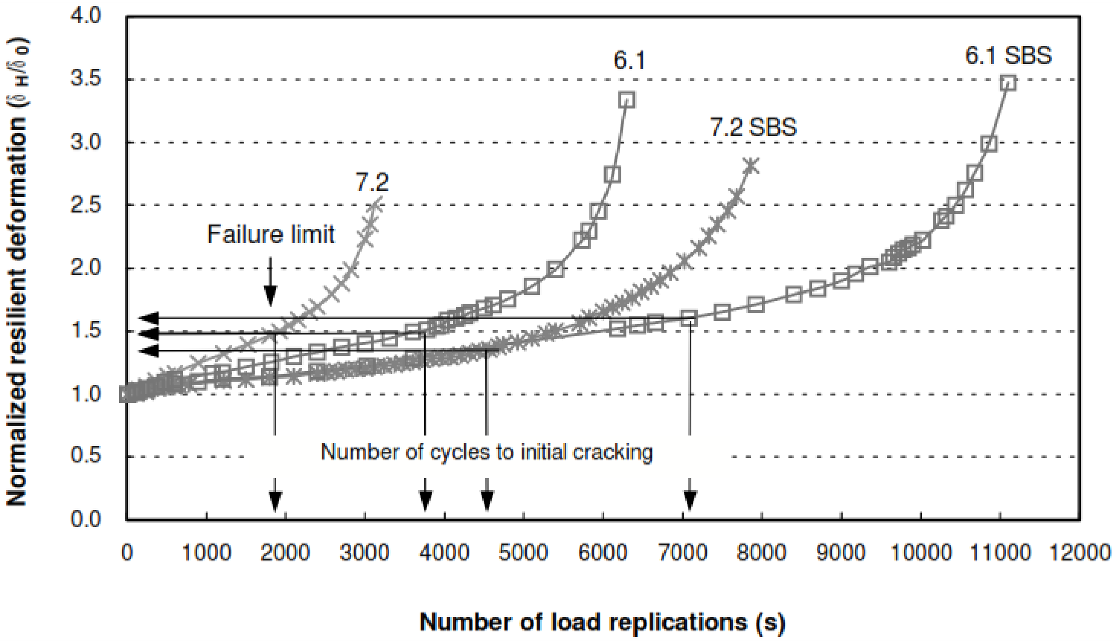
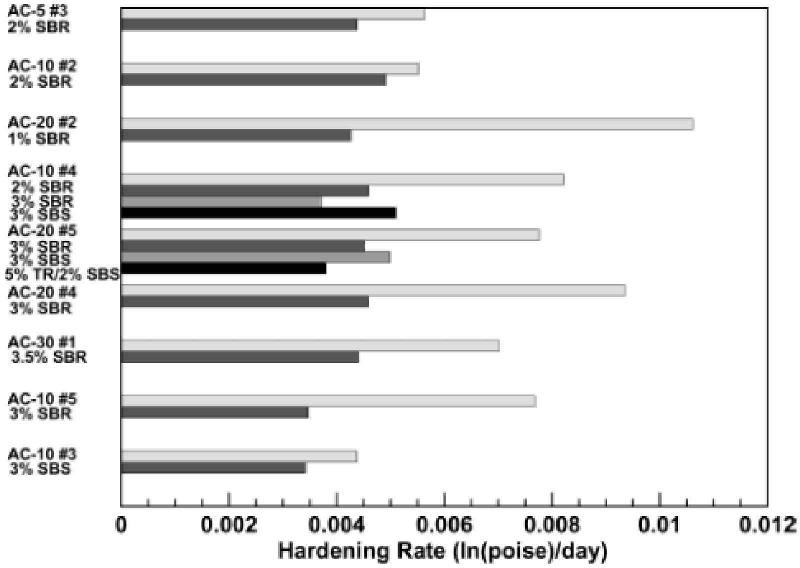


Figure 3- 12 Normalized resilient deformation versus number of load replications according to fracture test results (*131*)

3.3.7 Aging Resistance

Ruan (*99*) tested the aging resistance of asphalt binders modified by SBS, SBR, and rubbers. It was found that the polymer-modified binders have lower aging indices than their corresponding base asphalts. Figure 3-13 shows the hardening rate, oxidation rate, and hardening susceptibility of various modified binders. The figure shows that polymer modified binders have lower hardening rates than neat asphalts. The oxidation rate of the modified binders is lower than the base asphalt (*99*).



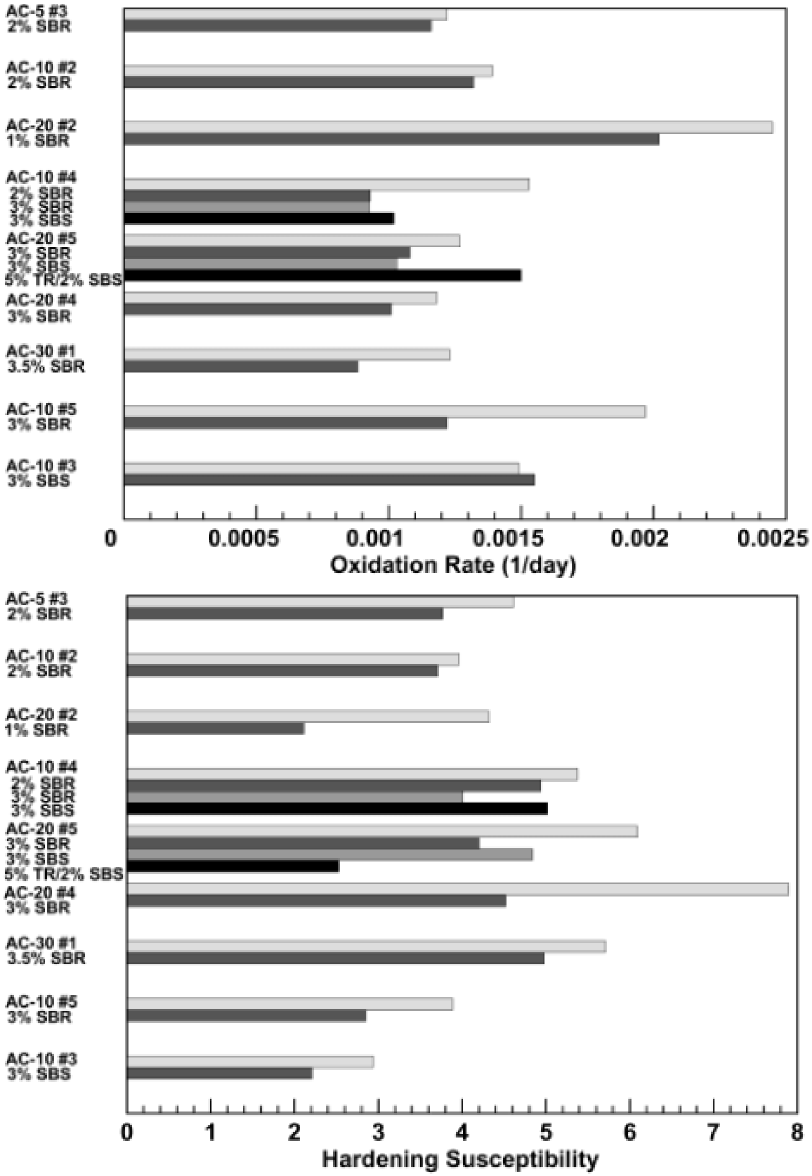
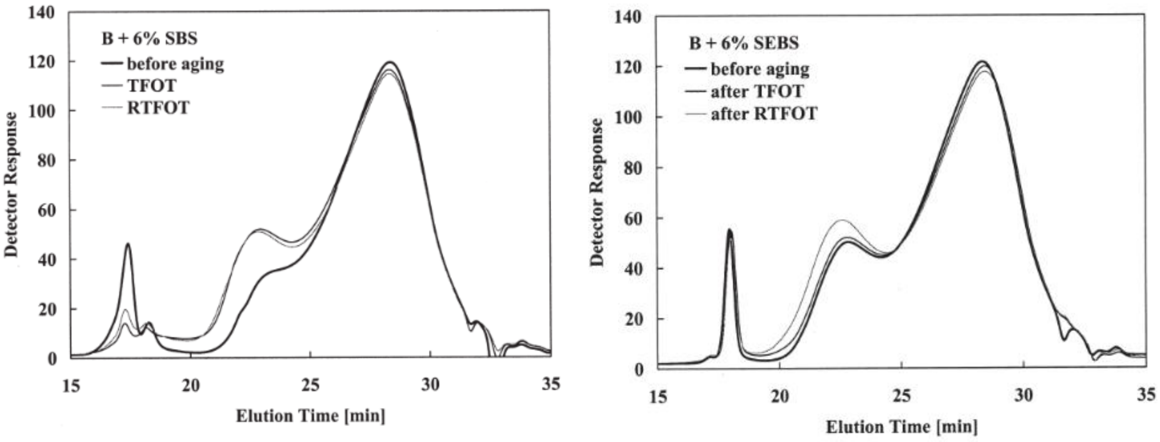


Figure 3- 13 Hardening rate, oxidation rate, and hardening susceptibility of various modified binders (*99*)

Another report from Sweden compared the modification effects of EVA, EBA, SBS, and SEBS on the performance of asphalt binders with low (3 wt.%), medium (6 wt.%), and high content (9 wt.%). Figure 3-14 shows the gel permeation chromatography (GPC) characteristics of SBS and SEBS modified binders with 6 wt.% weight of asphalt after aging. As shown in the figure, the elution peaks between 20-32 minutes show a molecular weight distribution of the asphalt, and the modified asphalt shows different elution peaks. The SEBS modified sample shows its peak at 18 min, while the SBS modified sample shows its peak at 15 and 20 minutes. The decrease in SBS peaks represents the degradation of SBS during the aging process. It was also found that the effect of aging is determined by the testing conditions (*133*).



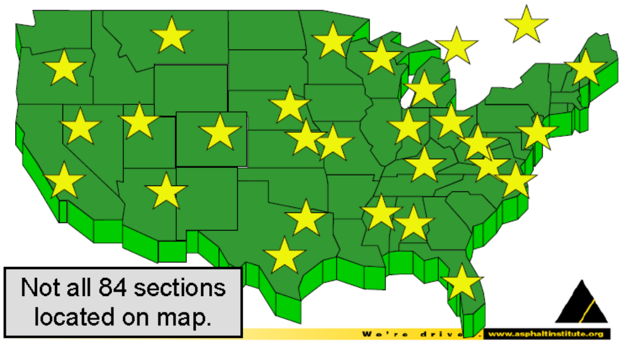
a) b)

Figure 3- 14 Effect of aging on the GPC characteristics of a) SBS and b) SEBS modified binders with 6 wt.% weight of asphalt (*133*)

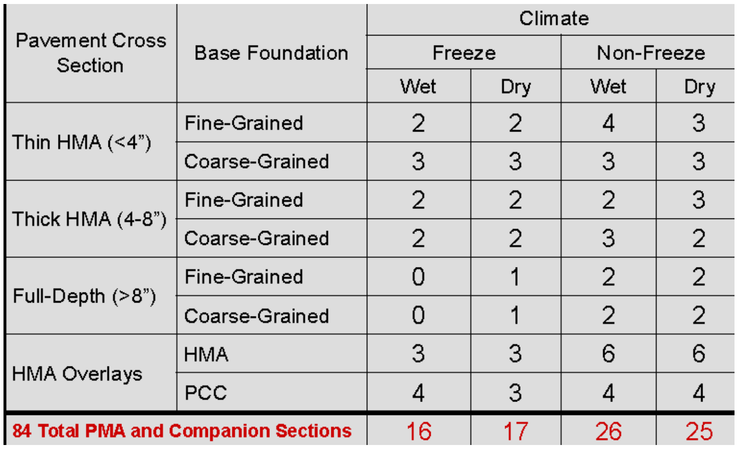
Chipps (*101*) reported that the aging resistance of the rubber modified asphalt relies heavily on curing conditions, rubber content and chemical compositions of the original binders. In this study, it was found that little rubber could be resolved in the binder with low curing temperature and shear rate, which resulted in a swollen phenomenon, and decreased the aging resistance of the modified binders. This issue was resolved by increasing the curing temperature and shear rate as the long polymer chains and cross link structure are partially degraded (*101*).

3.3.8 Long-Term Pavement Performance

A systematic study was completed by the Asphalt Institute in 2005 which analyzed field performance data of asphalt pavement test sections from 84 sites representing various pavement designs and climatic conditions across North America and provided rich data contrasting neat asphalt and polymer modified asphalt pavements. Many Long Term Pavement Performance (LTPP) sites were included in these 84 sites. As shown in Figure 3-15 (*134*), the study revealed that the polymer modified asphalt pavements featured significantly less distresses, in terms of less rutting depth and less percentages of thermal (transverse) cracking or fatigue (alligator) cracking. Many of the sites demonstrate the benefits of using plus grade PG asphalt binders. More details can be found in the Asphalt Institute ER-215 entitled “Quantification of the Effects of Polymer Modified Asphalt for Reducing Pavement Distress.”

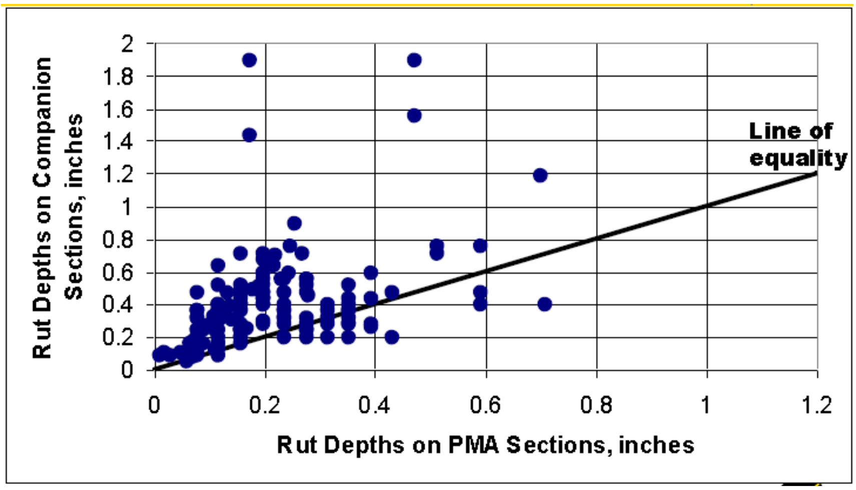

Not all 84 sections located on map.

(a)



Pavement Cross Section	Base Foundation	Climate			
		Freeze		Non-Freeze	
		Wet	Dry	Wet	Dry
Thin HMA (<4”)	Fine-Grained	2	2	4	3
	Coarse-Grained	3	3	3	3
Thick HMA (4-8”)	Fine-Grained	2	2	2	3
	Coarse-Grained	2	2	3	2
Full-Depth (>8”)	Fine-Grained	0	1	2	2
	Coarse-Grained	0	1	2	2
HMA Overlays	HMA	3	3	6	6
	PCC	4	3	4	4
84 Total PMA and Companion Sections		16	17	26	25

(b)



(c)

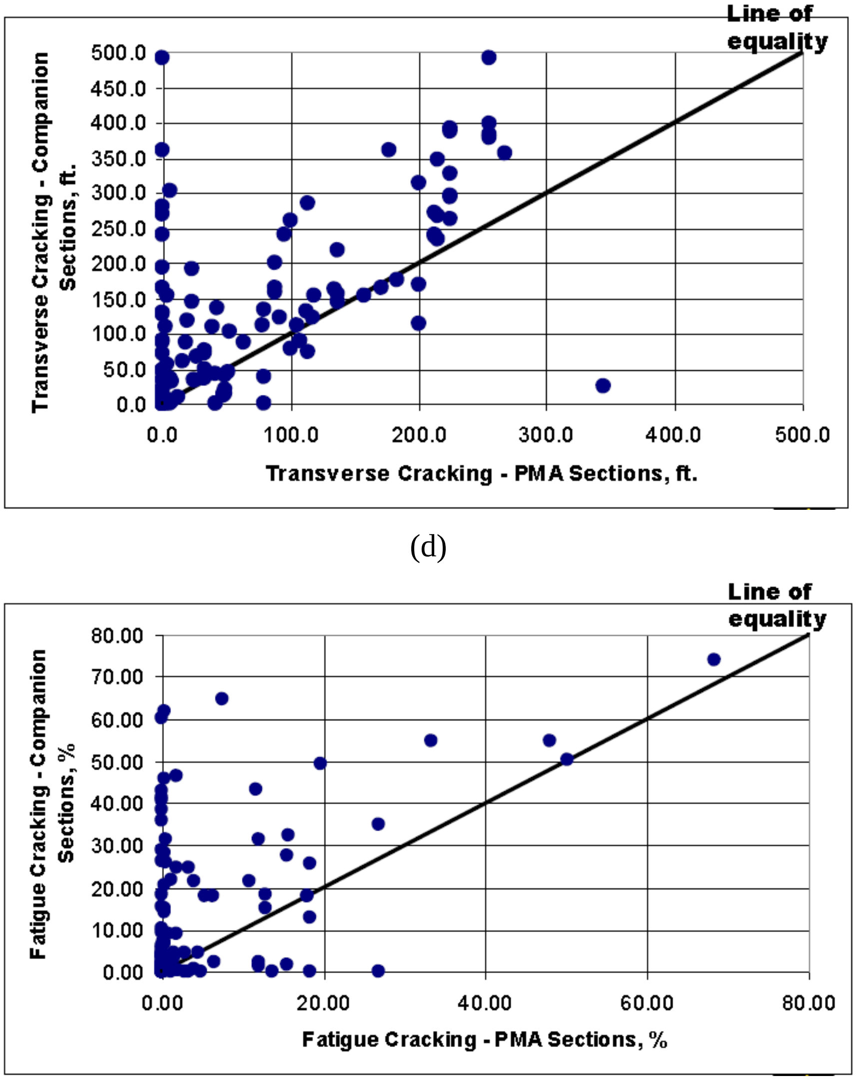


Figure 3- 15 ER-215 Study: (a) geographic distribution of test sites; (b) grouping of test sections; (c) comparison of rutting depths; (d) comparison of thermal (transverse) cracking; (e) comparison of fatigue (alligator) cracking (*134*)

Long-term pavement performance is complicated by many uncontrollable or un-documented factors in the field, and it is difficult to correlate laboratory testing results with field performance results. Thus, it is still too early to draw definitive conclusions regarding the magnitude of long-term field performance increase of polymer modified binders.

Although elastomeric polymers are in use by 48 of the continental United States, it is hard to accurately quantify their benefits. This is mainly due to the significant disagreement between laboratory and field results. The laboratory testing has consistently demonstrated considerable benefits of such polymer modification (e.g., predicted more than 10 years of service life increase), yet the field testing (mostly occurred in the last decade) generally showed less benefits. This is likely due to the fact that field test sections were constructed with much less quality assurance in terms of raw materials, mixing, pavement, compaction, and so on. As such, the benefits from the binder phase could be negated by weaknesses in other aspects of the asphalt pavement. The benefits of polymer modification also vary as a function of the asphalt pavement's service environment.

For NMDOT to investigate this issue, it would be crucial to ensure that laboratory tests better simulate the field construction scenarios as well as the service environments in the State of New Mexico. As such, the laboratory tests would more realistically predict the performance of asphalt pavements in the State of New Mexico, for both those with neat binders and those with PMBs. In addition, laboratory tests can be conducted in an accelerated manner, if coupled with appropriate modeling of the asphalt pavement.

In the 1990s, a survey on modified asphalt pavements was carried out to evaluate performance during the construction and in-service period. Over 30 end-to-end test pavements, representing 14 states, Austria, and Canada, were evaluated. The modifiers include PE, EVA, SBR, and SBS. However, the testing pavements were all less than five years old, thus the differences in performance is not obvious (*135*). Additional studies also found it difficult to obtain a solid long-term pavement performance conclusion (*136*).

Modified pavement did not show increased resistance to rutting; however, the cracking resistance was dramatically improved. Since 1988, a long-term pavement performance evaluation was investigated in Switzerland. In this investigation, 16 test sections measuring over 300 meters were constructed with an identical structure design. Twelve modified binders and four neat binders were used for comparisons. The 14-year results showed that the polymer modification led to some performance improvements for the wearing course asphalt pavement. One SBS modified section (with plus grade PG asphalt binder) exhibited outstanding resistance to cracking (*130*). More recently, Dreessen et al. (*137*) reported that 19-year results, the highlights of which are provided as follows:

1) The PMBs (especially the cross-linked PMB, a type of plus grade PG asphalt binder) were less affected by the field aging, relative to the neat asphalt binder.
2) The modified asphalt pavement sections have exhibited better weathering stability, i.e., relatively low decrease in mechanical properties, relative to the neat asphalt pavement section.
3) For the PMBs, the BBR laboratory test (*m*-value) provided good indication of the asphalt pavements resistance to thermal cracking and aging in the field.

3.3.9 Storage Stability

The storage stability of the polymer modified asphalt binders is largely determined by their compatibilities (*10*). Some studies believe that asphaltenes are strongly polar components in asphalt and thus the compatibility between the asphaltene and the polar polymer modifiers will be significantly affected and the final storage stability of the binders will be influenced accordingly (*138*, *139*). Recently, a new explanation of the asphaltene structure has been reported (*140*), and the storage stability of the modified asphalt binders has been further studied.

Some studies provided methods to mitigate the storage stability problems of low compatibility binders (*24, 26*), including sulfur vulcanization, adding hydrophobic clay minerals, functionalization, and adding reactive agents (*110, 141, 142, 143*).

3.3.10 Moisture Damage

The moisture damage of the asphalt pavement can be reduced by using the polymer modified asphalt binders (*144, 131, 145, 146*). Some studies also demonstrated that the modification effect of SBS is better than that of EVA (*147*). However, there is very limited information in the published domain on this subject.

3.4 KEY FINDINGS

- In Arizona, crumb rubber is commonly used in asphalt pavement. For the PG 76-22 TR+ binder, a minimum 2 wt.% of SBS and 8 wt.% of crumb rubber are required. The benefits include: a) Reduced reflective cracking via improved elastic properties (**elastic recovery of at least 55 percent** at 10°C); b) Increased aging resistance; c) Increased durability; d) Reduced noise; e) Improved cost-effectiveness.
- In Florida, according to the Accelerated Pavement Testing (APT) method, the rutting and fatigue cracking performance of HMA mixtures (with neat PG67-22) were improved by the SBS modification. After 100,000 Heavy Vehicle Simulator (HVS) passes, the **rutting** of the lane constructed with PG 76-22 and PG 82-22 binders **decreased 50 percent and 80 percent** compared with the lane without SBS modification. At 20°C, the **fatigue resistance** of the PG 82-22 (plus-grade, with SBS at 6 wt.%) and PG 76-22 (plus-grade, with SBS at 3 wt.%) binders was **20 times higher** than the PG 67-22 binder. The fatigue life of the PG 82-22 binder was about 7 times higher than the PG 76-22 binder.
- In Texas, plus grade PG asphalt binders (e.g., SBS co-block polymer-modified PG 76-22, PG 70-22, PG 58-34, and PG 58-40) exhibited outstanding benefits, relative to neat asphalt binders. Most of the elastomer modified binders have **as much as a 40 percent less hardening rate** than the neat binders. If the air voids in the Texas asphalt pavements are kept stable (lower than 2 wt.%), these reduced hardening rates can translate to 15 to 20 years of service life extension for asphalt pavement.
- In Oklahoma, three asphalt binders (PG 64-22, PG 70-28, PG 76-28 with an elastomer modifier (SBS) and two anti-stripping additives (Adhere HP-Plus and

Perma Tac Plus) were used to evaluate the modification effects. After the change of grade, the PG 76-28 can reach the level of PG 82-28.

- In Colorado field studies, though the rutting resistance of pavement constructed by polymer modified asphalt binders (EVA, SBR, or styrene block copolymer) was not remarkably increased, the cracking resistance was considerably enhanced in the sections constructed with modified asphalt binders. Compared with the control sections, the cracks in the modified sections decreased by 50 percent for longitudinal and transverse cracking.
- In Mississippi, the addition of polymer was found beneficial to the pavement performance at both high and low temperatures. The field evaluation further confirmed the improved rutting performance of the modified binder sections, relative to the neat asphalt section.
- Based on the evaluation of the states' specifications, the property requirements for polymer modified asphalt are higher than neat asphalt binders. The vast majority of states focused on elastomers (SBS, SB, SBR) or crumb rubber as polymer modifier (i.e., for plus grade PG asphalt binder) and have performance based binder specifications as their specification calls out either MSCR or elastic recovery. Different states have different requirements on the elastic recovery, flash point, solubility, and dynamic shear, but the requirements for rotational viscosity, creep stiffness and *m*-value, and mass change are similar. The current requirements for polymer modified asphalt in New Mexico are very limited.
- A systematic study was completed by the Asphalt Institute in 2005 which analyzed field performance data of asphalt pavement test sections from 84 sites representing various pavement designs and climatic conditions across North America and provided rich data contrasting neat asphalt and polymer modified asphalt pavements. Many Long Term Pavement Performance (LTPP) sites were included in these 84 sites. The study revealed that the polymer modified asphalt pavements featured significantly less distresses, in terms of less rutting depth and less percentages of thermal (transverse) cracking or fatigue (alligator) cracking. Many of the sites demonstrate the benefits of using plus grade PG asphalt binders.
- Long-term pavement performance is complicated by many uncontrollable or un-documented factors in the field and it is difficult to correlate the laboratory testing results with the field performance results.

CHAPTER 4 COST ANALYSIS

4.1 COST ANALYSIS

The cost analysis of PMBs has been reported by NCHRP, Asphalt Institute, and others (*148, 149, 150, 151, 134*). Such analysis is much needed in light of the increasing implementation of PMBs. It has been estimated that as much as 15 percent annual tonnage of asphalt binders applied contains various modifiers and that this percentage will increase in the next decade.

Currently industry professionals predict about $40 to $45 per ton for either a “grade bump” or changing to a plus binder, which is an acceptable cost for a more sustainable pavement binder (Stephen Hemphill, NMDOT, April 2014 – unpublished data accompanied by actual Change Order quotes from contractors). The information in the published domain thus far suggests that polymer modification of the asphalt binder can lead to improvements in the performance of the asphalt pavement, especially resistance to rutting, fatigue (alligator) cracking, and thermal (transverse) cracking in high-stress and climate-sensitive areas. These improvements, in turn, translate to a longer service life and reduced costs in pavement maintenance, rehabilitation, and reconstruction from a life cycle perspective.

Note that the binder cost increases by polymer modification have evolved over time. For instance, the cost of asphalt binder and HMA was about $175 per ton and $30 per ton, respectively, back in early 2000s. Currently, the cost of asphalt binder and HMA is about $700 per ton and $70 per ton, respectively. With SBS at about $1,500 per ton and added at 4 wt.% of asphalt, its modification currently only induces approximately $32 per ton in the cost of the binder, or at 5% binder $1.60 per ton in the cost of the HMA. Current real-world quotes suggest less than a 5% cost increase from a PG binder to a PG+ binder, which translates to an even small percent direct construction cost increase of the in-place HMA.

It is inherently difficult to accurately account for all the direct and indirect costs and benefits of using polymer modified asphalt binders (*150*). A study at the Missouri DOT reported that a mere 0.4-0.8 years increase in service life would justify the cost of the polymer modification. This report found that service life was increased by 3.1 years with polymer modification based on studies from Colorado, Alabama, and Texas. In addition, the Colorado DOT reported that cost savings of $7,804 per lane mile could be reached. Based on this data, the Missouri DOT could save approximately $24 million by using polymer modified asphalt binder (Keith, MoDOT – unpublished data). Based on the results from Texas, SBS and SBR modified binders have 40 percent lower DSR function hardening rate than the neat asphalt binder. This suggests that the SBS or SBR modification increases the service life of asphalt pavement by 2.5 years (Figure 4-1). An Alabama study found the SBS/SBR modified pavement has 4 years additional service life than neat asphalt pavement (Figure 4-2).

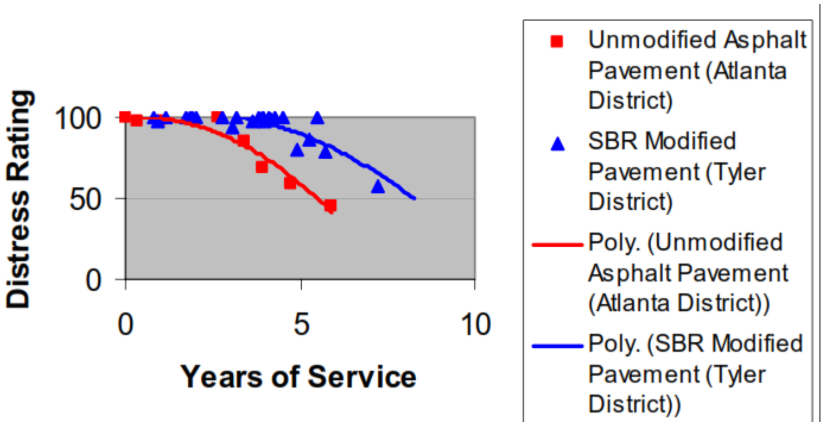


Figure 4- 1 Distress rating as a function of service years for neat asphalt vs. SBR modified asphalt mixtures in Texas

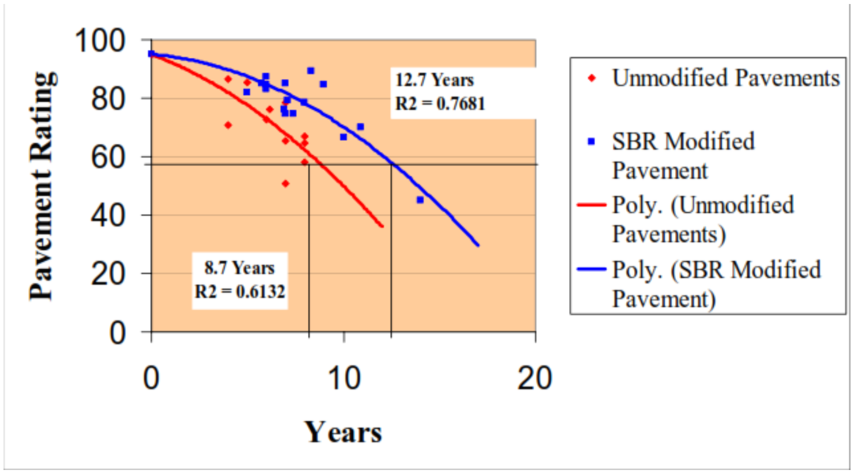
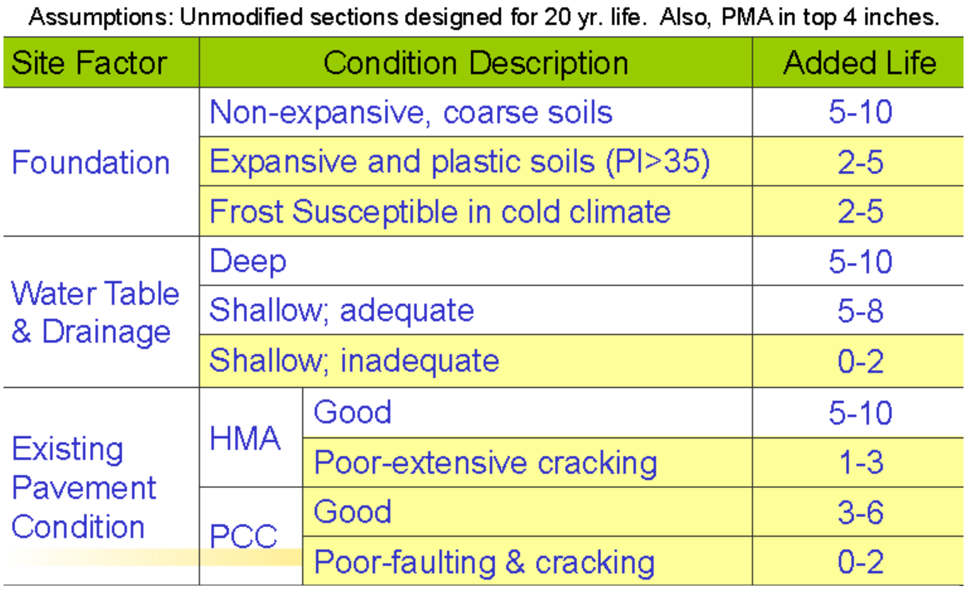


Figure 4- 2 Pavement rating as a function of service years for neat asphalt vs. SBR modified asphalt mixtures in Alabama

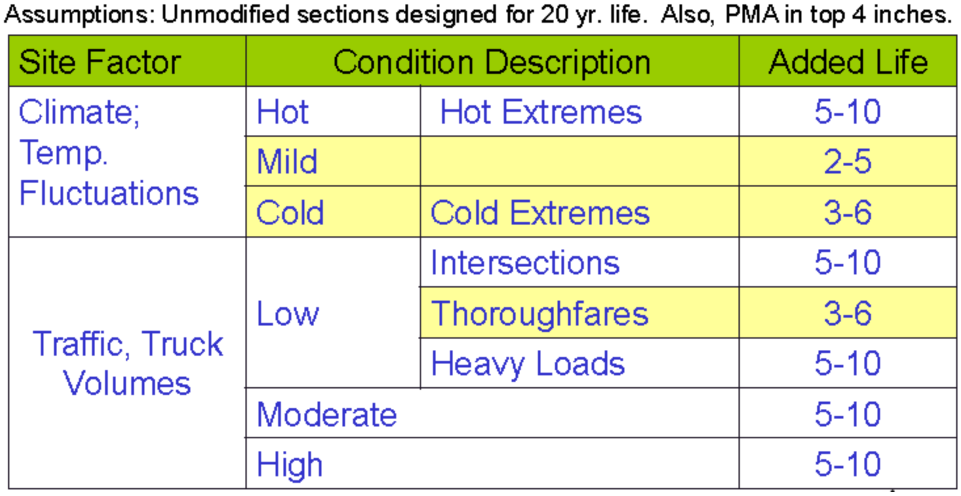
The Asphalt Institute ER-215 study employed mechanistic-empirical (M-E) distress prediction models to translate the fatigue cracking and rutting benefits of polymer modification to extended service life (*134*). The study found that polymer modification to asphalt binder would lead to a service life increase of 2 to 10 years, "depending on soil, traffic, climate, drainage and existing pavement conditions" 151). The summary of expected service life increase based on the M-E analysis is shown in Table 4-1. Note that such predictions were made possible by comparing damage index to actual field distress measurements. More details can be found in the Asphalt Institute ER-215 entitled "Quantification of the Effects of Polymer Modified Asphalt for Reducing Pavement Distress". Figure 4-3 shows the expected damage index as a function of service years for neat asphalt versus PMB mixtures (151).

Table 4 - 1 Summary of expected service life increase due to polymer modification



Assumptions: Unmodified sections designed for 20 yr. life. Also, PMA in top 4 inches.

Site Factor	Condition Description		Added Life
Foundation	Non-expansive, coarse soils		5-10
	Expansive and plastic soils (PI>35)		2-5
	Frost Susceptible in cold climate		2-5
Water Table & Drainage	Deep		5-10
	Shallow; adequate		5-8
	Shallow; inadequate		0-2
Existing Pavement Condition	HMA	Good	5-10
		Poor-extensive cracking	1-3
	PCC	Good	3-6
		Poor-faulting & cracking	0-2



Assumptions: Unmodified sections designed for 20 yr. life. Also, PMA in top 4 inches.

Site Factor	Condition Description		Added Life
Climate; Temp. Fluctuations	Hot	Hot Extremes	5-10
	Mild		2-5
	Cold	Cold Extremes	3-6
Traffic, Truck Volumes	Low	Intersections	5-10
		Thoroughfares	3-6
		Heavy Loads	5-10
	Moderate		5-10
	High		5-10

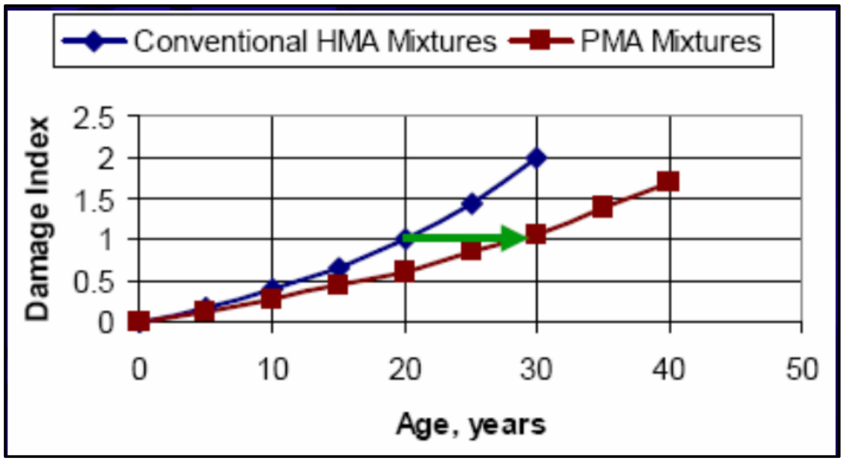


Figure 4- 3 Damage index as a function of service years for neat asphalt vs. PMB mixtures (*151*)

More recently, the Asphalt Institute ER-235 study presents calibration factors for rutting, thermal cracking, and fatigue cracking specific to polymer modified asphalt pavements. These calibration factors take into account the improved performance of PMBs and guide the selection of pavement thickness using the new AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG) (*151*). More details can be found in the Asphalt Institute ER-235 entitled “Calibration Factors for Polymer-Modified Asphalts Using M-E Based Design Methods”.

4.2 KEY FINDINGS

- It is estimated that as much as 15 percent annual tonnage of asphalt binders were applied with various modifiers and that this number will continue to increase in the next decades. Currently industry professionals predict about $40 to $45 per ton for either a “grade bump” or changing to a plus binder, which is an acceptable cost (less than 5% cost increase) for a more sustainable pavement binder.
- Even a slight 0.4-0.8 year increase in service life would justify the cost of the polymer modification. The polymer modification increased the service life of asphalt pavement in Colorado, Texas, and Alabama by 3.1 years, 2.5 years, and 4 years, respectively. The Asphalt Institute ER-215 study across North America predicted a service life increase of 2 to 10 years, depending on the specific pavement site conditions.
- To ensure cost-effective polymer modification for PMBs, it is important to adopt reasonable design of asphalt pavement and implement good quality control of the modification process.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

As indicated at the beginning of this report, studies have shown that the use of polymer modified binders (PMBs) is an important approach to enhancing the long-term performance of HMA or WMA. However, field and laboratory testing of pavement performance has produced conflicting information, and the cost-effectiveness magnitude of PMBs remains in question.

This synthesis has presented information on the evaluation of polymer modified asphalt binders from both field and laboratory testing results. Advantages and disadvantages of various types of polymers used for binder modification have been summarized. The influential factors for the properties and performance of polymer modified asphalt (e.g., asphalt and polymer characteristics, polymer-asphalt compatibility, and polymer content) have been systematically discussed. Case studies from several states have been summarized, along with the relevant asphalt binder specifications from select DOTs (e.g., Arizona, Colorado, Florida, and Oklahoma). Finally, the current information for cost analysis of PMBs has been discussed.

The key conclusions are as follows:

- All plastomers, elastomers, and rubbers provide advantages and disadvantages for their use as asphalt binder modifier, as listed in the following table:

Table 5-1 Pros and cons of using elastomer, plastomer, or rubber for asphalt modification

	Plastomers	Elastomers	Rubbers
Pros	Increased high-temperature properties, aging resistance, and storage stability; good compatibility with asphalt matrix with minimal viscosity change; thermally stable	Increased viscosity, stiffness, and elastic response of binders, particularly at high service temperatures; improved cracking resistance at low service temperatures	Better rutting resistance and higher ductility
Cons	Contribution to elasticity enhancement therefore cracking resistance is very limited	Aging resistance not as strong as asphalt pavement modified by plastomers unless periodic fog sealed.	Sensitive to decomposition and oxygen absorption; low compatibility with asphalt matrix

- Recent years have seen the introduction of PG Plus Binders, the success of which hinges on the use of elastomer and/or rubber for binder modification. The performance of asphalt pavement modified by *elastomers* depends on the asphalt source, the asphalt-polymer compatibility, and the polymer content. Appropriate polymer content and asphalt-polymer compatibility will lead to the formation of a continuous highly elastic polymer network in the asphalt matrix, which improves the cracking resistance of asphalt pavement at low service temperatures and its rutting resistance at high service temperatures. However, the elastomer modification tends to decrease the aging resistance of asphalt pavement unless periodically i.e. semiannually fog sealed. Rubber modification results in better rutting resistance and higher ductility of the asphalt pavement, but the modifier is sensitive to decomposition and oxygen absorption.

- The content of added polymer in the asphalt matrix is an import factor that influences the properties of PMB. In most cases, the content of plastomers and elastomers are at the low and medium levels (no more than 7 wt.%), while the rubbers are usually at the high content level (typically 15 to 20 wt.%).
- Compatibility between asphalt and modifiers will prevent agglomeration of the polymers in the asphalt matrix during storage, pumping, construction, and service. The content and size of the asphaltenes and polymers, and the aromaticity of the maltene phase are the main factors that determine the compatibility. The storage stability of the SBS modified asphalt (a common plus-grade binder) is typically improved by adding sulfur or alternative vulcanization accelerator depending on the bitumen chemistry.
- Based on the evaluation of the states' specifications, the property requirements for polymer modified asphalt are higher than neat asphalt binders. The vast majority of states focused on elastomers (SBS, SB, SBR) or crumb rubber as polymer modifier (i.e., for plus grade PG asphalt binder) and have performance based binder specifications as their specification calls out either MSCR or elastic recovery. Different states have different requirements on the elastic recovery, flash point, solubility, and dynamic shear, but the requirements for rotational viscosity, creep stiffness and *m*-value, and mass change are similar. The current requirements for polymer modified asphalt in New Mexico are very limited.
- A systematic study was completed by the Asphalt Institute in 2005 which analyzed field performance data of asphalt pavement test sections from 84 sites representing various pavement designs and climatic conditions across North America and provided rich data contrasting neat asphalt and polymer modified asphalt pavements. Many Long Term Pavement Performance (LTPP) sites were included in these 84 sites. The study revealed that the polymer modified asphalt pavements featured significantly less distresses, in terms of less rutting depth and less percentages of thermal (transverse) cracking or fatigue (alligator) cracking. Many of the sites demonstrate the benefits of using plus grade PG asphalt binders. Long-term pavement performance is complicated by many uncontrollable or un-documented factors in the field and it is difficult to correlate the laboratory testing results with the field performance results.
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sustainable pavement binder. Even a slight 0.4-0.8 year increase in service life will justify the cost of the polymer modification. The polymer modification increased the service life of asphalt pavement in Colorado, Texas, and Alabama by 3.1 years, 2.5 years, and 4 years, respectively. The Asphalt Institute ER-215 study across North America predicted a service life increase of 2 to 10 years, depending on the specific pavement site conditions. To ensure cost-effective polymer modification for PMBs, it is important to adopt reasonable design of asphalt pavement and implement good quality control of the modification process.

- In Arizona, crumb rubber is commonly used in asphalt pavement. For the PG 76-22 TR+ binder, a minimum 2 wt.% of SBS and 8 wt.% of crumb rubber are required. The benefits include: a) Reduced reflective cracking via improved elastic properties (**elastic recovery of at least 55 percent** at 10°C); b) Increased aging resistance; c) Increased durability; d) Reduced noise; e) Improved cost-effectiveness.
- In Florida, according to the Accelerated Pavement Testing (APT) method, the rutting and fatigue cracking performance of HMA mixtures (with neat PG67-22) were improved by the SBS modification. After 100,000 Heavy Vehicle Simulator (HVS) passes, the **rutting** of the lane constructed with PG 76-22 and PG 82-22 binders **decreased 50 percent and 80 percent** compared with the lane without SBS modification. At 20°C, the **fatigue resistance** of the PG 82-22 (plus-grade, with SBS at 6 wt.%) and PG 76-22 (plus-grade, with SBS at 3 wt.%) binders was **20 times higher** than the PG 67-22 binder. The fatigue life of the PG 82-22 binder was about 7 times higher than the PG 76-22 binder.
- In Texas, plus grade PG asphalt binders (e.g., SBS co-block polymer-modified PG 76-22, PG 70-22, PG 58-34, and PG 58-40) exhibited outstanding benefits, relative to neat asphalt binders. Most of the elastomer modified binders have **as much as a 40 percent less hardening rate** than the neat binders. If the air voids in the Texas asphalt pavements are kept stable (lower than 2 wt.%), these reduced hardening rates can translate to 15 to 20 years of service life extension for asphalt pavement.
- In Oklahoma, three asphalt binders (PG 64-22, PG 70-28, PG 76-28 with an elastomer modifier (SBS) and two anti-stripping additives (Adhere HP-Plus and Perma Tac Plus) were used to evaluate the modification effects. After the change of grade, the PG 76-28 can reach the level of PG 82-28.
- In Colorado field studies, though the rutting resistance of pavement constructed by polymer modified asphalt binders (EVA, SBR, or styrene block copolymer) was not remarkably increased, the cracking resistance was considerably enhanced in the sections constructed with modified asphalt binders. Compared with the control sections, the cracks in the modified sections decreased by 50 percent for longitudinal and transverse cracking.

- In Mississippi, the addition of polymer was found beneficial to the pavement performance at both high and low temperatures. The field evaluation further confirmed the improved rutting performance of the modified binder sections, relative to the neat asphalt section.

5.2 RECOMMENDATIONS

- NMDOT is strongly recommended to adopt MSCR into the binder specification and implement plus grades of PG asphalt binder, in light of very small cost increase and significant performance improvements in plus-grade asphalt pavement. To optimize the use of such binder in the State of New Mexico, NMDOT is recommended to investigate the appropriate use of PMBs that suit the local traffic and environmental conditions and the appropriate curing and mixing conditions to maximize long-term performance of such plus-grade binders in dense graded asphalt pavement.

- When it comes to the use of PMBs, agencies cannot simply rely on the use of properties (elastic recovery or MSCR) as a performance specification and ignore the prescriptive spec. (e.g., appropriate SBS content and molecular weight to ensure good compatibility with asphalt binder). The compatibility issue between SBS and asphalt may not be evident in the laboratory test but may aggravate over time due to storage, non-uniform mixing during construction, or in-service changes over time. In other words, one could have a PMB that passes the laboratory performance specification but show poor performance for dense graded mix in the field. So to be safe, it would be preferable to add prescriptive specifications.

- The NMDOT specification of PMBs has been successfully applied in the OGFC. However, some requirements still need to be optimized in a dense graded mix binder. This is considering that the OGFC is only used as a highly porous surface and its stress condition, binder content, and porosity are considerably different from the dense graded mix. Changes are proposed to the specification for dense graded mix binder, as a result of this study (see the Appendix).

- Use elastomers and plastomers at no more than 4 wt.% or use crumb rubber at 15 wt.% to 20 wt.% by weight of asphalt binder. It is ideal to form double interlock continuous phases of both elastomer and plastomer in the asphalt matrix.

- The asphalt source must be analyzed before mixing with polymers to guarantee their compatibility. Specifically for SBS block copolymer modification, the content of butadiene must be as high as 60 percent to 70 percent and the molecular weights of the styrene fraction must be higher than 10,000 to guarantee the polystyrene-rich domains. This is typically done by the asphalt supplier.

5.3 SUGGESTED FUTURE STUDIES

Future research should focus on the NMDOT service environments and the unique challenges and constraints in the State of New Mexico:

1) Identify commercial and/or innovative elastic polymer modified binders that meet the proposed NMDOT binder specification;

2) Test engineering properties of interest in the laboratory in an accelerated manner (both binder and mixture);

3) Monitor the asphalt pavement sections constructed with select plus grade binders and periodically assess their characteristics;

4) Conduct life cycle assessment of cost and sustainability for the neat and plus grade asphalt pavements.

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APPENDIX A. PROPOSED NMDOT BINDER SPECIFICATION

State: New Mexico	**Materials:**
Date Last Reviewed:	**Web Address:** www.nmshtd.state.nm.us
Materials Engineer:	**Contact Info:**

Asphalt Binder		
Section 402	Description	Performance-graded asphalt binder shall meet the requirements of AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder.
	PMA's	None stated.
	Exclusions	None stated.

New Mexico		**Table 1: PG Requirements for Performance-Graded Asphalt Binders**							
Property		**Test Method: AASTHO (T), ASTM (D) or other**	**Requirements by Performance Grade**						
			58-28	**64-28**	**64-22**	**70-28**	**70-22**	**76-22**	**82-22**
ORIGINAL									
Flash Point, °C		T48	230 min	230 min	230 min	230 min	230 min	230 min	230 min
Rotational Viscosity, Pa·s	135 °C	T316	3.0 max	3.0 max	3.0 max	3.0 max	3.0 max	3.0 max	3.0 max
Dynamic Shear, kPa (G*/sin δ, 10 rad./sec)	At Grade Temperature	T315	1.00 min.	1.00 min.	1.00 min.	1.00 min.	1.00 min.	1.00 min.	1.00 min.
RTFO RESIDUE		T240							
Mass Change, percent		T240	1.00 max.	1.00 max.	1.00 max.	1.00 max.	1.00 max.	1.00 max.	1.00 max.
Dynamic Shear, kPa (G*/sin δ, 10 rad./sec)	At Grade Temperature	T315	2.20 min.	2.20 min.	2.20 min.	2.20 min.	2.20 min.	2.20 min.	2.20 min.
PAV RESIDUE		R28	100 °C, 20hrs, 305 psi						
Dynamic Shear, kPa (G*/sin δ, 10 rad./sec)	At Test Temperature	T315	19 °C	22°C	25 °C	25 °C	28 °C	131°C	34 °C
			5000 max.	5000 max.	5000 max.	5000 max.	5000 max.	5000 max.	5000 max.
Creep Stiffness, MPa	At Test Temperature	T313	-18 °C	-18°C	-12 °C	-18°C	-12 °C	-12 °C	-12 °C
			300 max.	300 max.	300 max.	300 max.	300 max.	300 max.	300 max.
m-Value			0.300 min.	0.300 min.	0.300 min.	0.300 min.	0.300 min.	0.300 min.	0.300 min.
Direct Tension, percent Strain	At Test Temperature	T314	-18 °C	-18°C	-12 °C	-18°C	-12 °C	-12 °C	-12 °C
			1.00 min.	1.00 min.	1.00 min.	1.00 min.	1.00 min.	1.00 min.	1.00 min.
NOTES		None.							

New Mexico	**Table 2: PG Requirements for Performance-Graded Asphalt Binders**

Property		**Test Method: AASTHO (T), ASTM (D) or other**	**Requirements by Performance Grade**						
			58-28	**64-28**	**64-22**	**70-28**	**70-22**	**76-22**	**82-22**
ORIGINAL									
Specific Gravity	25°C	T228-06	Report	Report	Report	Report	Report	Report	Report
Penetration, tenths of mm	25 °C	T49	-	-	-	-	-	-	-
Elastic Recovery, percent	25 °C	T301	-	-	-	-	-	-	-
Ductility, cm	25 °C	T51	-	-	-	-	-	-	-
Force Ductility, Force Ratio	4 °C	T300	-	-	-	-	-	-	-
Viscosity, Poise	60 °C	T316	-	-	-	-	-	-	-
Toughness and Tenacity	Toughness, in-lbs.	D5801	-	-	-	-	-	-	-
	Tenacity, in-lbs.		-	-	-	-	-	-	-
Softening Point, °C (°F)		T53	-	-	-	-	-	-	-
Separation of Polymer, °C (°F)		D5976	-	-	-	-	-	-	-
Solubility, percent		T44	-	-	-	-	-	-	-
Homogeneity (Screen Test)		-	-	-	-	-	-	-	-
Spot Test		T102	-	-	-	-	-	-	-
RTFO RESIDUE		T240							
Elastic Recovery, percent	25 °C	T301	-	-	-	-	-	-	-
MSCR	J_{nr}	TP70	-	-	-	-	-	-	-
	percent Recovery		-	-	-	-	-	-	-
NOTES		None.							

New Mexico		**Table 3: PG Requirements for PMB**	
Property		**Test Method: AASTHO (T), ASTM (D) or other**	**PMB**
ORIGINAL			
Flash Point, °C		T48	230 min.
Rotational Viscosity, Pa·s	135 °C	T316	3.0 max.
Dynamic Shear, kPa (G*/sin δ, 10 rad./sec)	64 °C	T315	1.00-2.50
RTFO RESIDUE		T240	
Mass Change, percent		T240	1.00 max.
Dynamic Shear, kPa (G*/sin δ, 10 rad./sec)	64 °C	T315	2.20-5.50
PAV RESIDUE		R28	100 °C
Dynamic Shear, kPa (G*/sin δ, 10 rad./sec)	At Test Temperature	T315	-
			-
Creep Stiffness, MPa	At Test Temperature	T313	-18 °C
			300 max.
m-Value			0.300 min.
Direct Tension, percent Strain		T314	-
NOTES			

New Mexico		**Table 4: PG Plus Requirements for PMB**	
Property		**Test Method: AASTHO (T), ASTM (D) or other**	**PMB**
ORIGINAL			
Specific Gravity	15.6°C	T228	-
Penetration, tenths of mm	25 °C	T49	-
Elastic Recovery, percent	25 °C	T301	60-65 min.
Ductility, cm	25 °C	T51	-
Force Ductility, Force Ratio	4 °C	T300	-
Viscosity, Poise	60 °C	T316	-
Toughness and Tenacity	Toughness, in-lbs.	D5801	-
	Tenacity, in-lbs.		-
Softening Point, °C (°F)		T53	49 (120) min.
Separation of Polymer, °C (°F)		D5976	10 max.
Solubility, percent		T44	98 min.
Homogeneity (Screen Test)		-	-
Spot Test		T102	-
Polymer Content, SBS, percent (solids-based)			3.0 min and 5 max.
Molecular weight of styrene fraction in SBS			>10,000
content of butadiene			60 percent - 70 percent
Tire Rubber, percent		-	15.0 – 20.0
RTFO RESIDUE		T240	
Elastic Recovery, percent	25 °C	D6084	-
MSCR	J_{nr}	TP70	1.
	percent Recovery (3.2 kPa)		1.
NOTES		1. The MSCR value needs to be identified after local testing.	

APPENDIX B. SUMMARY OF PMB SPECIFICATION IN ALL STATES

STATE	MSCR	ELASTIC RECOVERY, %	POLYMER TYPE	POLYMER CONTENT
Alabama	-	PG 76-22 (50 min) -- (RTFO)	SBS, SB, and SBR	1.5% in PG 64-22, and 2.5% min in PG 76-22 (*FTIR determination of the content of styrene and Butadiene before using*)
Alaska	-	PG 58-28 (50 min) and PG 64-28 (60 min) -- (RTFO)	-	-
Arizona	-	PG 70-22 TR+ (55 min) and PG 76-22 (55 min) TR+ --(ORIGINAL)	Crumb Rubber + SBS	8% Crumb rubber + 2% SBS (min)
Arkansas	-	PG 70-22 (40 min) and PG 76-22 (50 min) --(ORIGINAL)	SBS, SB, and SBR	-
California	-	PG 58-34M (75 min) PG 64-28M (75 min) and PG 76-22M (65 min) -- (RTFO)	Crumb Rubber (PPA is not allowed)	10% (min)
Colorado	-	PG 70-28 (50 min) and PG 76-28 (50 min) -- (RTFO)	NO acid or alkali modification	-
Connecticut	* supplemental requirements in development * The binder shall meet the requirements of AASHTO M-320(M) and AASHTO R-29(M).	-	-	- Unless otherwise noted, PG 76-22 asphalt modified with a SBS polymer.
Delaware	-	-	-	*using elastomers by default, there is no

				plastomer source in the state.
Florida	$J_{nr,diff}$ (%)--75 (max), and $J_{nr3.2}$ (kPa^{-1})--"V" 1.0 max in PG 76-22 (PMA) and PG 76-22 (ARB) and "E" 0.5 max in PG 82-22 (PMA). %R3.2 ≥ 29.37 ($J_{nr3.2}$)-0.2633	-	SBS, SB	-
Georgia	$J_{nr3.2}$--1.0 max. Recovery 35% min.	-	SBS, SB, SBR, Crumb Rubber.	10% Crumb Rubber min, and polymer additives with 4.5% weight of crumb rubber.
Hawaii	-	-	-	Tropical, ocean moderated temperatures: not relevant to the continental United States
Idaho	-	50	-	-
Illinois	-	60 min in SB/SBS modified PG 64-28, PG 70-22, and PG 70-28, 70 min in SB/SBS modified PG 76-22 and PG 76-28, 40 min in SBR modified PG 64-28, PG 70-22, and PG 70-28, 50 min in SBR modified PG 76-22 and PG 76-28. Should be 80% min, when specified for mixture IL-4.75.	SB, SBS, SBR	-
Indiana	-	-	SBR	2.5% min
Iowa	* Effective in Jan. 2015	65 (min)	NO Acid	-
Kansas	-	45 min in polymer modified PG 64-28	Supplier determines	-

		and PG 70-22, 65 min in polymer modified PG 70-28 and PG 76-22, 70 min in polymer modified PG 70-34, 75 min in polymer modified PG 76-28, PG 82-22 and PG 82-28.	polymer.	
Kentucky	-	75 min in PG 76-22	SB, SBS	-
Louisiana	-	40 min in PG 70-22M, and 60 min in PG 76-22 and PG 82-22.	-	-
Maine	* supplemental requirements in development; currently using Special provisions.	-	-	-
Maryland	-	-	Elastomers	-
Massachusetts	* supplemental requirements in development	-	SBR	-
Michigan	* Effective in Jan. 2015	For SBS modification, 60 min in PG 58-34, PG 64-28, PG 70-22, and PG 70-28. 70 min in PG 64-34, PG 76-22, and PG 76-28. For SBR modification, 40 min in PG 58-34, PG 64-28, PG 70-22, and PG 70-28. 50 min in PG 64-34, PG 76-22, and PG 76-28.	SBS, SBR	-
Minnesota	* Effective in Jan. 2015	65 min in 92, 98, 104 °C (Spec base) and 60 min in 92, 98, 104 °C (Spec	-	-

		w/ Tol).		
Mississippi			SBS, SBR	
Missouri	-	55, 65, 75 min in 92, 98, 104 °C, respectively.	Ground Tire Rubber	Ground tire rubber with 4.5% of transpolyoctenamer rubber.
Montana	* Researching using the % recovery from the MSCR test as an indicator of presence and effectiveness of polymer and ultimate binder performance (and replacement for PG+ specifications).	-	-	* All of the PG 70-28 and almost all of the 64-28 grades supplied for MDT projects are polymer modified in large part to meet Superpave grading requirements (as called for by the contract).
Nebraska	* Effective in Jan. 2015	65 min	SB, SBS, SBR	-
Nevada	$J_{nr3.2}$, kPa^{-1}, 2.00 max, $R_{3.2}$, %, 30.00 min, $J_{nr,diff}$, Report.	-		
New Hampshire	* supplemental requirements in development * following the M332-14 and T350-14 specifications	-	SB, SBS	* uses a PG 64E-28 grade for polymer modified asphalt binder
New Jersey	-	60 in PG 76-22	SB, SBS	-
New Mexico	-	-	-	-
New York State	-	60 min in PG 58-34, PG 70-22, and PG 76-22.	-	-
North Carolina	-	-	SB, SBS, SBR	-
North Dakota	* Effective in Jan. 2015	-	-	-
Ohio	-	65 min in PG 64-28M, and PG 70-22M, 75 min in PG 76-22M, and 90 min in PG 88-22M.	SB, SBS, SBR	SB and SBS with butadiene content higher than 68%

Oklahoma	% recovery, (3.2 kPa) 95 min	65 min in PG 70-28OK, and 75 min in PG 76-28OK.	-	-
Oregon	-	50 min in PG 70-22 and PG 70-28.	-	-
Pennsylvania	-	60 in PG-76-22	SB, SBS	-
Rhode Island	* supplemental requirements in development; currently using Special provisions.	-	-	-
South Carolina	-	-	SB, SBS, SBR	-
South Dakota	* Effective in Jan. 2015	60 min	SBS, SBR	-
Tennessee	-	45 min in PG 70-22, 65 min in PG 76-22, and 70 min in PG 82-22.	SB, SBS, SBR	-
Texas	-	See table 3-4	-	-
Utah	Report only	See table 3-4	-	-
Vermont	* supplemental requirements in development; currently using Special provisions.	-	-	-
Virginia		70 min in PG 76-22		
Washington	-	60 min	-	-
Washington D.C.	-	-	-	-
West Virginia	-	70 min in PG 76-22	-	-
Wisconsin	* Effective in Jan. 2015	65 min in 92, 98, 104 °C (Spec base) and 60 min in 92, 98, 104 °C (Spec w/ Tol)	-	-
Wyoming	-	60 min	-	-

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